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It is with great pleasure that I welcome you to the twenty-second AMSAT Space Symposium and Annual meeting in the Washington D.C. Area.

It is very fitting that this year we should meet again in the Washington Area as Washington D.C. was the birthplace of AMSAT Thirty-Five Years ago. Now we are in a process of renewal as a new AMSAT President has just been elected by your Board of Directors, and I, by the time you read this, will be the Immediate Past President.

The Past four years have seen 9/11, Economic depression, and the failure of several world renowned companies. In spite of this AMSAT, with your support, has maintained its financial viability and has launched ECHO AO-51, which under the circumstances is an achievement.

Now we have returned to the place of our birth for renewal and refreshment. With new members of the Board of Directors (2003 and 2004) together with a new vision and mission, we will work together to develop EAGLE a high orbit satellite with exciting new Ham digital opportunities as well as maintaining the more traditional operations.

This satellite will, like its predecessors, cost dollars to build. It will therefore rely on the members of AMSAT to provide most of the funding, and we must therefore work together to help develop that funding. Washington is a place to start the process by renewing your subscription to AMSAT, the Presidents Club, and making direct donations to the EAGLE fund.

This meeting is unusual as it is the first time that a Joint meeting between AMSAT and ARISS has taken place, and I offer a special welcome to the international ARISS delegates who are present, I hope you enjoy our symposium and find it interesting.

To the delegates from other AMSATs, I hope you find our meeting to be stimulating and our plans for further satellites to your liking.

Without fear of repeating myself, may I say "Welcome" wherever you have come from.

Robin Haighton VE3FRH
President AMSAT-NA

ECHO's Last Month on Earth
(The ECHO Launch Campaign)

Chuck Green, N0ADI

This is the record of ECHO's last month on earth. It is also known as the ECHO launch campaign. I'll include nontechnical things I saw and experienced during this time as well.

The ECHO launch campaign began for me on June 1, 2004 when I left Tucson. I would not return to Tucson until July 1, 2004. The itinerary took me first to Colorado for two days with Jim White and ECHO. Then I took ECHO to SpaceQuest in Virginia where I put the finishing touches on it and did final testing. Then on June 9 I carried ECHO to Moscow. After one night in Moscow, I took ECHO to Baikonur, Kazakhstan for its launch. I was joined by the SpaceQuest team in Virginia and their two satellites also being launched with ECHO. They are Dino, Mark, Glen and Lyle. All the transportation and customs arrangements had been taken care of by them. Baikonur comes within 300 km of being 180 degrees longitude from Tucson, a long way away.

I left Tucson around noon and flew to Denver where Jim picked me up and took me to his home in Parker, CO. We went over the status of ECHO, making a list of the things that still needed to be done before it would be ready for launch. Jim also gave me his first cut at the final check-out procedure.

The next day I made modifications and additions to the wiring harness. There were several small changes needing to be done to the wiring. I finished it after lunch and Jim checked it all out functionally.

I then went through the check-out procedure several times as Jim updated the instructions for completeness. ECHO was working very well! We started packing ECHO just before dinner. First it was bagged and then slid into its very well padded shipping case. We put a static protection wrist strap and a pair of white gloves in a bag and put that on top. If the security people want to inspect ECHO I would ask them to put the wrist strap on and wear the white gloves.

I won't tell you about the wonderful steak dinner barbecued on Jim's deck. After dinner we discussed all the world's problems and came up with solutions to each.

The next morning Jim joined me for breakfast and then took me to the airport. This gave me three hours to get checked in and through security with ECHO. I took ECHO as carry-on baggage which means I had to take it through all the security checkpoints at the airport.

First I obtained my boarding pass and checked my luggage. Then it was off to security. The queue was about 30 minutes long as we zigzagged back and fourth across this large open area. With my very full briefcase in one hand and ECHO in the other, my arms were getting longer.

Security was interesting. They couldn't see anything except a big black blob on the x-ray machine so they wanted a closer look. First, they were confronted by two yellow static warning stickers pasted across the lid-to-box interface. They would have to tear them if they wanted to open the box. It took them about five minutes to decide they had to open the box.

So they opened the lid where they were confronted by the bag with wrist strap and white gloves. They set that bag aside and now they could see the bottom of ECHO through its anti-static bag. But that's all they could see because of all the padding around ECHO. I told them that if they wanted to open the anti-static bag, I wanted them to put the wrist strap and white gloves on. The young lady who was the one that opened the box said "no way I'm putting that thing on my wrist!" By then several of her coworkers were also standing around giving advice.

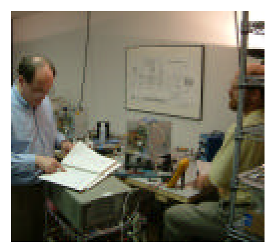
The wrist strap and white gloves were more than they were prepared to deal with. They didn't know what to do. So they called their supervisor. It didn't take her long to figure out she didn't know what to do either. So she called her supervisor. Now there were lots of people standing around scratching their heads.

This supervisor at least knew to ask some questions. He asked, "is this thing actually going into orbit?" "Yes," I said cheerfully. Then there was more head scratching and finger poking. Then he asked if I had a business card. I had anticipated this so I had an AMSAT business card handy. By then another level of management had arrived and she asked if she could keep my card. I said yes and offered her another. She said one was enough and that I could go.

What a disappointment! I had all these other things ready to say. And no one had put on those white gloves and wrist strap. They never opened the anti-static bag ECHO was in. Oh well, I wasn't going to say anything more if it wasn't needed. And besides, having had about 15 minutes standing there while they debated the content of ECHO I had already put my shoes back on and was ready to go. I was out of there!

When it was time, I got on the plane and put ECHO in the overhead bin. I had been careful to get a flight on a 777 which has huge overhead bins. ECHO slid in with no problem. This reminded me of an experience 11 years ago taking AO-27 to the launch site and it did *not* fit in the overhead bin as expected. But that's another story. Back to the present. I couldn't help but to wonder if maybe there was still enough room in that overhead bin for the screaming baby across the isle.

Mark met me at the airport in Washington and took me to the hotel where I dropped my luggage. We then went straight to SpaceQuest to get to work. So, starting about 7 pm we worked until a little after midnight. SpaceQuest was one very busy place. There were three satellites being prepared. There were things everywhere. It took a while to clear a place for ECHO and me.



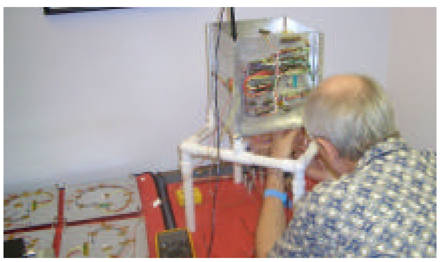
I unpacked ECHO, removed the wiring harness and unstacked all the modules. We reviewed the status of things and I was prepared to start finishing each module… tomorrow.

I spent most of the next day cleaning the inside of each module, putting RTV on every screw head and nut, and securing wiring with cord and RTV. I also removed the fuse from the main computer board and replaced it with a zero ohm resistor. And I replaced the Watchdog Enable jumper with wire. There was a connector in the top module to install. There were a few other minor things to take care of inside the modules, but they were quickly finished. I stacked the modules as each was completed. ECHO looked like a satellite again.

After dinner I worked on the solar panels. Each needed its wiring added, its connector installed, and a thermistor added and wired. I finished one of the six before it was midnight again.

The following day Mark needed the hybrid to do some testing of the splitter/preamp (for 10 meters). Obviously it is in the bottom module so I unstacked ECHO again. We spent quite a bit of time trying to get the splitter/preamp working. We finally concluded that it was not going to work. Stan Wood would build another one the next day and we would get it on Tuesday. I also did some more work on the solar panels. And I took a lot of pictures.

I spent the next day doing nothing but solar panels. They are finished now. We also quit early, about 10 pm, went to dinner and I was actually in bed at 11:30.



The next day involved a series of human errors while attempting to test ECHO. It took all day to work through them but we finally got the testing environment properly set up and all the tests ran without difficulty. ECHO looked good!

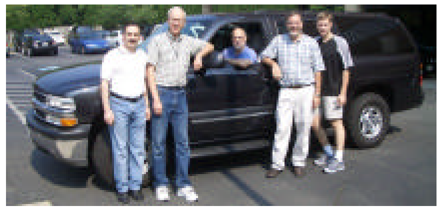
I also put the last module on the stack and installed the wiring harness for the final time. I secured all the screws, replaced the coax that is in the chimney and installed the corner rods which hold the stack together. The solar panels were packed along with the magnetic rod and corner reflectors. Things were coming together well (and, as usual, at the last minute).

The next morning we closed out the top box (receivers) and cleaned the outside of the satellite. I tied up a few things and installed the separation switches. I put a temporary protective cover on the top and chimney side.

We put ECHO in the vacuum chamber for an hour and pushed it hard with both 70 cm transmitters running full power. The battery went down quickly under this load since we were not providing any outside power. But it made it through the test. Everything worked well that we could test. The satellite was only a little above room temperature after this and the top two trays were basically at room temperature.

We also checked the sensitivity of all the 2 M receivers and SQRX and they were all very good. SQRX is the least sensitive because of the way it is coupled to the antenna. We also characterized the Received Signal Strength Indicator (RSSI) of the SQRX for future use. And we measured the power out of the 70 cm transmitters at various power settings, again for future use. ECHO was then placed in its shipping container ready for the trip to the launch site.

We left SpaceQuest about 10 am on the 9th of June and drove to New York, JFK.



Then we started the process of getting through everything to get the three satellites and us on the Aeroflot flight to Moscow. First we got in a line. The line wasn't going anywhere, just forming as we were about three hours before scheduled take-off time. It was the check-in line for the flight. There were already a few people ahead of us.

Then Dino, Mark and Lyle went to the customs office with the paperwork for our satellites. That took quite a while and in the end the lady just told them to go ahead without doing any paperwork. Meanwhile, Glen and I were trying to figure out how we were going to move five people's things and the three satellites along in the line. We managed to advance quite a way when Mark and Lyle showed up. Dino was still stuck with the customs people.

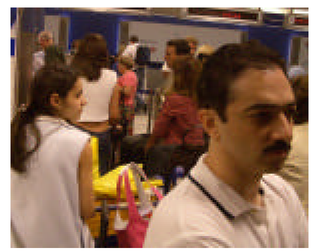
Finally Dino showed up just before it was our turn to check in. Check in went smoothly until the lady noticed the satellite boxes we had. She told us to go ask this guy on the other side of the room about it. So we did. That was a mistake. I think the only English word he knew was "no" and he pointed to the little rack used as a fit check for carry-on items. We walked over to the rack but is was obvious our satellites would not fit in that little space so we just walked past it and on to security.

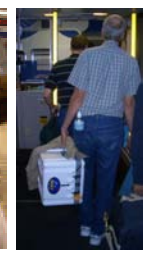
We had notified security in advance that we would be bringing the three satellites and had the names and phone numbers of several levels of security management ready. But since they were expecting us, there were no problems. We were early and there were very few people around. They took one of the satellites and opened the box. They just poked around a bit and we were on our way to the gate.

Since we were early we sat in the waiting room at the gate for quite a while. A couple of times the guy that had told us "no" came through the area. He didn't seem to notice us, but we couldn't be sure. He walked around in such a way as to make sure everyone understood he was the man in charge of everything.

They were running a little late. We didn't start boarding until it was time to leave and this was a completely full flight.

Guess who was taking the boarding passes. Yup, it was the guy who had told us "no" before. This did not look good. But he was concentrating so hard on the boarding passes that I don't think he even saw what we were carrying. We went right through and onto the plane. We quickly put the satellites in the overhead bins. We knew this would also be a 777 with large overhead bins.





There were additional delays waiting to take off. We finally got off the ground about 1.5 hours late. And somewhere off the east coast of Canada it became tomorrow.

Almost everyone on the plane was Russian. We were definitely a very small minority. I was seated next to a young Russian woman. She was just right for someone to sit next to. She was friendly but didn't talk too much and was not large. She spoke very good English. She told me that the buzz among the passengers was that we were very suspicious characters with those three white boxes. She said most people believed we were carrying donor organs. That works for me.

Finally, we descended through the clouds and landed in the rain in Moscow. Getting through customs was easy. SpaceQuest had hired a company called Express Service to help us through. These people have passes so they can enter the area where the passengers are before they go through customs. They checked to make sure we didn't have to declare anything except the satellites and ground support equipment. They then took Mark and Dino and the satellites with ground support equipment through the customs process with absolutely no difficulty. And the rest of us went through the green line with nothing to declare. The longest delay we had was waiting for our checked bags.

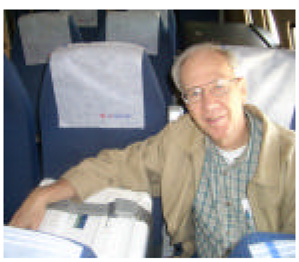
We then took the hotel shuttle bus and checked into the hotel. We rested a bit and then Lyle and I had dinner with Alexander

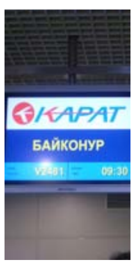
Zaitzev, RW3DZ who came to see us. Dino, Mark, and Glen joined us after dinner as they had a dinner meeting with some people from Kosmotras.

We were up at 4:40 am the next morning to be driven to the other side of Moscow to another airport where our flight to Baikonur would depart.

This was a smaller airport and there was not any English on the signs. We finally found the correct place where we waited for the Express Service people. We also met up with the Italian team and the team from Saudi Arabia there. It was good to meet old friends from Saudi Arabia. I went there three times in 2000 when they were preparing their first two satellites. The world has sure changed since then.

We finally got through all the mess associated with checking our bags and getting our boarding passes. It is extremely helpful having the people from Express Services. If it weren't for them, we would probably still be back at the airport.





It was cool, going on cold, in Moscow when we departed. It was hot in Baikonur. We then stood in this building that was probably actually a bomb shelter with only a couple of doors and no windows while the dog sniffed our luggage just outside. There were more forms to fill out before getting through this mess. This time there were plenty of military people out on the runway to meet us as well as just standing around watching us.

Since Baikonur is administrated by both the Russians and the Kazakhs we were able to see how much they cooperated, or should I say, tolerated each other. Customs was handled by the Kazakhs while passport control was handled by the Russians, both at the same table in this very hot room. This is a controlled city and the only way you get here is by invitation. We were told that if we leave the city without our papers we would not be able to get back in.

The security presence (they used to be called the KGB but that has changed to something else) is very understated but also very obvious. Some things they don't try to hide. Like the guy with the video camera standing in front of our bus taking everyone's picture. Then he got on the bus and photographed what we were doing there. Once when he was photographing me, I waved back at his camera. He actually smiled when I did this, but he quickly caught himself and returned to his usual blank expression. He was obviously not a regular, just a contractor.

Let me go back to the airplane. It was a fairly large Russian plane, a TU154, maybe 40 years old. Maintenance is not high on their priority list. About all they did was paint it approximately every 5 years or so (determined by counting the layers of chipping paint on the seat-back in front of me). It was painted a dull gray. The interior was falling apart. And the patches on the wings added to the character of the plane. It never got much above 11,000 feet. I suspect it could no longer maintain cabin pressure. And besides, there were no oxygen masks in the likely event of a problem. So they just stayed low. The faint smell of kerosene was an

added feature at no extra cost.

Lunch was interesting. We had our choice of "fish or meat". I chose the mystery meat. That was a mistake. I think it was chicken, but it was the skinniest chicken you ever saw. At least it was sliced thin with a very thick layer of breading on it, top and bottom. It was very filling; one bite was enough.

The head was a disgusting experience. The toilet wouldn't flush. And when I tried to get some water from the sink faucet, there was none. But for those lucky few that did manage to get their hands wet, there was a single hand towel hanging from the wall for everyone to use. I probably should have used the head on the other side of the plane. I'm sure it must have been much better; right.

Another nice touch was the fire brigade that was there to meet us when the plane stopped. They were there to hose down the breaks so they wouldn't catch fire and burn the plane before they could get us and our luggage off. That would be bad for business.

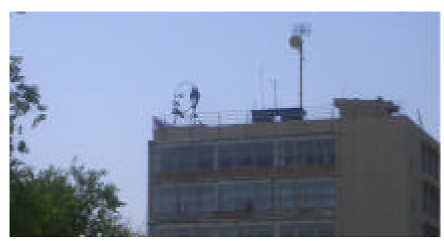
There isn't much to see out the window in this part of the world. But that's probably a good thing because I don't think the windows had been cleaned for the last 30 years.

We finally got through the control people and onto a bus to take us to our hotel. The trip was quite a sight. At first it was small run-down buildings. Next we went through a check-point at the edge of town where we could then see large run-down buildings. But the hotel was very nice. Apparently we were staying at the nicest hotel, the Sputnik Hotel. The teams from Saudi Arabia and France were also staying there.

We had dinner about 9 pm, finishing about 10 pm. Lyle and I then asked about access to the internet. We were told that we could have access in the meeting room but that it was difficult and that no one had succeeded yet. They gave us a full page of instructions how to do it. They were right, it was difficult. The telephone line had been blocked for outside calls; that didn't help. And the incomplete user ID and wrong password added to the challenge. But a little persistence paid off and we got on to the very slow dial-up connection to the internet

The next day was Saturday. More important, it was Russian Independence Day, a holiday. So there was no opportunity to work on preparing ECHO for launch. That would have to wait until the next day.

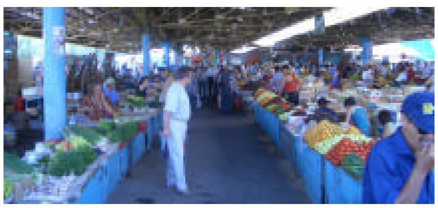
A tour of the city had been arranged for us with the bus leaving at 10 am. We didn't want to wait too late because it would be getting hot and the air conditioning on the bus wasn't working. They told us the day before when riding from the airport that they would have it fixed for us the next day, but somehow I doubted it.



Our guide, Boris, is an ex-military officer who spent 16 years here in Baikonur. He loves this city and is very proud of the accomplishments achieved here. He very much enjoyed telling us all about it… through an interpreter, Anna. Mostly, we stopped at monuments. This city is full of monuments. It was very interesting and I took a lot of pictures (something that is only allowed within the city and inside the satellite integration building some 60 km away).

It was all a little sad though. It's all falling apart. There was clearly no maintenance taking place. We were taken to a small observation structure overlooking the river. It was here that the decision was made who the first man to go into space would be. This clearly has great meaning to those who were a part of this place. I doubt it will still be standing a few years from now.

We also went to the bazaar where there were all sorts of fruits, vegetables, spices, etc. being sold. We were warned about what was safe to eat. I just bought bottled water since the tap water is not safe to drink. This place was large and crowded.



When we were getting off the bus back at the hotel, the Italian team challenged the French, US, and Saudi teams to a game of football at 7:30 pm. Lyle didn't go so that left four guys on the US team. We borrowed a Russian goalie and took on the Saudi's.

About half way through the game I felt a slight twinge in my left calf. But there were no substitutes so I kept playing. It got worse. Buy the end of the game I could hardly run. We really didn't stand much of a chance against the Saudi's and felt really good that they only scored three times. We did manage to get two shots off but none scored.

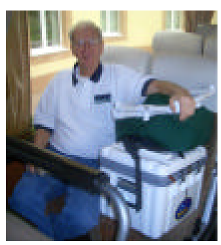
Then the Italians beat the French. So we then played the French. That didn't go any better. Again we gave up three goals without really giving their goalie much to do. By the end of this game, walking was really painful. So we walked the ½ mile back to our hotel. By the way, the Saudi's beat the Italians. And in celebration of the Saudi victory Dr. Turkey invited everyone to a party to be held the night of the 17th when integration should be finished.

After changing, I went straight to the pool. Glen and Dino were already there. Mark showed up shortly. Swimming was not difficult at all and actually made my calf feel better… until the Italians showed up. They wanted to play water polo. We couldn't pass that up. An hour later, I was ready for bed! But it was now 10 pm and time for dinner.

Dr. Turkey had invited almost everyone to dinner. One of his people is an excellent cook and had made arrangements to work with the hotel cook to prepare a traditional Saudi dinner, lamb, rice, fish, veggies, etc. It was excellent. So, about midnight, I finally found my pillow. But I was asleep before my head found it.

Let's see, the Americans (including one member born in Damascus), with a Russian goalie playing the Saudis, French and Italians… I think that's the way the world is supposed to work. Ironic that it takes place here in a place with such historic meaning for the last 50 years.

The next day was our first day working on ECHO to get it ready for launch. It is about 60 km to the integration facility but the road is so bad that the bus took almost 1.5 hours to get there. Each day we would go to the integration facility and return to the hotel on the bus so we would have no flexibility with our work schedule. We left the hotel at 8 am and returned to the hotel about 7 pm each day. Most days the trip would take about one hour each way but we went slow that first day because we were carrying many of the satellites.



The driver skillfully avoided the pot holes, well, most of them. The road is narrow but paved and in really bad condition. It was quite a ride. We were forbidden to take pictures along the way. And there were about 6 security people on the bus with us to make sure everything goes as it should. There were lots of interesting sights along the way but mostly things were abandoned. Everything appeared to be falling apart. It's really sad when you think of all the accomplishments that took place here.

When we arrived, each team was assigned an office. For us, this was where we would eat our lunch which we brought with us, prepared by the hotel. We were then given a briefing telling us about safety procedures and that we must always follow the same path through the building and not go other places. Once we started off in a direction we were not supposed to go and we were quickly stopped. Apparently in the next room was something they didn't want us to see.

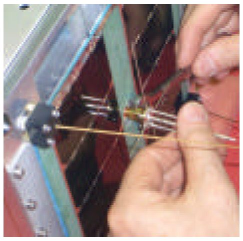
They had people everywhere watching us. When they gave the briefing, there were three photographers that came in to record the procedure. Then we were allowed to go to the clean room. Our shipping containers had been cleaned and placed in the clean room for us during the briefing.

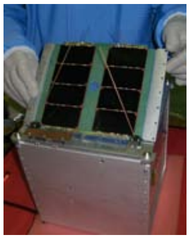
One of the satellites uses propellants and was already fueled; mono-methyl-hydrazine, etc. So we were each issued one very old, obsolete, and used gas mask. But we were not given any instructions as to how to use them. We figured it out. They make no requirements for us to keep them with us. That's strictly optional. And doors were locked for security reasons. Tables were in front of other doors, and we had to walk past the fueled satellite which was in the same room with us to get to where ECHO was. And there did not seem to be a safety officer. It was a disaster waiting to happen. Fortunately, we would only be in this situation for three days. How incredibly different from Kourou!

We took ECHO out of its shipping case and set it up on our table. We installed the bottom antennas, bottom solar panel, and corner reflectors. Then we turned ECHO on and successfully communicated with it over the umbilical from my computer. We then went through most of the test procedure Jim gave me and everything looked good to that point. The four two meter receivers and the two 70 cm transmitters were successfully tested. The next day we would do additional testing of the SQRS. We also installed the magnet before leaving for the day.

The ride back looked the same as the ride to the integration facility. This is a very desolate place. Mostly flat. We did see a few camels of the two hump variety. Walking was not easy that day.

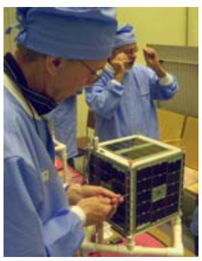
I added another challenge to my list of things to do while here. I'd try to find a way to make one of the security people smile.





The ride out to the integration site was a little faster the next day. We still hit all the bumps except they came at quicker intervals and were hit at a higher speed.

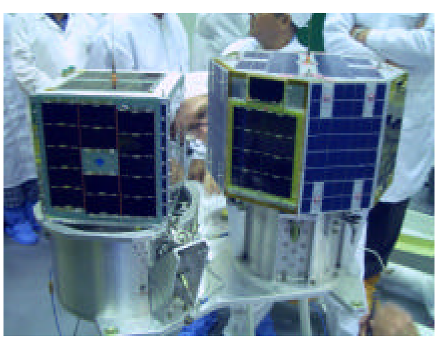
We finished preparing ECHO. All solar panels were installed as well as the remaining antenna. This was a slow process involving Loc-Tight on each screw (and there are a lot of screws holding the solar panels). Each panel was plugged into the satellite and the connector secured as it was placed against the body of the satellite. The antennas were then installed and secured.



We also did a fit check by placing ECHO on the base it would fly on to make sure everything was adjusted properly. A couple of adjustments to the base and everything was ready for integration.

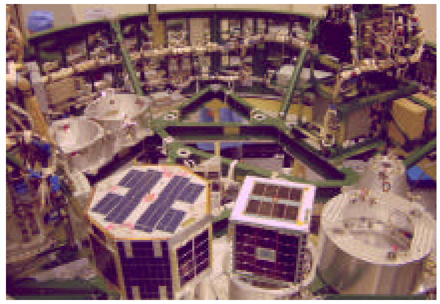
It was then time to weigh ECHO. We put it on a double-balance scale and it weighed in at 11.14 kg. Formal documents were prepared for the occasion and signed by Dino and Boris Zacarov, director of payloads.

We then put ECHO on the "dispenser" plate. This is a slab of aluminum about ½ square meter and 2-3 cm thick. ECHO and the Italian satellite sit on it. I then removed the carrying handles and closed out the top surface of ECHO.



The dispenser plate was then placed on the platform from which all the satellites are deployed. We were ready to fly.

In the afternoon we were taken to a place of great significance to those who are a part of the space and strategic programs here. It is a launch site where one of their ICBM's was to be flown for the first time. There was an event during preparation which caused



the second stage to ignite which ignited the first stage and… In the end, over 100 people died in that accident. That was October 24, 1960. The site was not restored. A monument now stands at its center. We were allowed to take pictures here so we walked around the area looking at what was once a very sophisticated facility. It is now mostly crumbling concrete.

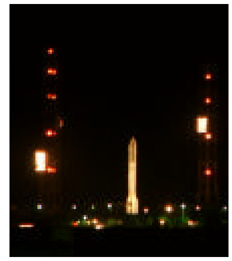
Three years later, again on October 24 there was another accident at another test launch facility where even more people were killed. Now, no one in Baikonur works on October 24. Instead, they all gather at a memorial monument in town to remember those people who died in service to their country.

I was passing through the hotel lobby late after attempting to get on the internet. Dr. Turkey was there talking with two others. He was going to Lebanon after integration and would be back for the launch. He invited me to go with him. An intriguing idea but I thought this place was enough adventure for this trip; maybe next time.

The following day most of the other satellites were mounted on their dispenser plates and placed on the launch platform. Things were drawing to a close.

The next day started with a wake-up call at 1:45 am. Yes, this was considerably earlier than usual. I had had two hours sleep. But there was an unusual opportunity and most people wanted to see it. The bus arrived to pick us up at 2:30 am and took us far out onto the base where the launch platform is for the Proton rocket. We knew fairly well just where we were as we traveled in the dark for about an hour because by now we recognized all the potholes hit along the way. This rocket is considerably bigger than the SS-18 ICBM we would be using to launch ECHO. It stands 75 meters tall. And it would be launched in about an hour.

We were allowed to take pictures from the observation position 2.5 km from the rocket. It looked impressive standing there. There was an occasional announcement in Russian over a loudspeaker. They told us when they switched to internal power. And they told us when there was a minute to go. But there was none of the 5-4-3-2-1 stuff that the French and Americans like to do at their launches. When it was time, the sky lit up and off it went. It was very spectacular as it climbed into the sky and arced over heading downrange. It was heading for a Geostationary orbit, taking 3.5 tones directly to its final orbit.



We could see two stagings as the second, and then the third stage took over. This is a four stage rocket. The sun would be up in another 30 minutes but the second staging was high enough that the smoke from this was lit up by the sun. It was all rather dramatic.

It lasted about a minute, then we got back on the bus for another hour of human vibration testing before arriving back at our hotel. There was about an hour remaining before we would have to get up and have breakfast before getting back on the same bus and riding over most of the same obstacle course to the integration facility for the day. But it was worth it.

All satellites except one of the three satellites prepared by the Saudis and the Russian satellite were in place on the launch platform. These two satellites would share a dispenser plate. The Saudi satellite was on the dispenser plate and they were ready to mount the Russian satellite. The Russian satellite was the only satellite that had not been seen by any of the other teams. For the next two hours there was a lot of measuring, pointing and other activity. It was all in Russian and none of the teams were being told what's going on. Finally, it was time for lunch so we all left the clean room.

While at lunch, Boris and his interpreter, Anna, came into our office where we were eating to read a formal statement. The Russian satellite would not be installed. It would not fly on this launch. Unresolved problems with its software were given as the reason. People in Moscow were working on what to do with the unterminated wiring connectors that would have been attached to the satellite's support base for pyrotechnic ignition and separation confirmation. They were to have this resolved in an hour and the integration process would then continue. By the end of the day, nothing had been decided.

This left us with time on our hands, a dangerous situation when there are radio amateurs around. Two of the Italians came into our room and we started to consider what could be done with the situation. We came up with a crazy idea. We would build another satellite… overnight. The Italians liked the idea and we would ask the other teams to help. We would use a dual-band HT that we had brought for testing ECHO along with extra batteries and solar panels that the Italians had. Throw in an antenna and lots of RTV and Kapton tape and we'd have a satellite ready to go by morning. Dino went to Anna to tell here of our idea. She took it to Boris. He called Moscow with this proposal.

We then asked if we could see the base plate on the Russian satellite as we would need it for our proposed satellite. The entire American team was taken into a back office where the Russian satellite was being prepared. We were given total access to it. They showed it to us from every angle. We did not photograph it.

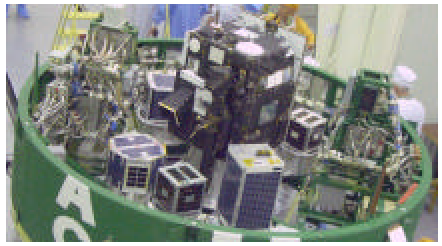
After about an hour, the call came back from Moscow. We would not be permitted to fly our proposed satellite. No explanation was given. We were not surprised. There would obviously not be time to vibration test it and without this test, there would be no way they would risk the other satellites with our new and untested satellite. We were thanked for our proposal and we praised the creativity of the Russian satellite that would unfortunately not fly. It was to deploy a solar sail to navigate the heavens. Hopefully, it can fly on the next launch.

We were not really disappointed. Remember the two hours sleep we had had the night before? So, at the end of the day we went back to the hotel for a little rest before dinner.

We normally would have headed for bed after dinner. But this was the night of Dr. Turkey's party to begin at 10 pm. So we went to the party. It was a quiet party and mostly we sat around and talked. The Kazakh girls hired to put on the party wanted to liven things up so they started a drinking contest about midnight. The French and Italians thought this was great fun. The Russians liked it as well. I disappeared and went to bed. I'm told the party ended about 3 am. That was a very long day.

There were plenty of red eyes the next morning. We went to the integration facility and watched the last Saudi satellite be put in place.

Then they installed the frame that sits on top of the satellites and integration was finished. They placed a seal on the joint between the two parts to satisfy our state department rules.



More forms were signed as each team formally turned their satellites over to Kosmotras. They would perform a few closeout items and the entire package was then turned over to the Russian military to be placed on the rocket already in the silo.

The faring would also be installed after we leave. This is considered "sensitive" which is the word they always use when they mean "classified." It is designed for carrying a military payload and they didn't want us to see it. The military payload would obviously be a load of nuke's aimed at your head. I think using these SS-18's for putting satellites in orbit is a much better idea. Things are changing.

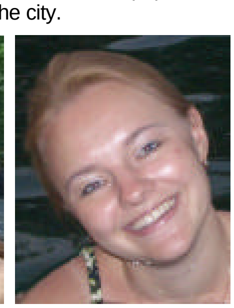
We left the integration facility for the last time around noon and went back to the hotel for most people to pack. The flight to Moscow would be leaving in a few hours. Remaining would be two of the French team, two of the Italian team, and me. The Italians were staying at the Cosmonaut Hotel nearby. I packed up as well and moved to the Cosmonaut. It cost about ¼ as much as at the Sputnik Hotel and I couldn't justify staying at such an expensive hotel. We would not have stayed there at all but that was the only place we could get reservations. Now that people are leaving I could get a room at the Cosmonaut.

The Cosmonaut is where the Russian Cosmonaut's stay when there is a manned flight. It seems like it was built about 50 years ago and, while receiving more maintenance than most buildings, it is still run down. I finally found the light switch for the bathroom; it was down the hall the other side of the bedroom door. Actually, each place has two bedrooms and a sitting room with a couch and two large stuffed chairs. That's also where the refrigerator and television are. There's no telephone, no trash can, and no soap. I'd get over it.

The two Italians, Mario and Fabrizio, that were staying are both PhD's in Astronautics and are with the University in Rome. They are half my age. They speak English well so we had no problems communicating. After I checked into the hotel they invited me to go running with them. I would have except that my leg was not completely healed so it would not be a good idea. When they returned, we went swimming in the pool.

At the Sputnik the pool was inside and very well kept. Here it is outside and had never had any chemicals added. The bottom was a little slippery from things growing there but otherwise it was just fine. And it was much bigger than at the Sputnik (10 x 25 meters).

About 10 pm we went into town for dinner. Things happen later here than I was used to. I suspect this was because for most of the summer it will be rather hot here. This was my first experience with the local culture. Previously all of our food had come from the hotel. For the next ten days we would have nothing to do but explore this small city. The city had a wall around it and our papers did not allow us to leave the city.

The Italians had met a young Kazakh girl, Gaukar, and she went to dinner with us. This made things a little easier as she was able to keep us from making too many mistakes. She only spoke Kazakh and Russian so neither Italian nor English were helpful. But the language problem just made it all that much more fun. For the next ten days she would be our almost constant companion.

The next day we went swimming in the afternoon. The cool water of the pool was very nice. And the Italians now had a new ball. Hopefully this one would hold air. We swam and tossed the ball around a while when Vladimir and Anna showed up to swim. Boris was busy directing the fueling of the rocket.

Now there were six of us in the pool, two Russians, one Kazakh, two Italians, and one American. You know what that meant, the Italians saw the opportunity for water polo. Anna was not too sure about this but relented. The rules were briefly explained. The most important one is that you do not attack someone else unless they have possession of the ball. If someone has the ball, almost anything goes as long as they keep the ball. So we started.

Vladimir and I squared off several times. That was great fun. The two Italians, Fabrizio and Mario, were up against each other and those encounters were rather intense. But the surprise of the day was Anna. Once Fabrizio was driving for a score with "only" Anna between him and the goal. Remember the rules, Fabrizio had possession of the ball. At this point Anna morphed into a raging animal. The water was flying with such intensity that it was sometimes hard to see them. When the last drop of water fell back into the pool there was a dazed and confused Fabrizio, no longer in possession of the ball. He didn't notice the scratches on his ribs at first because of his sore jaw where her left hook caught him. No way would I to try to score against her! We declared the game over and went back to just throwing the ball around.

Gaukar took a taxi back to her home and we rested for an hour before dinner. Then we met Gaukar at a restaurant she thought we would enjoy. It was the best local food we had found so far. Just as we finished eating, Vladimir and Anna showed up so they joined us. We recalled the events of the day. Vladimir asked Fabrizio how he was feeling and he said he thought he would survive. Anna warned him against playing with Russian women.

Mario knocked on my door about 2 pm the next day and we were off to lunch. I was informed by Fabrizio that we would be joined by two girls they ran into the previous night at the disco. Everywhere you go with these Italian guys, girls show up. It turns out that I know these girls as they work at Hotel Sputnik. They knew me as Mr. Green in room F14. They didn't know I was no longer there. I informed them that I was no longer Mr. Green in room F14 but was now Chuck, staying at Hotel Cosmonaut. After lunch we were ready to go swimming.

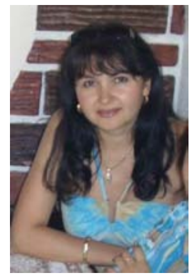
So it was back to the swimming pool. It was a good way to pass some time each hot afternoon. We were there a while when Boris, Vladimir and Anna showed up. Boris informed us that the rocket was now fueled and ready to go. Then a bunch of other guys showed up. We recognized some as Russian soldiers we had met guarding the gate to the hotel.

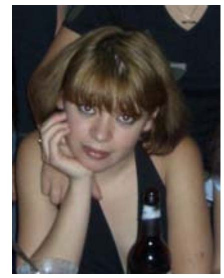
Once we were invited to go walk along the river with Gaukar and her friend Nellie. Going to the river was a bit like going to the beach. But the sand was actually just very fine silt. It gets into everything. And the river was nothing you would want to swim in. The locals do, but I doubt we would survive if we did. It originates in Afghanistan, flows through Uzbekistan and into Kazakhstan. At least that's what a young Russian soldier told us while making a map with rocks on the ground. It carries a lot of silt and a few other things its picked up along the way.

This city is a walled city, Russian style. The river runs along one side. We have learned that the city has about 17,000 people and was never bigger than that. So, going to the bank of the river is really the best this place has to offer. And Gaukar doesn't know anything better. She was born here 19 years ago and will probably die here. It's actually a bit sad as she is very intelligent. She received the normal 11 years of school only because she happened to be born in this Russian city and she qualified to go to the school the Russian kids go to. The other school in town is just for Kazakh kids. I wonder what education the rest of this part of the world offers? Are we fortunate, or what?

After swimming in the hotel pool that afternoon we went to dinner. Olga had called and she wanted to go to dinner with us. She had been Dr. Turkey's interpreter but since the Saudis were all gone she was a bit bored. Olga is an ocean of knowledge about things around here, and elsewhere. She was born here 40 years ago. But she went to the University and has been many places in the world. She taught school here in Baikonur for 10 years. She taught at the school Gaukar attended but they don't remember each other. She is now a free-lance interpreter. She has more energy than any 10 normal people.

For the first time we were able to convey complex thoughts to Gaukar, through Olga. The highlight of the evening was when Olga told Gaukar how educated these two Italians were. The look on this young girls face was something to behold.





Gaukar took a cab home. After a while, Olga also took a cab home. So, for a rare moment, it was just the two Italians and me. It didn't last long, maybe three minutes when we meet another girl; one of the girls that works at Hotel Sputnik. We pass the Sputnik on the way to the Cosmonaut so we walked with her.

She was born in a near-by country but I couldn't understand which one. She came to Baikonur so she could get an education which would then allow her to get a job at the hotel. Imagine, leaving your home so you could get an education to qualify to work in a hotel.

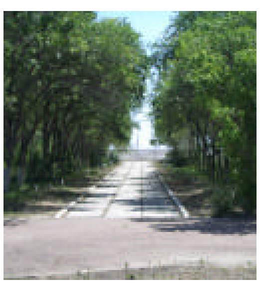
After kisses, we continue on to our hotel. This girl had obviously been spending way too much time with the French guys who were still staying at Hotel Sputnik. When I was in Kourou, I saw that the American girls really liked this aspect of French culture. Seems that the Kazakh girls like it as well.

I have learned all sorts of things from these local people. I learned that if you have pneumonia or tuberculosis the best thing to take is about a teaspoon of dog fat. I'm not sure just where to file that bit of sage advice.

One morning I went out to walk around the hotel grounds. This hotel is run by the military. Actually, almost everything in this town is associated with the military in some way. Hotel Sputnik is the exception. So we have a military guard at the front gate.

I walked by the pool on the way to a very special place. But I see that the pool was almost empty. They were pumping the water out. Later in the day I would see that the military then goes in and scrubs the bottom, with brushes, by hand, in the sun. I'm sure these are conscripts. I'm told they do this about once a month during the summer. There would be no swimming that day.

The special place is a walkway leading to a place that overlooks the river. It's worth going there just for the view of the river. Along both sides of the walkway are trees that have been planted, one for each Russian Cosmonaut that has flown in space. There is a plaque in front of each. It starts in 1961 with Yuri Gagarin. The next tree is for Gherman Titov. The lack of maintenance of this place is sad. And the last entry I found was 2002.



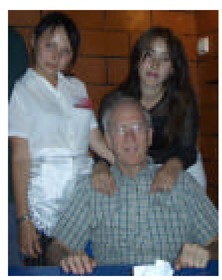
One evening Fabrizio, Mario and I were to meet Gaukar at a restaurant for dinner. We arrived at the restaurant before Gaukar. Boris, Vladimir and Anna were already there eating (coincidence) so I went over to talk with them for a while. When walking back to our table, I see two friends from France sitting at their table so I stopped to talk with them.

Then Gaukar walked in. Wow! She was dressed to kill (this may be strictly an American expression). She was wearing a slender ankle length dress and high heals. Her long black hair was laying on her shoulders. The restaurant got noticeably quieter as every guy in the place looked. The other half of those in attendance were also looking, but it was daggers coming from their eyes. I took her to our table while the French guys sat there totally stunned. What fun!

She had learned that she never knew just how many other girls would be around to compete with. She wasn't taking any chances that night!

After bringing Mario and Fabrizio back to consciousness, I went back to the French guys and brought them back to meet her. They said a couple of impressive sounding sentences to her in French. She had no idea what they said, nor did I, but she was clearly delighted. She was having the time of her life!

I had a great time living among those mostly college age people. And they put up with me cheerfully. Every once in a while, when there were two or more girls around and Fabrizio had my camera, the girls would want to "make a picture for his wife." They thought the pictures would embarrass me. Not a chance!



Once we had a discussion regarding pasta. There was nothing there that would satisfy the Italians. So Olga invited us to all come to her home where Fabrizio, assisted by Mario, would prepare dinner. They were delighted with the idea.

So, about 5 pm one evening we started shopping for what was needed. A small amount of pork was required so we stopped first where meat was being sold. It was all out on display where the customers could pick through it, much like we do fruit in our stores. Any part of the animal was available there. The pig's heads were proudly displayed for you to choose from. We chose a different cut.

The whole process took about an hour. Italians put a lot of different things in their spaghetti. It would probably have taken a couple of hours longer had Gaukar not been with us. It would be easy to get lost in all the choices there.

Olga's home is a typical middle class residence. Although they call it a home, it's really a small apartment. I have not seen anything that we would call a house. Everyone lives in these tenements. We walked through the area looking for the correct address. But it was hard to see the addresses for all the graffiti. Gaukar just walked right in one of the doors to see if it was the correct place. I would have been reluctant to walk in there, but she didn't hesitate. We did learn a few days before that she had studied martial arts. I guess that made us guys feel a little safer there.

After a couple of tries, we found the right entrance. The stairwell was small but adequate. Everything was bare concrete. It had been painted once, but that's mostly peeled off now. Our footsteps echoed as the four of us climbed to the fifth floor.

Inside, she had done what she could by covering the floors with carpets. Some of the walls were done the same way. It was all very typically Russian. So, about 6:30 we showed up at Olga's home loaded with everything that would be needed.

It takes a couple of hours to prepare spaghetti the Italians would eat. During this time the phone rang. It was Gaukar's mother. It seems that she and Fabrizio stayed out a bit late the night before (major understatement) and she was ordered to be home by 10 pm. And her sister would be coming by to make sure that happened. Oops.

That night I learned about a Russian tradition and saw it in action. The subject came up when Fabrizio dropped a fork on the floor. It seems that if you drop a fork on the floor a girl will shortly arrive. If a knife is dropped, a guy will be arriving. Two minutes later the doorbell rang. It was Mavluda, one of the girls that works at Hotel Sputnik. She had been invited, but it's still a bit weird. And when we were cleaning up after dinner, another fork was dropped. Almost immediately the doorbell rang. It was Gaukar's sister. A quick look at the clock showed it was 10 pm. She was expected, but again, it seemed weird.

After Gaukar and Mavluda had gone we received the most incredible sociology lesson imaginable as Olga explained how things were, and are now, in what was the Soviet Union. She also told us how to understand the dynamics we saw, and were often puzzled by. About the Kazak and Russian interaction. About Kosmotras and specifics about the people we interacted with. About people from Moscow. This went on for two hours. These two hours were worth the entire trip. Cultural differences are huge here!

We then cleaned the place up as we had made quite a mess. Olga complained the entire time. She wanted us to just leave it for her to do the next day. Actually, it was already the next day. It was time for her to get a lesson in western sociology.

We then walked back to the Cosmonaut. That walk was from one edge of town to the other. It took about 40 minutes. It had cooled considerably from the heat of the day and there was a significant breeze which blows during the night there. It was all very pleasant.

While at the pool one day we met a Russian officer from Belaruski. He was very friendly. There were two other Russian men there who were also friendly. Their car was parked on the path next to the pool; a bit bold. A group of soldiers came by and he seemed to know them. He offered us beer, nuts, apricots and a salted, dried fish. I had passed on the beer and apricots. I ate a few nuts. So when the fish was brought out I had run out of excuses.

He skinned it, removed the head and tail along with the internals and offered it to us. He said it was good with beer. I could see why. It was incredibly salty. But I had no choice but to eat some. A little later I went back to my room to fetch a Pepsi.

Language was a problem between us but we managed to communicate with the help of Gaukar's book (English-Russian). The Russian officer then made a very nice gesture by pointing out that a Russian military officer was eating with an American and two Italians. The world continues to change.

The days started to feel very repetitive. That's because they were. This city is a lot like living on a small island; one that you can walk the length of in 40 minutes. These people are totally bored but they don't recognize it as such. They don't know anything different. When anything different (us) does come along, they are drawn to it. I'm sure we would be the same way soon.

One night after dinner we walked through a park we had not seen before. A twelve year old boy came up along side us and said "hello." I responded and soon we were talking. His English was nearly perfect. They teach English in school and this was the first time he had ever used it to speak with someone other than in school. He was delighted!

One morning I obtained access to the internet in Boris' room. In his room was a high level person in Kosmotras that I had met at the airport in Moscow. Also in the room was a military officer that I was not introduced to. We sat at the same table while I used the internet but he never acknowledged my presence. He just kept working on his computer.

It was a bit weird as I read a message from Mark including the text of an official Russian statement regarding the fact that the Russian satellite would not be flying. It told about where it was then and what was being done with it. It said it had been taken to a southern facility on the base where it was to undergo functional testing. The reason this was a bit weird was that as I sat at the table reading this message I could look across the room and see the satellite sitting in the corner. I didn't say anything.

We met many of the soldiers that were assigned to the hotel. They were often at the pool when we went there so we played various games with them. The soldiers enjoyed this a lot. They tried to learn a few words in English and Italian while we picked up a few Russian words. Small things like this shrink the world.

One night I was passing through the hotel gate when I heard my name called out from the guard shack where the soldier stays at night. It was a little after 1 am. I walked over in that direction and the guard came out. He handed me a bag of apricots the soldiers had picked earlier that day. He was incredibly delighted to be able to do this. I accepted it graciously and went to my room. If it were only this easy to change the rest of the world.

The day before the launch many people came back to Baikonur. This included another eight Italians, about the same number of Saudis and a bunch of people from France.

There was then a meeting at Hotel Sputnik where they very formally went over things briefly and asked a representative of each satellite to say a few words about it and its readiness for launch. Since I represented three satellites by two different organizations, I did double duty. It was all very structured and cold. There were four high level people running the meeting.

Then we all got on a bus and were off to a museum out on the base. It was full of things showing various accomplishments in space. It's the best maintained thing I've seen since I've been here. It was all very nice.

I had dinner with the Italians that night. One of them told me about how he had been

approached three times in Moscow by Russian soldiers asking for money. They had indicated that they were hungry. He had given them what he thought was a small amount and was overwhelmed by how grateful they were.

It made me think about when I was in the army. The post surgeon had lined everyone up in front of his doctors and anyone overweight was put on a diet. I was one of the very few that did not end up on a diet.

I didn't see any overweight soldiers around Baikonur. But they are fortunate because they can forage for food from the trees and bushes around the hotel. We had seen them doing this. I doubt the soldiers in Moscow have that opportunity.

After dinner I went back to the hotel. When I arrived at the hotel gate, I was met by another of the Russian soldiers. He knew I was leaving the next day. He talked about it in Russian. I picked out enough words and watched his hands enough to see he was talking about me being on the airplane the next day. He then reached out and gave me a big hug and I responded in kind. If anyone had told me before I left home that this would happen I would have said they were crazy. Crazy is sometimes good.

Launch day started with a Kosmotras supplied breakfast at 8 am. I hadn't been up before 8 am for some time. But I managed.

Then there was another of those very formal meetings. There were formal readiness reports regarding the rocket. All the high level people were there including the director general and the general in charge of the military forces that would launch the rocket.

Someone representing each satellite was asked to state the readiness of their satellite. I did this for the three US satellites. Again, it was all very formal. Then the general declared that there was no reason not to proceed with the launch.

A little while later we all got on the busses and headed out to the viewing site. On the bus I was asked to do an interview with a TASS reporter. She didn't' speak English but one of the Kosmotras interpreters did his thing. It went very well.

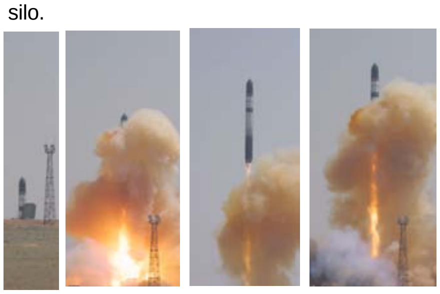
At the viewing site there were lots of military people standing around watching us. We were told that we could use our cameras but they could only be pointed in the direction of the launch silo about three kilometers away.

All those military guys were there to watch which way we pointed our cameras. There were two and a half buss-loads of people there and most had cameras. There was no way they could watch everyone at once. I didn't see anyone actually take a picture while looking the wrong way but many received warnings, including me.

While we were waiting I was asked to do an interview for the Saudi crew that was doing some kind of documentary. They had two students ask me questions. They asked if I had ever been in Saudi Arabia. Those that didn't know were surprised when I said yes and that led to other questions. The entire interview was done in English so they were surprised and delighted when the last thing I did was to thank them in Arabic. Small things go a long way.

They were going to set up two telephones for all these people to use to call home reporting the successful launch. Anna knew I wanted to make such a report. I asked if it would be possible to do a test call before the launch. She said yes so as soon as they set up the first phone, I made the call.

The test was successful so I just held the line open with Mark in Virginia. I could see the launch from where I was standing. We lost the connection once so I just called again. A few minutes later the launch occurred. I was able to tell Mark exactly when. First there was a huge eruption of smoke as the rocket was pushed rapidly up out of the silo.



After going mostly straight up for a few seconds it began to head south and back over us. Soon we could hear the roar of the engines. Mark was also able to hear it over the telephone.

Because it quickly went back over our viewing angle under our shelter, everyone ran out behind the shelter so they could continue to see it. I hung up and went out to see as well. We could see the first stage separate and the second stage take over.

I stood near an interpreter. Every ten seconds there was a repot. It was a bit repetitive, but also reassuring that everything was going well. The second stage shut down and the third stage took over. After 900 and something seconds the satellites began to be separated. One at a time in rapid succession their names were called out. All satellites were separated successfully.

There were a lot of cheers and hugs and about every other kind of emotion you could think of. I ran back inside the shelter and called Mark again to report the successful separation of our satellites.

Then there were congratulation photos, group photos, multi-group photos and just about every other combination you could think of. As a group of one, I wasn't all that interesting, but the other groups invited me into their groups eagerly.

Then we got back on the busses and took the short ride over to the launch site. The huge defensive door over the silo was standing open and smoke was still coming up out of the silo. They had put up a protective rail around the pit so no one would fall in. Looking inside was dark and threatening. Everything was soot black.

I had taken several pictures when the military guys came running over saying "no photos" over and over. It didn't help much. If the soldier was there yelling in your face, you didn't take any pictures. But everyone else was. It was hopeless. For about half an hour everyone took all the pictures they wanted.

We all got back on the busses to return to our hotel. On the way back the Italians receive an SMS message saying that their satellite had been heard after one orbit. The look at their satellite was only four degrees above the horizon but that was enough to hear it. The bus erupted in celebration.

There was then a press conference. The same group of stone-faced people conducted this meeting as well. They were elated just after the launch. But in this meeting they never cracked a smile. Again they were very formal about it. Smiling comes hard for these people.

The press conference was followed by a reception. Someone representing each satellite, the rocket, the military, Kosmotras, etc. was expected to give a toast. I did my part again.

When the General was making his toast, he mentioned that this rocket is in fact a weapon and could be used as such if needed. I had thought about that as it was flying back over my head. It hasn't been all that long since this could have been the case. But it would likely have been heading north with totally different cargo. When you think about it that way as you watch it rise into the sky, it's an ominous sight.

Then we had about a half hour to pack and get back on the busses to be taken to the airport. I was already packed. I had already given most of my left-over food I had brought from the US to the soldiers but I still had a couple of items remaining. So I took them out to the front gate.

While talking with the soldier there I noticed his key ring. He had shown it to me when I first moved to Hotel Cosmonaut. He had coins from many countries on it. But he didn't have a US coin. So, the next day I had given him a nickel, a dime, and a quarter. I was surprised to see there still was not a US coin in his collection. I asked about it.

He showed me the condition of his uniform. It was falling apart at the seams, literally. He managed to communicate to me that he would use the money I had given him to maintain his uniform. Without thinking about it I had given him a months pay. He was concerned about how I would react to his decision. I indicated my approval and he was relieved. I recalled how I was once criticized by my first-sergeant during an inspection because you could actually tell that my left boot had been worn once before.

We then went to the airport. The flight to Moscow was a charter flight. There was no passport control, no customs at departure, nothing. Just a check to see that your name was on the list. Mine was. But that didn't keep them from making it interesting.

When they tried to start the first engine, there was very little success. They worked on it for about 45 minutes when people started getting off the plane. It was hot on the plane sitting out in the sun with no air being pumped through. People opened every possible thing, including the emergency exits.

I got off the plane to see what was up. There had been several rumors going around regarding the problem. I walked under the plane and inspected the landing gear. There was not one tire that didn't need replacing. Some were really bad with several layers of the cords showing

I then went out behind the plane where I could see them working on the engine. A man climbed up a ladder and opened a hatch on the side of the engine. He then took out a hammer and started tapping here and there. Suddenly the engine sprang to life, everyone piled back on the plane and we were off. Whatever works!

The flight was normal and the food was about the same as last time except the chicken had lost some weight. The head was more disgusting than before and the hand towel was missing. Other than that, we made it to Moscow with no further difficulty.

I spent the next day in Moscow with a local radio amateur. We went around and saw many of the places you are supposed to see when you visit Moscow.

The next morning I went to the airport for my flight to Los Angeles. I went through all the control points, passport and other papers check, customs and security. It all went very smooth and there were no difficulties. This was the first time I had to do this alone since I left Denver.

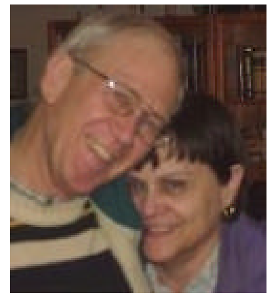
The flight from Moscow to Los Angeles was long but uneventful.

Getting my bags and going through customs and passport control in Los Angeles went really fast. I then went to the United terminal for the last leg of my journey.

The flight left the gate right on time. I sat there as we taxied along. This often takes a while at large airports so I decided to rest my eyes for a few minutes before we took off. After about a minute, consciousness returned but I didn't open my eyes. I wondered how soon we would be departing. I decided to open my eyes and see if we were near the end of the runway. What I saw was Tucson below us; we were about ready to land. I guess that minute was a little longer than I had thought.

After landing I retrieved my bags and just walked out of the terminal to the street. This was the first landing in a long time that I didn't have to show my passport to anyone. And no one cared about what I was carrying with me. It seamed a little strange.

When I reached the street there was the most beautiful girl I had seen in a month passing by. I went home with her.



Cathy (the girl that took me home) and I

All 2500 of the pictures can be seen at http://bach.as.arizona.edu/gallery/echo

Echo Commissioning

By Echo Command Team
Jim White, WD0E and Mike Kingery, KE4AZN
August 2004

Abstract

Amsat-NA's newest satellite, Echo, was launched on 29 June 2004, from the Baikonur Launch site in Kazakhstan. This paper presents the commissioning activities of the Echo Command Team for the first few weeks after launch. It describes how the command team prepared for commissioning, each step of the process, along with the successes and problems, and how they were overcome. This is a unique look inside the process of getting a satellite up and running after its launch and orbit insertion.

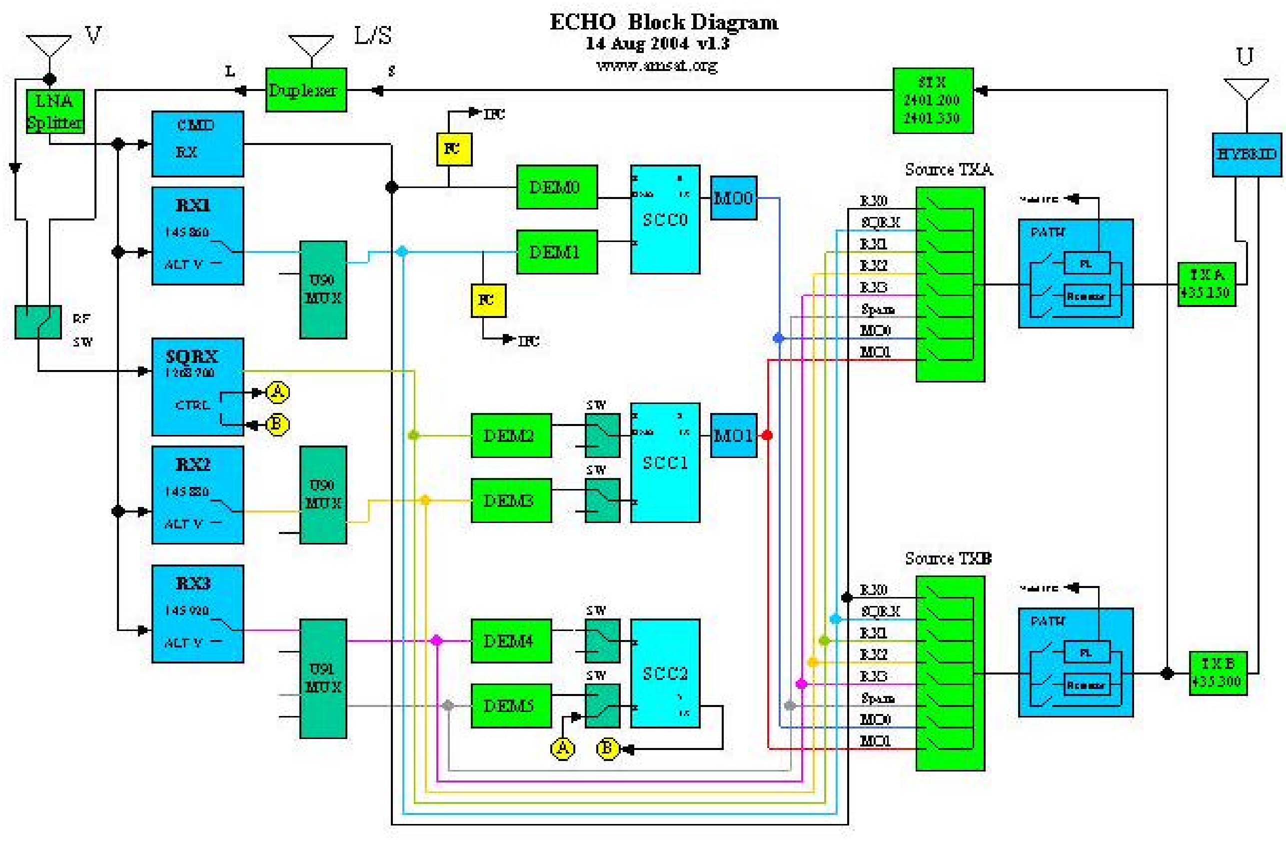


Figure 1
Echo Satellite System Block Diagram

Satellite Integration Testing, December 2003

Jim White, WD0E, Mike Kingery, KE4AZN and Harold Price, NK6K, met at SpaceQuest on December 7, 2003, to begin the process of integrating the Echo software and hardware. SpaceQuest provided all the core modules of Echo including a wiring harness that allowed the modules to be tested. Prior to this visit, Jim had written a housekeeping task and Bob Diersing, N5AHD, had done a boot loader. Harold had modified his SCOS kernal, which he donated to AMSAT. Harold also donated the file system for the BBS to AMSAT. But prior to integration, none of this code had been run on the real Echo hardware or even run on similar hardware. Duplicating hardware is an expense AMSAT can seldom afford. A price is paid in each volunteer's time and mission risk. Those tradeoffs are often hotly debated.

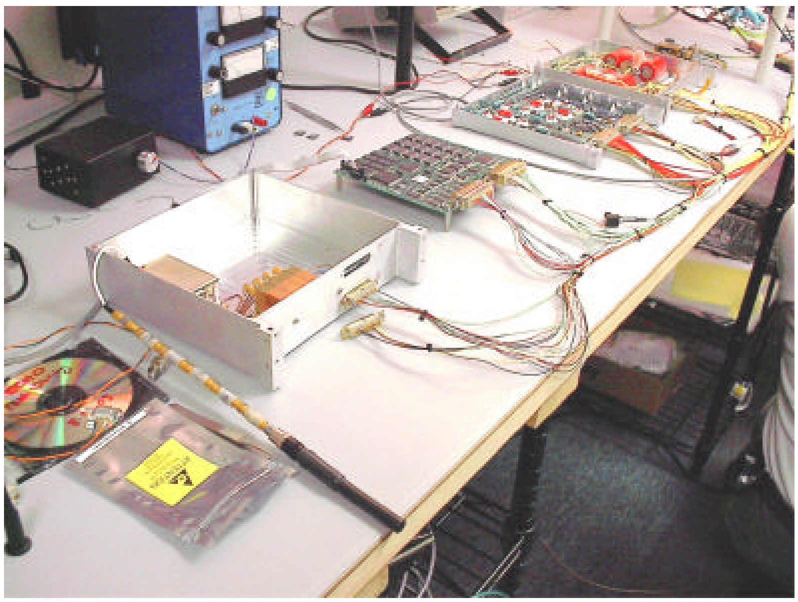


Figure 2
Echo Flight Modules on the Test Bench at SpaceQuest

In short order, this team had the kernal and an initial housekeeping task (PHTH) running on Echo. The main housekeeping task (PHTX) was also loaded and started so the file system could be tested. That process went relatively quickly. Having finished this work, we began the integration and calibration phase. Harold was able to depart after just a day and a half. All work to that point was done using the wired umbilical into the Integrated Flight Computer (IFC).

The next few days were devoted to adding code to the housekeeping task to properly initialize all the parts of Echo so when that code was started, all the hardware would be in a low power safe configuration and we could talk to it over the radios at 9k6 V/U. The most time consuming portion of that effort was tuning up the code that sets the two UHF transmitters on frequency. Since all the transmitters in Echo are frequency agile in their bands, and since a complex string of bits must be sent to them to set up their synthesizers, it was essential that we get this code right and that it be absolutely reliable. Furthermore, the modulators that drive the transmitter have a set of adjustments that must also be set correctly at startup. All of those settings must also be adjustable from the ground by command, so code was written and tested that allowed controllers to change everything in the satellite that can be adjusted. After about 5 days of focusing on this area, we determined the initialization values for 46 separate hardware and software adjustments. Jim passed these along to Bob, who coded them into the boot loader. Bob sent us that code and we tested it. Since Bob did not have real hardware to test on, it took several iterations over two days to get it running correctly. The boot loader is the only code in the satellite that cannot be changed, so quite simply, mission success depended upon getting this exactly right.

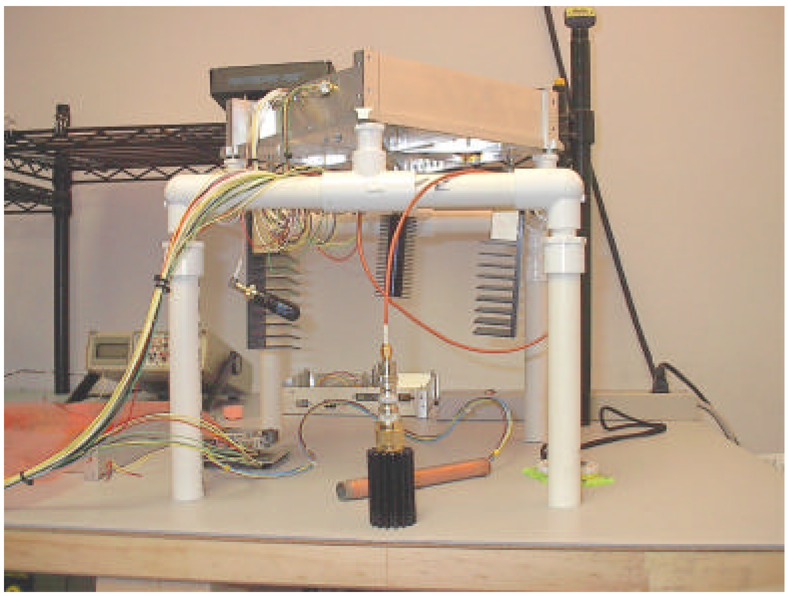


Figure 3
Echo Transmitter Module on Test Bench at SpaceQuest

Mike departed after a week of intense effort and Jim took a half day off to meet with the program manager and others about operations and design issues. The next major task was the calibration of the telemetry system that resides primarily in the Battery Charge Regulator (BCR). Jim and Bob Bruhns of SpaceQuest then spent 5 days calibrating the core 64 telemetry channels in the BCR. One channel was not calibrated because it would have been necessary to cut a trace in the BCR to insert a meter, and this was deemed too risky for the benefit gained.

At the end of the two weeks, it was necessary to have a working boot loader and an initial housekeeping task that we could rely on to bring the satellite up properly after separation, and after any software crash or reset. On the morning of the last day, Jim declared we had met that goal, and the programs were burned into the flight boot ROM and the chip was soldered onto the IFC. This was a critical step, because once the chip is soldered in, removal is very risky. A few hours of testing showed both the boot loader and PHTH did the job (although later it was discovered an error had been made in the PHTH code that makes it a bit less efficient to load code from the ground).

The SpaceQuest team worked with Jim to test the fire code, which is another critical piece of hardware/firmware that simply must work 100 percent of the time. This is a string of bits used to reset the satellite if it is not responding to normal command methods. It is directly analogous to hitting the reset button on older PCs. The test was successful and the ROM containing those codes was also soldered to the IFC. A final test was completed as Jim was packing up his computer to run for the airport.

On review, it was clear that 95 percent of the planned software development, testing, calibration and integration had been completed. The timeline established between SpaceQuest and AMSAT for completion of these processes had been met. Software is never "finished", but the remaining items could be worked out over the next couple of months.

Satellite Final Integration, June 2004

In early June, Chuck Green and Lyle Johnson met at SpaceQuest to do the final testing and integration of all the parts of Echo. Prior to this, Jim had trained Chuck on a simple operational checkout procedure. The facilities for testing Echo at the launch site would be very limited and the ability to fix anything that might be wrong, even more limited. The amount of equipment that could be transported to Biakonur was limited to what could be carried in the hands of the traveling party. Every part, tool, cable, and disk had to be listed in advance and individually checked through customs. It would be impossible to take the satellite apart. In addition, the time allocated for test and checkout prior to integration with the launch vehicle was quite limited. Given these limitations, Jim and the team had agreed on a limited list of tests and a set of criteria to be used to decide if Echo would be launched or returned for repair and launched another year. This is never a pleasant process and there was considerable debate. However, the driving factors were that the launch expense would have to be paid even if the satellite was not launched, and the primary mission of Echo could be accomplished perhaps in a limited way, even if quite a bit of it was found to be broken during those final tests. For example, even if two of the 6 solar panels were damaged, there would be enough power to do the main mission. Or, if the S band transmitter or SQRX receiver did not work, the main mission could still be accomplished. In the end, the list of equipment that had to work in order for the satellite to be launched, rather than returned to go another time, was quite small. Fortunately, it was never necessary to work down that list very far.

Satellite Integration at Launch Site, June 2004

After traveling to Biaknour, the team from SpaceQuest and AMSAT began the post-ship testing and launch preparation. During those tests, Chuck and Lyle were unable to get the SQRX receiver to work right. They could see from its digital S meter that it was hearing their test signal, but they could not get the audio switched through to a transmitter. After considerable difficulty establishing an Internet connection from the integration facility, they sent Jim an email describing the problem and asked if they were doing the test right. Recognizing they only had another day of testing and noting the 10 hour time difference, Jim replied with a lengthy set of test procedures designed to pin down the problem in several different ways. The next day in Biaknour, Chuck and Lyle were informed that integration of Echo to the launch vehicle had been advanced one day, to that day. They had no further time to test Echo (or even get on the Internet). They did not get Jim's email until two days after Echo was bolted to the rocket. The question of the SQRX operation was now very uncertain.

The two SpaceQuest satellites were also integrated to the rocket at the same time, and the following day, all the team members except Chuck, left the launch site to return to the U.S. Chuck stayed behind as the representative of both AMSAT and SpaceQuest, but had no access to the satellites. The story of his trip, the integration and launch, are worthy of a book and will not be described here other than to say that when called upon he represented our interests very well, and with great professionalism.

Echo Software Development

Ground Control Software – ComEcho

Command Stations use a computer program called ComEcho (Command Echo) to communicate with the satellite. This program was written by Jim White and Mike Kingery in MS Visual Basic. It includes all the necessary functions to control the satellite, and also has a full telemetry receiving and viewing package included.

Whole Orbit Data Software – WodEcho

Whole Orbit Data (WOD) is collected from the satellite and downloaded via Echo’s File System. The WOD file contains telemetry data from selected channels over a specified period of time. It can be run at high sample rates, for example, 3 seconds over a single orbit to gather satellite attitude data, or at slow sample rates over multiple orbits to watch data for longer periods of time.

A program called WodEcho (Whole Orbit Data Echo) is used to take the binary data from the downloaded file and create a Comma Separated Variable (CSV) file similar to the telemetry data file created by TlmEcho. The data can then be viewed and analyzed by any program capable of reading a CSV file.

Telemetry Software – TlmEcho

The software program TlmEcho (Telemetry Echo) has been published for satellite enthusiasts to copy the telemetry data sent by Echo. All of Echo’s Telemetry, both analog and digital, can be viewed in real time with the software. The program has the exact same screens and data capture capabilities as the software used by the command stations. The program can be downloaded from the Amsat-NA website at www.amsat.org. The current version is 1.0.5, as of this writing. Future enhancements are planned, upon completion of Echo commissioning.

Many amateur stations around the world have used the program since Echo was launched to copy, collect, and submit telemetry data to the Echo archives. More information about this can be found at the website.

About the time of launch, a database for Echo Telemetry was created by Tim White. It is a true MySQL database that resides on the coloradosatellite.com server. Telemetry captured from Echo may be uploaded to that database through a web server interface and data may be extracted using a date/time criteria set. Also, graphs of many of the key TLM items may be generated by the server software for instant viewing.

First Contact with Echo, 29 June 2004

The command team's plan was to make first contact with Echo during the morning of the launch, when the satellite first flew over the continental US. This gave Echo a good 8 hours to outgas and reach thermal equilibrium. Echo was launched in a minimum power state. The IFC, receivers, and modems were powered up after separation from the launch vehicle, but all transmitters were off.

We received word in the early AM hours that the launch was successful. Echo was launched at 1030 UTC on 29 July 2004, from the Baikonur Cosmodrome aboard a Dnepr rocket. Chuck Green was at the launch site and called Mark Kanawati with the good news as the launch was taking place. He called back a few minutes later with news that all the satellites had successfully separated from the launch vehicle. This was in the middle of the night back in the US. After Mark got the news, he called Jim, who subsequently called Mike. The important information here was that Echo was in orbit and got off on time. That told us that the trial Keplarian elements we had all worked so hard on should be OK to use for first contact.

One of the major concerns with the first few orbits of a new satellite is the Keplarian element data. Will we have AOS even close to our predictions, or must we hunt around to find the satellite? Our trial elements were the result of a good deal of hard work and coordination between Kosmotros, SpaceQuest, Jim, Stacey Mills (W3SM), and some additional resources available to Jim. These turned out to be very accurate. We were within 30 seconds of actual AOS, which certainly made the job during the first few passes much easier.

At separation, the Echo IFC contains only an absolute minimum of software. This is called the Boot Loader (BL), which was written by Bob Diersing, N5AHD. The BL is stored in Read Only Memory (ROM) onboard the satellite, as is a copy of the Initial Housekeeping Task (PHTH) and the SCOS kernal which was again donated to AMSAT for this satellite by Harold Price, NK6K. The BL has multiple capabilities most of which are used only if there are hardware problems in the satellite that must be investigated. Normally, its only job is to move the kernal and PHTH from ROM to RAM and run them. Both of those programs may also be uploaded from the ground if necessary. The BL also has the ability to respond to a beacon request from a ground station, by turning on the A UHF transmitter for a few seconds. On the ground we use a program called GroundStation, recently rewritten by Skip Hansen, WB6YMH, to interact with the BL. The PHTH task has a faster and easier to use boot loader as well as a greater ability to respond to ground station commands, and can also control more of the satellite's functions. The smarter loader in PHTH is then used to load a copy of the final housekeeping task called PHTX along with the AX.25 protocol stack, called QAX, donated by Harold. Once these are running we have the full capabilities of the housekeeping task and can proceed to load the file system code and other tasks.

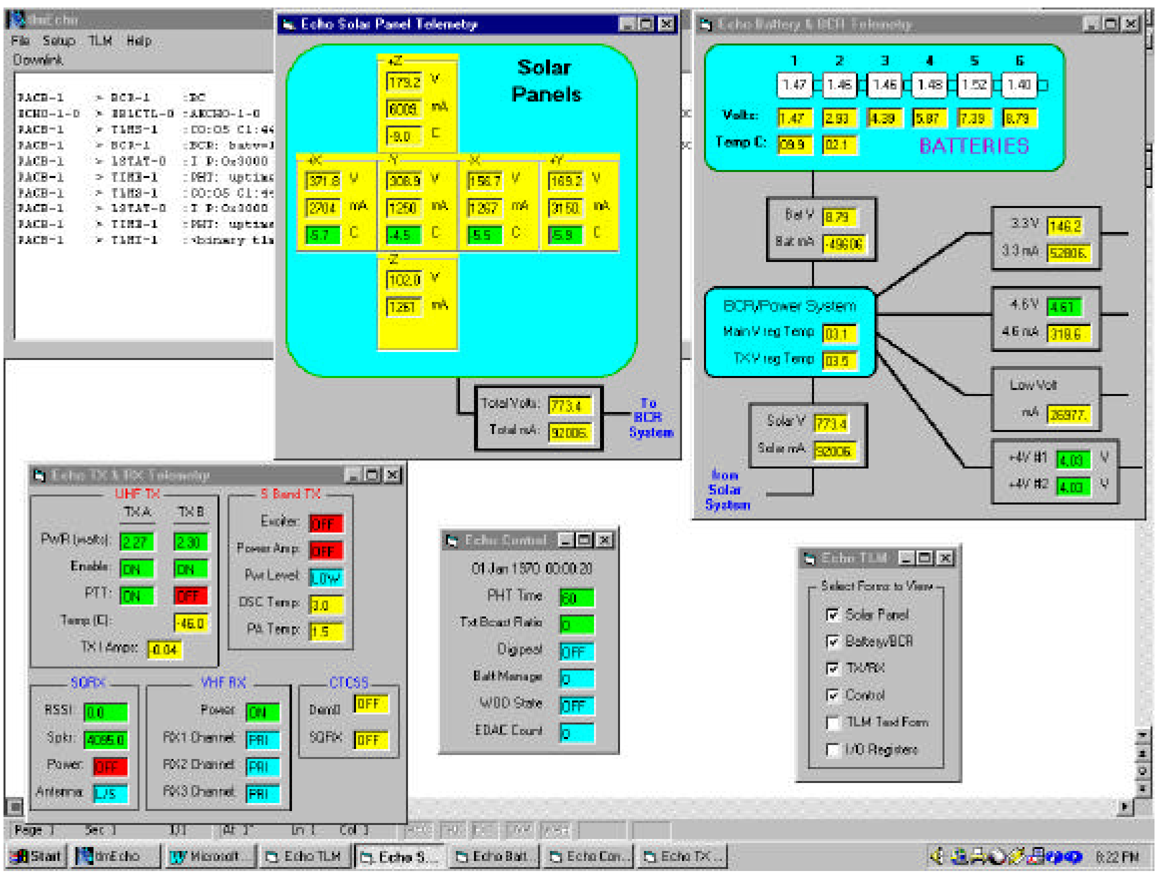


Figure 4
First Telemetry Frame received from Echo on 29 July 2004, by Mike, KE4AZN, shown from the TlmEcho program screens.

The first pass of Echo over a command station was 29 July 2004, at 1450 UTC. Mike was the fortunate command station to first see Echo. The initial plan was to beacon Echo to see if we could get a response. If we were successful with that early enough in the pass, we would load PHTH and the kernal from ROM and turn on TXA (435.150mhz). This would allow us to get our first bit of telemetry, and check the health of Echo.

At 1452 UTC on 29 July 2004, Echo responded to its first command, sent by Mike. With a simple beacon request from the ground station, Echo turned on its UHF transmitter. Echo had transmitted its first signals from orbit! The command team was ecstatic to have established contact with Echo. Mike was then able to command Echo to move the PHTH task and the kernal into memory, and executed (started) them. Mike sent the command to turn on TXA and we began to immediately receive data on the digital downlink. Echo's health looked exceptionally good from the data received. Echo was off and running. TXA was commanded off well before LOS and we called it a good first pass.

Software Loading and Commissioning, Day One

At this point in the process, the key objectives were to first be very careful not to cause a problem with the satellite and second, to analyze all the telemetry to insure all the hardware was working as expected. Since we had a great deal of telemetry data from integration and pre-launch testing, we knew what to expect for most measurements. There are about 40 key telemetry points and each was looked at carefully to see if it matched the expected value. Of critical importance was a review of the operation of the power system. If it was producing the expected amount of power we could safely operate the transmitter and proceed to load software. Any anomaly at all would have to be investigated to assess its impact on the mission. Caution in all actions was extremely important. This satellite was going to be in orbit and in service for a long time. Rushing through testing and evaluation was not in anyone's best interest.

Jim took the second working pass with Mike monitoring. Jim commanded the satellite while Mike was on the phone logging and tracking progress. This became the pattern for the next several days. We would pre-plan everything to be done on a pass, then establish a speaker phone/headset landline connection a few minutes before AOS. One would work through the plan communicating with the satellite while the other logged. We kept the log up to date at both stations.

With PHTH loaded and running, the next task was to load QAX, and then the complete housekeeping task, PHTX. Jim had AOS at 1629 UTC and turned on TXA. The downlink signal showed a good deal of fading. The feeling was that Echo was tumbling, which would later be proven true. The loading of QAX was completed successfully. The PHTX load was started, but we would not have time to complete it on this orbit. The loading process was stopped with several minutes of pass time left to allow ample time to lower the power of TXA, as it was decided, to allow Echo to continue to transmit for a complete orbit. Power was reduced to ½ watt as we completed our second commanding session with Echo.

At the start of the third pass, it was noted that there was no telemetry in the downlink, but Echo was responding to commands. The load of PHTX was completed, but when the task was started, the software crashed and Echo stopped transmitting a downlink signal. A beacon request was sent with the GroundStation program and Echo responded properly. The satellite software had in fact crashed, and the internal watchdog timer had reset Echo back to the Boot Loader state. PHTH and the kernal were again loaded from ROM and executed. We again loaded QAX. We then started the load of PHTX but could not complete it before the end of the pass. The load was stopped and TXA power was lowered to ½ watt.

We suspected that we were running the telemetry downlink rate at too high of a speed for PHTH to handle. We have the ability to regulate how fast we want the telemetry sent from Echo, from a fast rate of 3 seconds to a slow rate of 90 seconds. The memory buffers might be getting overloaded with data from the telemetry capture. We decided that on the first pass in the evening we would manually crash the software, and begin using a 90 seconds telemetry rate. This would give us the time needed to load QAX and PHTX, and get them up and running. This turned out not to be the problem after all. As future testing would indicate, it was a mismatch between the command sent by the ground software and the way it was interpreted by PHTH.

That evening, with the first pass starting at 0203 UTC on 30 June, Mike manually crashed the software, loaded PHTH/kernal from ROM, and began the software loading process again, beginning with QAX, then PHTX. Mike was able to complete the load and get PHTX running and start the load of Mfile. Jim completed the load of the file system software, Mfile and Flt0, and issued the start commands. PB messages were seen in the downlink but the file system would not respond to a Directory Command in WISP. We had inadvertently loaded the wrong version of Mfile to the satellite. We would have to crash to BL and begin again.

Predicted AOS and LOS events were very close to actual times. Our preliminary keps were very good. Signals from Echo were excellent, and at output power settings of 1 to 1.5 watts, S9+40 signals were copied.

There are several reasons as to why the command stations desired to get the PHTX housekeeping task and other Echo software up and loaded as soon as possible. PHTX would give up full control over the Satellite functions. When we have the File System loaded we can get Whole Orbit Data (WOD) from Echo and take a better look at all functions through multiple orbits. Also, there are settings in the Battery Charge Regulator (BCR) that are used to maximize the output power from the Solar Panels. Those settings can only be changed from PHTX.

Software Loading and Commissioning, Day Two and Beyond

We were able to complete the load of software through the file system and get it up and running. At that point, Mike took a short Whole Orbit Data (WOD) run to insure that it would create and store the file correctly. Mike downloaded the file and after using WodEcho, had a properly formatted CSV file of the Echo Telemetry data. Mike started another WOD collection to be downloaded later. At this point, we paused and collected multiple WOD files to take a closer look at Echo's telemetry data, specifically the battery and power management data points. Jim had set the BCR setpoint to the value noted during integration. The BCR setting maximizes the output of the solar system to give Echo every milliamp available from its Solar Panels. It was noted that this setting was working very well in orbit. Also at this time, we were able to get our first look at Echo's attitude by setting up a WOD collection with a fast sample rate, which is discussed later in this paper.

Next, Mike loaded up the RX control task that controls the SQRX receiver hardware. Because of the unsuccessful test in Kazakhstan, there was concern that SQRX was not going to be functioning. Jim issued the command and powered up the SQRX. A few "S meter read" commands were sent and we received back data, but were not sure that we had valid numbers. Jim set the SQRX frequency to one of our VHF uplink frequencies and proceeded to send commands through SQRX. Mike also sent commands via the SQRX frequency and it was apparent that the SQRX was working. The next morning, Jim switched the SQRX into FM repeat mode and Mike transmitted a voice signal through Echo for the first time. This was 6 July 2004. Later that day, Jim configured the SQRX for L band reception and Mike again talked through Echo, this time using L band for the uplink. The test confirmed that the relay that switches between the VHF and the L/S antennas, for the SQRX input, was functioning properly. It was happily noted in the log that SQRX was working fine, and we both breathed another sigh of relief.

Jim modified the PHTX task to fix some minor problems and incorporate a new command to aid in our testing of the UHF transmitters. It is possible to reload the housekeeping task, PHTX, without having to crash all the software running on the satellite. When the new housekeeping task is started, it just replaces the old task and the satellite continues to function properly. This is one of the nice features of the SCOS software package.

During our first few days, we had difficulty commanding Echo when TXA power level was set to 2 watts or greater. Though we have not completed our tests at the present time, it is felt that most of this apparent problem was related to ground station issues. As Mike likes to say, commanding a satellite will cause every minor imperfection in your ground station to appear. The new function built into PHTX would, when enabled, automatically reduce the power of both transmitters to 1 watt if a command is not received by Echo every two minutes. After we loaded up the newly coded PHTX, we tested the function, found a minor bug, modified PHTX, and reloaded again.

Over the next few days, Mike tested the 38k4 high-speed digital downlink on TXA, and successfully copied data from Echo. The S band transmitter was turned on and copied on two occasions. Initial temperature data for the S band hardware was collected. More testing of the S Band transmitter, and the 38k4 digital downlink (on both UHF and S Band), is planned after the initial user period has ended. Testing of the SQRX as a digital uplink on VHF and L band was completed.

We then proceeded to test the FM repeater mode and verify our settings. There are multiple parameters in the Echo IFC that must be set correctly for the digital modes and for FM repeat mode to operate properly. Though test settings were determined and documented during integration, they must be rechecked and maximized with Echo in orbit. This job required both command stations, one sending commands, and the other providing the test signal on the uplink. Over the next few days, we tested and found the correct settings to begin with. We will continue to work with these parameters as we fly Echo. It was noted that for FM repeater mode we need to have the resistor path selected for the transmitter. This is the opposite of our integration notes. Upon completion of FM repeater checkout, Mike loaded up the new PL mode control task coded by Jim. When the start command was issued, the satellite software crashed and Echo stopped transmitting. It was determined that with the satellite's broadcast ratio set to a fast sample rate, the load was not completed properly. This was another lesson for the logbook.

At this point, we decided to pause while Jim and Harold worked on QAX code. During this period, Mike worked on his ground station to improve his ability to uplink to Echo. Trying every combination of two radios (FT-847 and IC-910H) and two TNCs (Sprint-2 and TNC3S) he was able to find the best combination for loading software to Echo. The QAX software work was going to take some time and we wanted to continue on with the commissioning process. So, with the ground station testing done, Mike went ahead and reloaded all the software to Echo and restarted the satellite. With Mike's improved setup, software loading was much faster, and there were fewer missed packets.

With the satellite back up and running, we proceeded to test the PL control software in FM repeater mode. This was new software that Jim developed which had never flown, or been tested on Echo. After a couple of days of work, Mike had figured out the correct configuration for enabling and running the satellite in PL mode. Jim noted improvements that could be made to the code, as we now understood how Echo's hardware responded to the PL mode setup.

Mike proceeded to test each of the 3 dedicated VHF receivers in FM repeater mode and also rechecked the PL mode function. Mike then ran a test with each UHF receiver to gather current drain data at multiple low to medium power levels. This data was needed to check power budgets and determine how we wanted to proceed regarding transmitter power output levels during the upcoming experimental user period.

At this time, the command team took a breather from the hectic pace of commissioning and enabled the satellite for use by the world's amateur radio population. Testing and WOD collection continued in the background, while the users enjoyed their first days with Echo, now known as AO-51.

Hardware Checkout

UHF Transmitters

Each of the UHF transmitters has been tested extensively and both are working well. When Echo is beaconed, it is TXA that responds to the beacon request and turns on for a few seconds. TXA is currently being used as our digital link, while TXB is used as our FM repeater link. Both have been tested to moderate power levels at this point. Power drain on the batteries in various configurations of TXA and TXB has been tested and documented. More testing is planned to verify the power drain at higher output power levels for each transmitter. The frequency of the TXB transmitter was moved to 435.300 mhz due to the fact that GO-32 began operation on 435.225 mhz at the time Echo was launched.

Receivers

Each of the 3 dedicated VHF receivers has been tested in FM repeater mode on their primary frequencies. One has been tested on its secondary frequency. All are working as expected. Software is currently being modified in order to allow the user receivers to operate as a 9600 baud digital uplink as well. This will be tested when the new software is uploaded to the satellite. The SQRX receiver has also been checked out and is working properly. It has been tuned to various VHF frequencies and tested as an FM repeater and a 9600 baud digital uplink. The antenna relay that switches the SQRX receiver's path from the VHF antenna to the L/S band antenna has been tested and is working fine.

VHF receiver 3 (RX3) on its primary frequency of 145.920 mhz has been used as the uplink receiver for the experimental user FM repeater window that started on 30 July 2004. The SQRX receiver was used on 4 Aug 2004, for the first Experimenter's Wednesday session when Echo was put in L/U FM repeater mode, and at various times as the FM repeater uplink. SQRX will be used for the planned BBS Experimenter's Day on Wednesday, 11 August 2004.

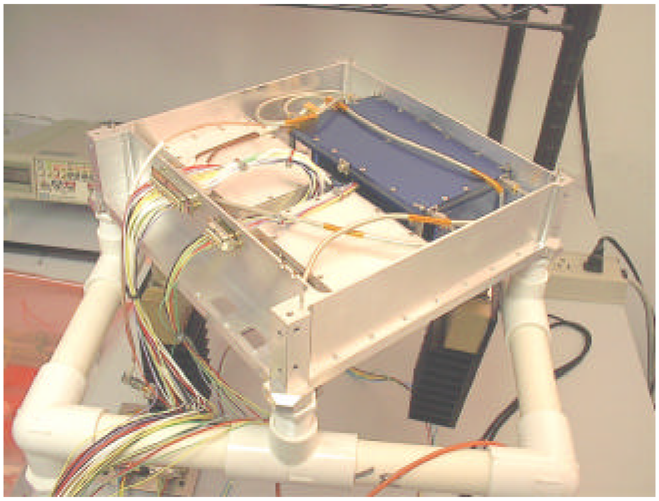


Figure 5 – UHF and S Band Transmitters

S Band Transmitter

As of this writing, the S band transmitter has been turned on for two brief windows while over a command station. Future tests will have the transmitter on for a complete orbit, then multiple orbits. The S band transmitter uses a good deal of satellite power, therefore it is important to be cautious when testing, in order to not put the satellite in a position to pull the batteries too far down in eclipse. Another concern was the temperature of the S band hardware when in operation. From the initial tests, the temperature rise appears to be of no concern, as the figure shows below. Anything under 40 degrees Celsius was considered to be a safe temperature for the S band hardware. However, because this transmitter is less efficient than the UHF transmitters, we also needed to carefully determine where the extra heat went in the satellite. The S Band transmitter is capable of operating in FM repeater mode and in the higher speed digital modes. It cannot properly deviate a 9600 baud digital signal.

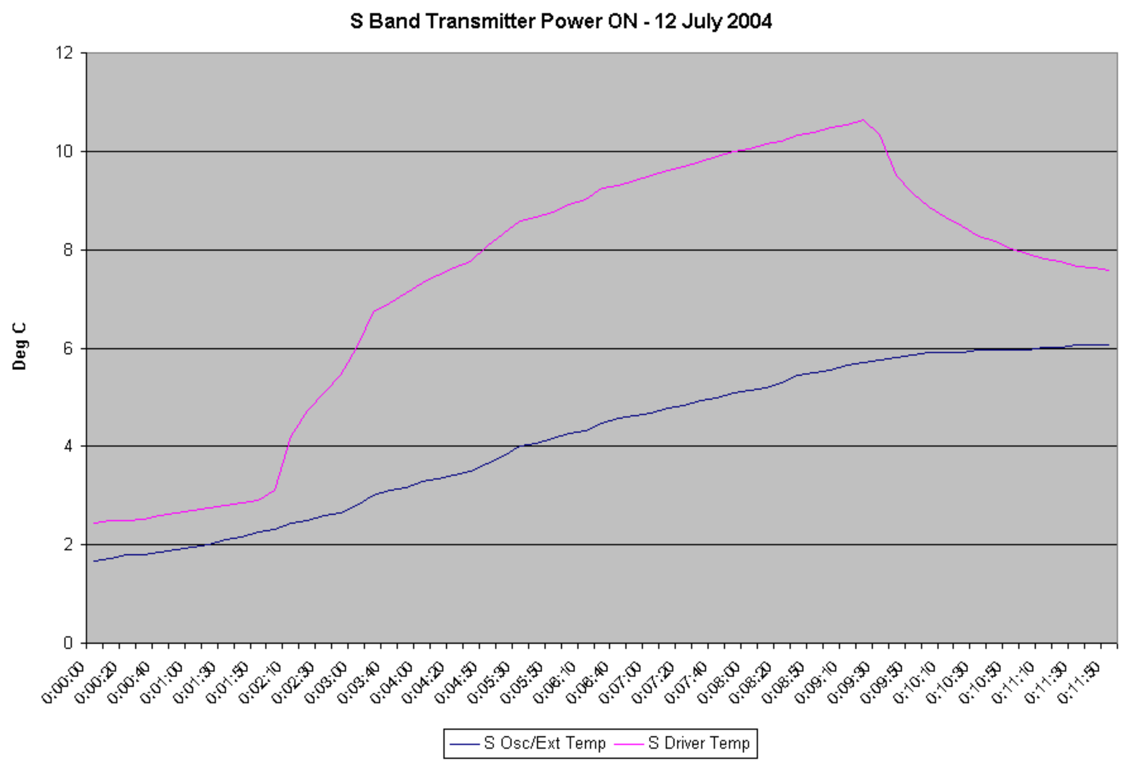


Figure 6 - S Band Transmitter Temperature Graph

38400 Baud Digital

Echo's ability to transmit a 38k4 signal on UHF has been checked out a couple of times. We have been able to decode data at 38k4 while operating Echo at 1 watt output power. More tests at higher transmitter output power are scheduled in the near future. With the wider bandwidth of the 38k4 signal, the transmitter on Echo will need to be set to a higher output power level to achieve good reception by ground stations. A number of stations from around the world have indicated they are 38k4 capable, so this should become an exciting mode on Echo.

CTCSS mode

While at SpaceQuest in December, a modification was made to the IFC that allowed the software to read the "valid CTCSS" output pin of the CTCSS encode/decode IC associated with each transmitter. There is a great deal of flexibility in the IFC. One of the things that can be adjusted is the path of the audio signal from each receiver or modulator to each transmitter. That path can be set as a straight connection (useful when the signal is low in amplitude) or to a resistor connection (used for most configurations). It can also be routed through a CTCSS decoder IC. That IC gates the audio and will only allow audio through which carries the selected CTCSS frequency. Since Echo has no carrier operated relay (COR), this is the only way to determine when a signal is being received. With this modification it became possible to detect an uplink signal meant for the satellite and turn on the transmitter. With a bit of coding, this made a mode very similar to a terrestrial PL controlled FM repeater possible.

Jim wrote a separate SCOS task to implement that mode. Once a second it checks the status of the "valid CTCSS" pin from the decode IC. If that signal is true, it turns on the transmitter and starts a timer. Every time the check shows a valid CTCSS is being received the timer is reset. If the timer expires, the transmitter is shut off. This mode has the major advantage of limiting the transmitter power on time to only those periods when the satellite is being accessed. At the time the software was created it wasn't known how much the transmitter would be on in this mode, but it was clear it would not be full time. Any DC power saved by not having the transmitter on talking to whales, was power that could be used to increase the transmitter output when it was being accessed by signals meant for Echo. The hang timer was initially set to 10 seconds to help ground stations find the downlink signal.

Echo Battery Voltage Study

Figure 7 shows the Battery Voltage of Echo during the Experimental User period, which started on 30 July 2004. The bottom line on the chart shows when the satellite was in the sun, and the line above indicates when the TXB transponder was turned on. During this time, TXA was running at .35 watts output and TXB was running at .60 watts output. The graph shows, that during heavy usage through an eclipse, the battery voltage dips down below 7.5 volts. To prolong the life of the satellite, we do not want to run the battery down too far, and this is the point we want to hold at the present time, about 7.45 volts. The actual parameter with which we are concerned is the battery capacity, rated in Amp Hours. Our batteries have a capacity of about 4 Amp Hours. The amount of battery capacity we use will directly effect the useful lifetime of our batteries. Remember, we cycle the battery every orbit. We must take good care of our batteries.

The graph also shows that the battery recovers well before the end of the illumination window. Therefore, we have some power available after battery recharge to use when we are illuminated. Presently, that power is lost as heat in the solar panels, because when the satellite does not need the power, the BCR will not draw the current from the Solar Array. At the time of writing, software was being developed to utilize this power. The satellite will sense when it is in the sun, when the batteries are fully charged, and will adjust the output power of the transmitters according to the available power from the solar panels. Accordingly, we will get every watt out of the satellite, and transfer that power to the transmitters.

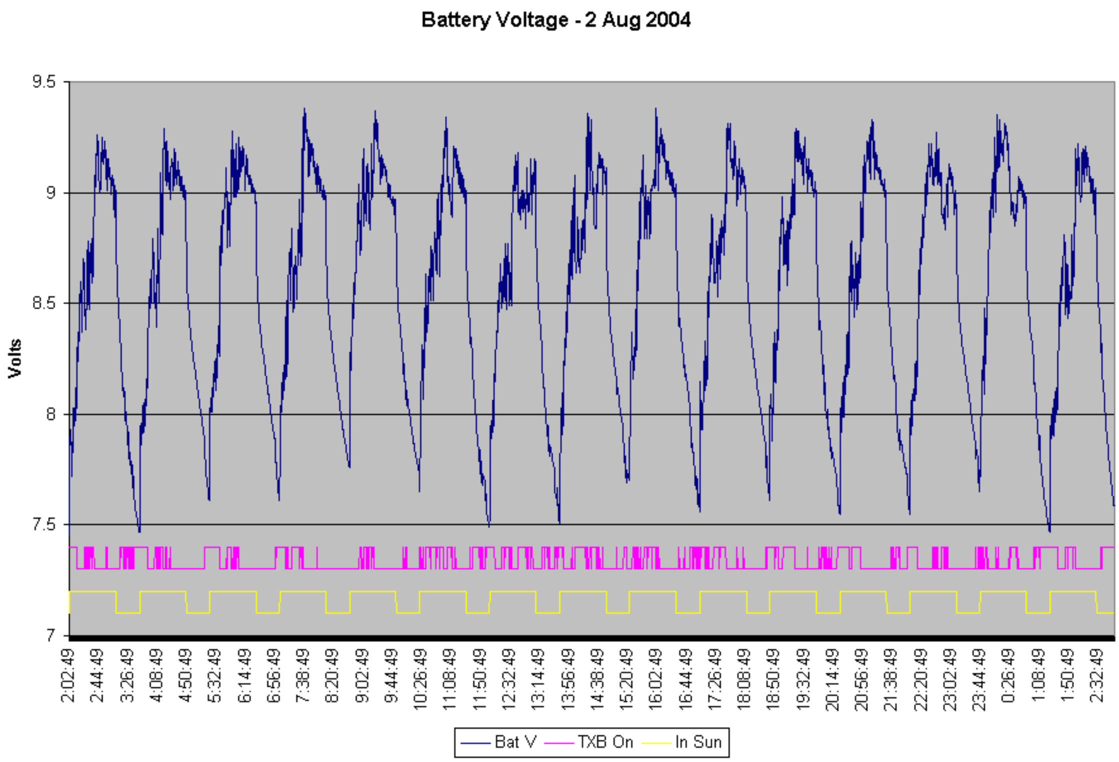


Figure 7 - Echo Battery Voltage

Echo Attitude

Our first check of Echo's attitude came on 4 July 2004, when we were able to get our first fast sample rate WOD file collected. The DC current values from each individual solar panel are used to determine the attitude of the satellite. Under normal conditions in the Northern Hemisphere the +Z axis will show power production while the –Z will show minimal power, which is light reflecting off the surface of the earth. The X and Y panels, as the satellite spins, will cycle through maximum power output to minimum power output. In the Southern Hemisphere, the Z panels are reversed because Echo will pitch over and the +Z axis will be pointed toward earth.

Figures 8, 9, and 10 show our first WOD data from the solar panels, and from that data it was obvious that Echo's attitude was not stable. It was spinning at a very fast rate, which was estimated later with more accurate data, to be on the order of 12 seconds. The satellite was not stable about its Z-axis, meaning that Echo was wobbling. Downlink signals noted by command stations were changing rapidly from Left Hand Circular to Right Hand Circular, which also indicated a tumble over the Z-axis.

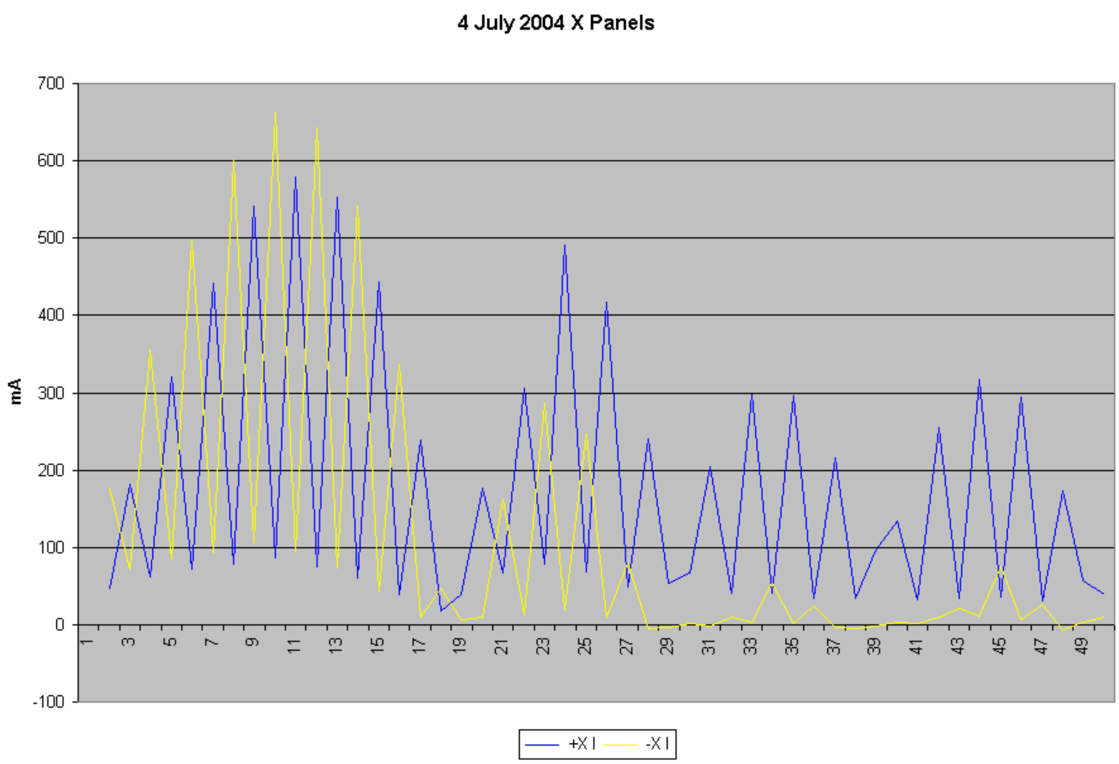


Figure 8 - Echo X Solar Panel Current, 4 July 2004

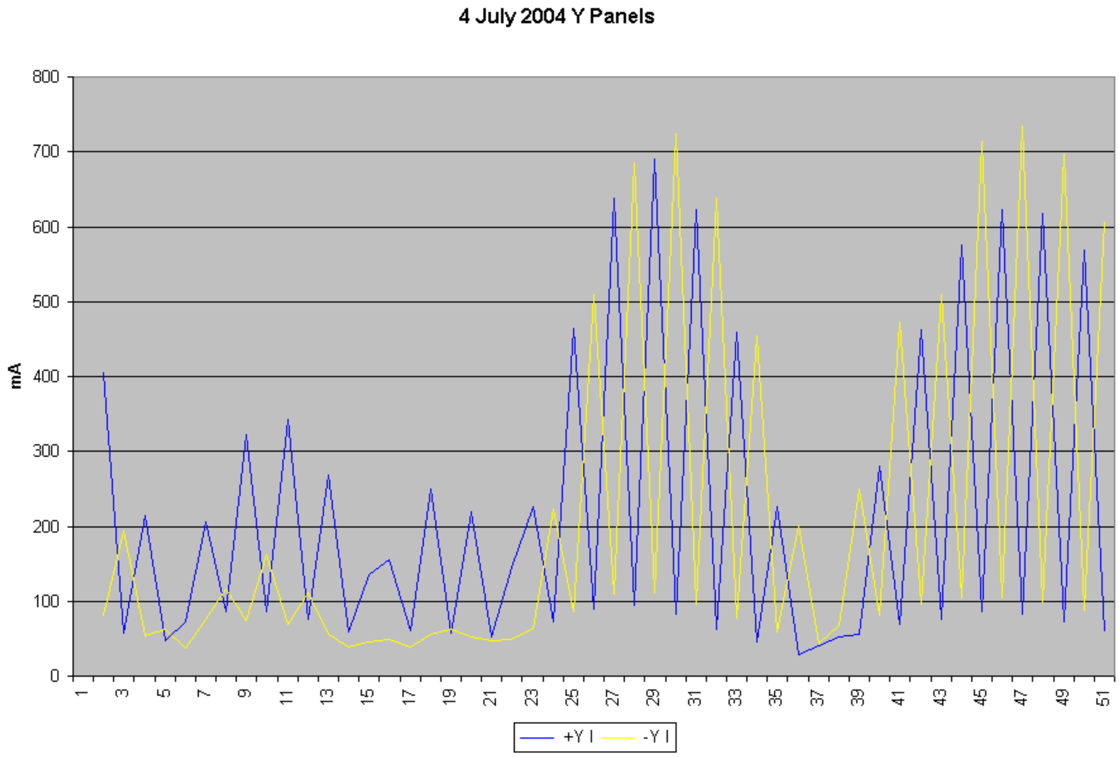


Figure 9 - Echo Y Solar Panel Current, 4 July 2004

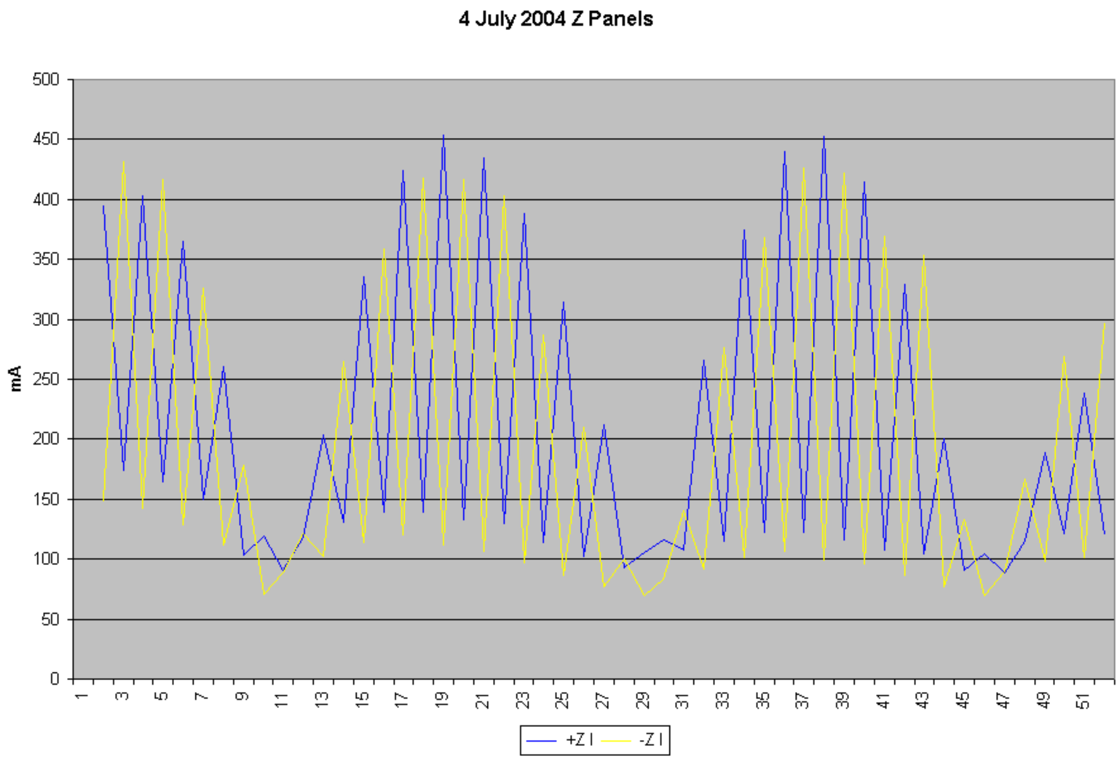


Figure 10 - Echo Z Solar Panel Current, 4 July 2004

Figure 11 – RF Test Setup during Integration at SpaceQuest

The next set of figures, 12, 13, and 14, are from 4 August 2004, and show a much more stable satellite. The X and Y panels are starting to show their proper spin cycle between illumination and in shadow. There is still an indication of wobbling in the data, but not nearly as severe as the previous month. The spin rate has slowed to around 35 seconds, which is allowing the earth's magnetic field to have more effect on the satellite and dampen out the wobble. The Z graph is starting to show the proper exchange of power generation from the Z panels, and the pitch over at or near the equator.

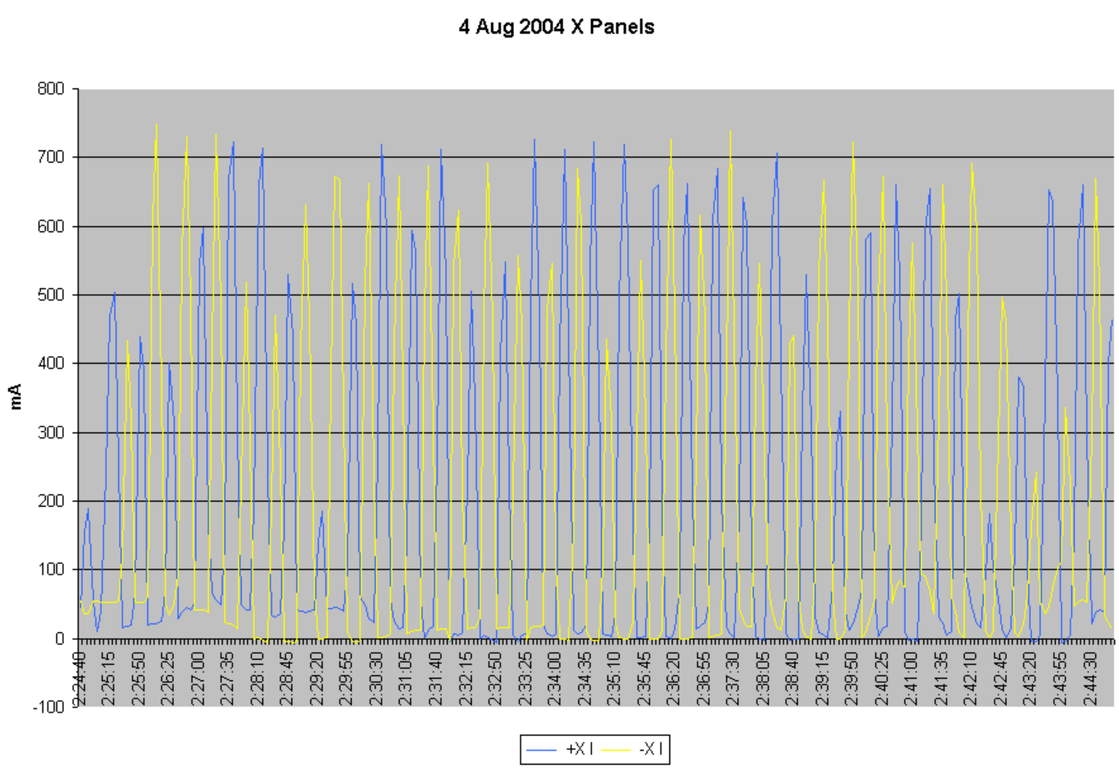


Figure 12 - Echo X Solar Panel Current, 4 August 2004

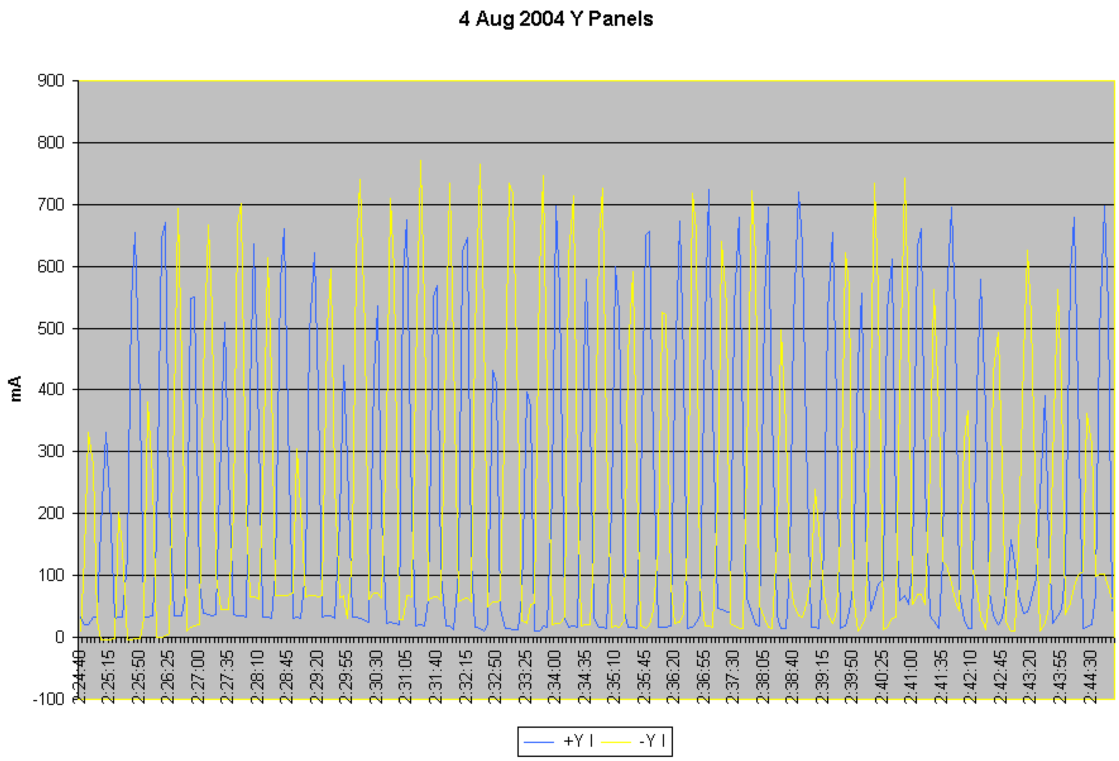


Figure 13 - Echo Y Solar Panel Current, 4 August 2004

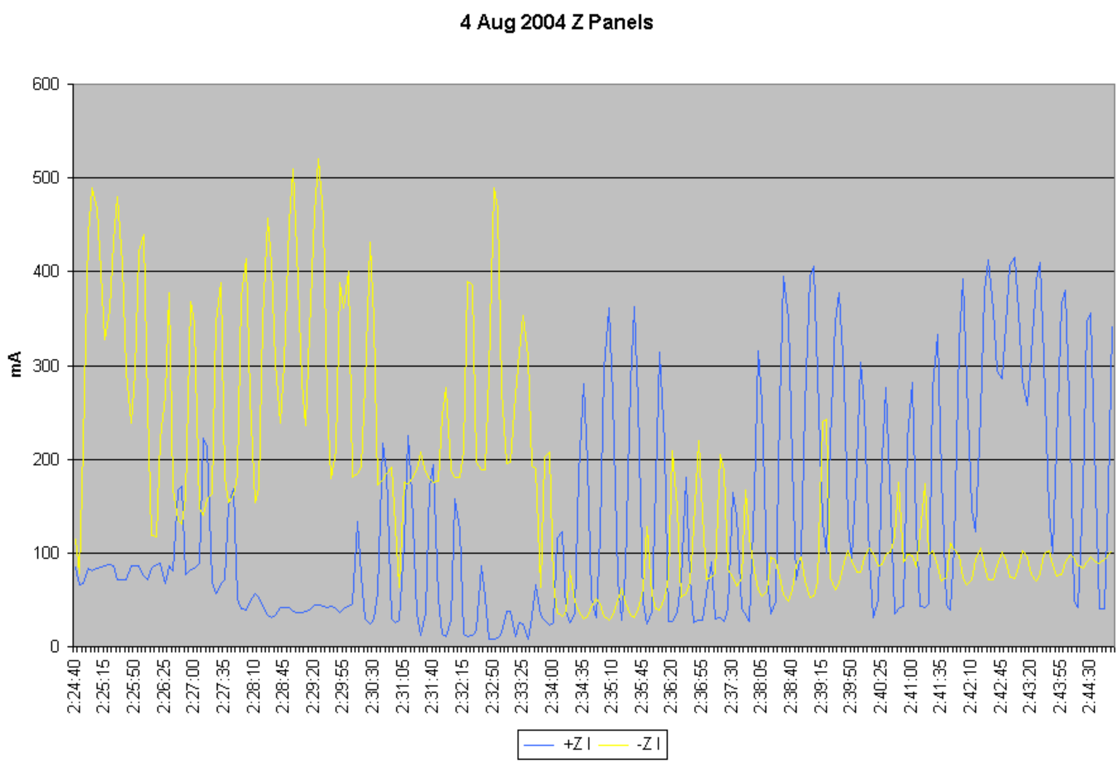


Figure 14 - Echo Z Solar Panel Current, 4 August 2004

More time will be needed for the satellite to achieve the desired stability, and more data will be collected to monitor the attitude of Echo. Note that there is less power produced from the Z axis panels, since they have fewer solar cells on them.

The command team would like to congratulate everyone involved in the development and design of Echo. We look forward to many years of enjoyment from Amsat-NA's new satellite.

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Echo Command Team

ECHO's New Transmitter – a Software-Centric View

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ECHO is a continuation of the AMSAT Microsat series of satellites. Due to advances in solar cell and battery charging technologies, it is able to do the work of two Microsats at once – namely it can act as a repeater like AO-27 as well as a store-and-forward mailbox with telemetry like PACSAT. The satellite also features an experimental torquer coil so that the alignment of the satellite can be reversed at will, and a new 1.2 GHz receiver/2.4 GHz transmitter pair. Useful additions to the satellite are a SQRX 10 MHz to 1.3 GHz receiver and a PSK-31 demodulator for use with 10M uplinks. A quiet improvement on board the satellite is the addition of two frequency-agile UHF transmitters.

Perhaps these transmitters are not as exciting as the experiments carried on board ECHO, but they are important additions nevertheless. Sure, any ham can walk over to their trusty Kenwood, spin the big tuning knob and enjoy the benefits of a PLL frequency synthesizer – so why is this a great improvement for AMSAT? Why would the additional complexity of a PLL-based transmitter be such a plus? Well, it turns out that a PLL-synthesized transmitter can actually be very simple, in fact much simpler than the old oscillator/multiplier transmitters of yore. Also, the fact that the transmitter frequency can be varied at will by command or a software update makes for a very flexible system that can easily deal with future frequency conflicts or band reallocations.

This paper is a short description of what a simple PLL-based transmitter (like the one in ECHO) is, and of the work involved in setting up and tuning it.

The FM Transmitter – an Abbreviated History

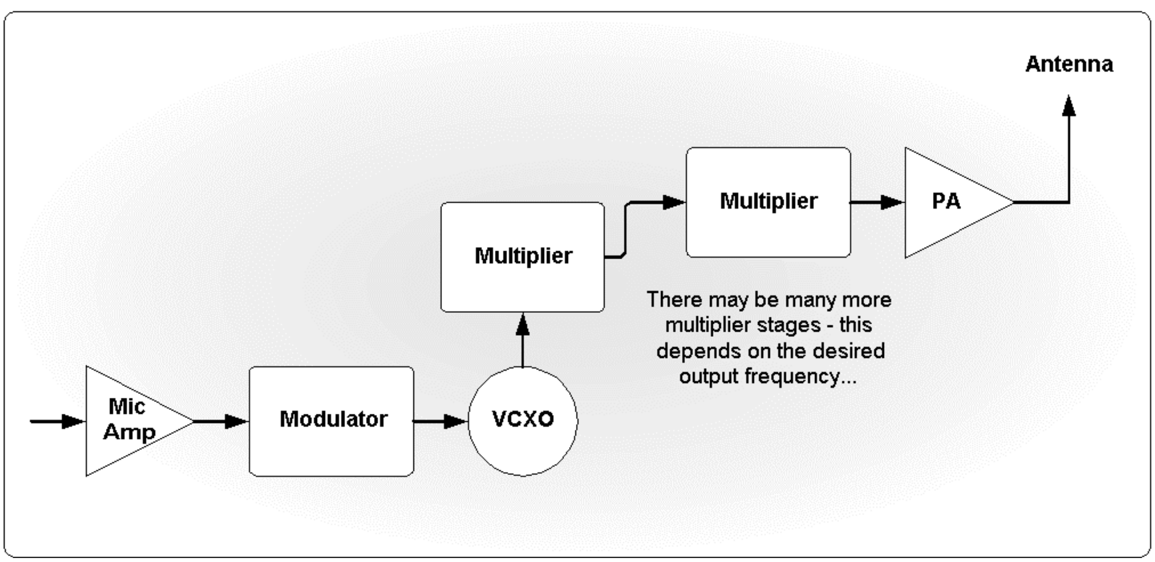


Figure 1 - Multiplier Transmitter

Until ECHO, Microsat transmitters were of the oscillator/multiplier design (see Figure 1). This type of transmitter is based on a low-frequency oscillator (< 30 MHz), whose signal is fed into a series of multiplier stages until the output is at the desired frequency. For a FM transmitter, the low frequency oscillator is replaced with a Voltage Controlled Oscillator (VCO). To modulate the transmitter, a varying base band signal (audio or digital) is used as the VCO control voltage to provide direct FM (there are also ways to phase modulate a carrier to produce an output waveform similar to FM, but I won't get into that here). The advantage of this system is that the VCO does not have to swing very far to produce decent deviation and can thus be designed to be quite stable. The multipliers not only affect the VCO center frequency, but also multiply the frequency swing. Another advantage is that with fixed-frequency transmitter, the software people don't have to wrap their minds around esoterica like dual-modulo prescalers and reference dividers.

There are quite a few disadvantages to this design. First of all, it's rather complex. Secondly, each stage requires many variable components that should be tweaked on a regular basis as they age – something that is obviously impossible for a satellite transmitter. Finally, each stage has to be physically shielded from its neighbors to avoid parasitic oscillations and other problems that can destroy the transmitted signal. Touchy components; extra weight required by shielding; degradation with time – every one of these is a good reason to find some other way of producing a signal.

Enter the Synthesizer

So if multipliers are so naughty and complex, why not just run an oscillator at the desired frequency? Unfortunately, crystal references cannot be made to oscillate at their fundamental at any frequency much higher than HF. VHF and higher oscillators rely on a crystal's overtone (multiples of the fundamental) frequency and suffer from the same problems as do multipliers. If you want to modulate this oscillator to produce FM, you exacerbate the stability problems. On the other hand you can ignore the problems associated with a VHF oscillator, and use a VCO instead. You would use a synthesizer to lock the VCO's output to a low-frequency reference oscillator. In this case you end up with a very robust signal source that can deal with aging components and that does not require much in the way of internal shielding or initial alignment. Simply put, the synthesizer takes the output from the VCO and feeds it through a programmable divider. The output of the divider is compared to the output of a highly stable reference oscillator. The synthesizer varies the voltage controlling the VCO until the divided output is phase-locked to the output of the reference oscillator. Because the VCO output is phase locked to the reference frequency, and because the connections between synthesizer and VCO form a loop, the system is known as a Phase Locked Loop (PLL see Figure 2).

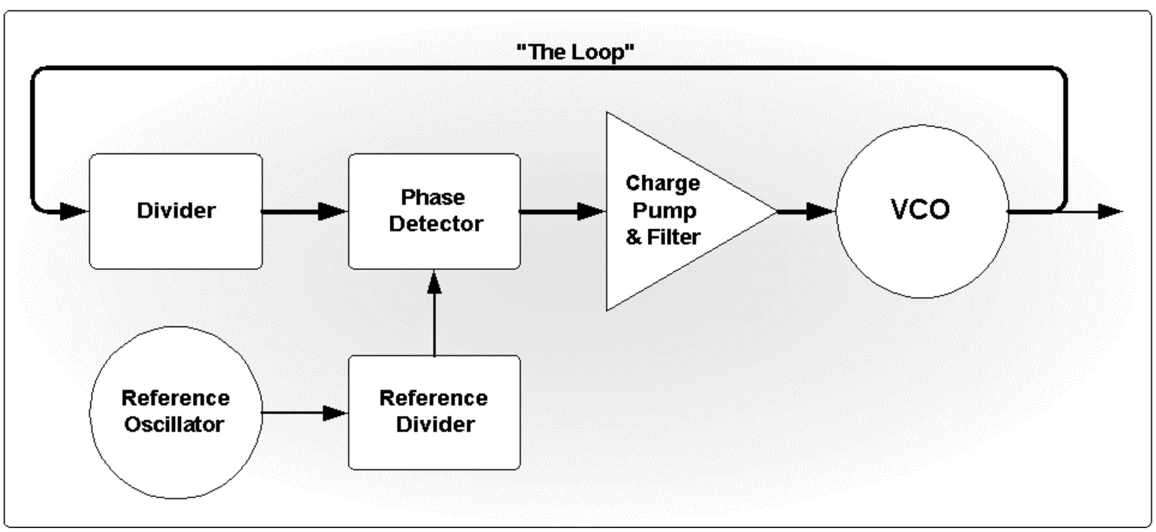


Figure 2 - A Basic PLL Synthesizer

ECHO's Transmitter in Brief

ECHO's transmitter is basically just a synthesizer set up to directly produce the desired output frequency. To FM modulate the output, the reference oscillator is configured to be a VCO with a very limited swing. The base band signal is applied to the reference, which then swings the output of the synthesizer. To minimize phase noise on the transmitter signal, the main VCO is also modulated. The output of the synthesizer is amplified to the desired power level and fed to the antenna. For the rest of this paper, I'm going to ignore most of the transmitter circuitry and concentrate on the synthesizer.

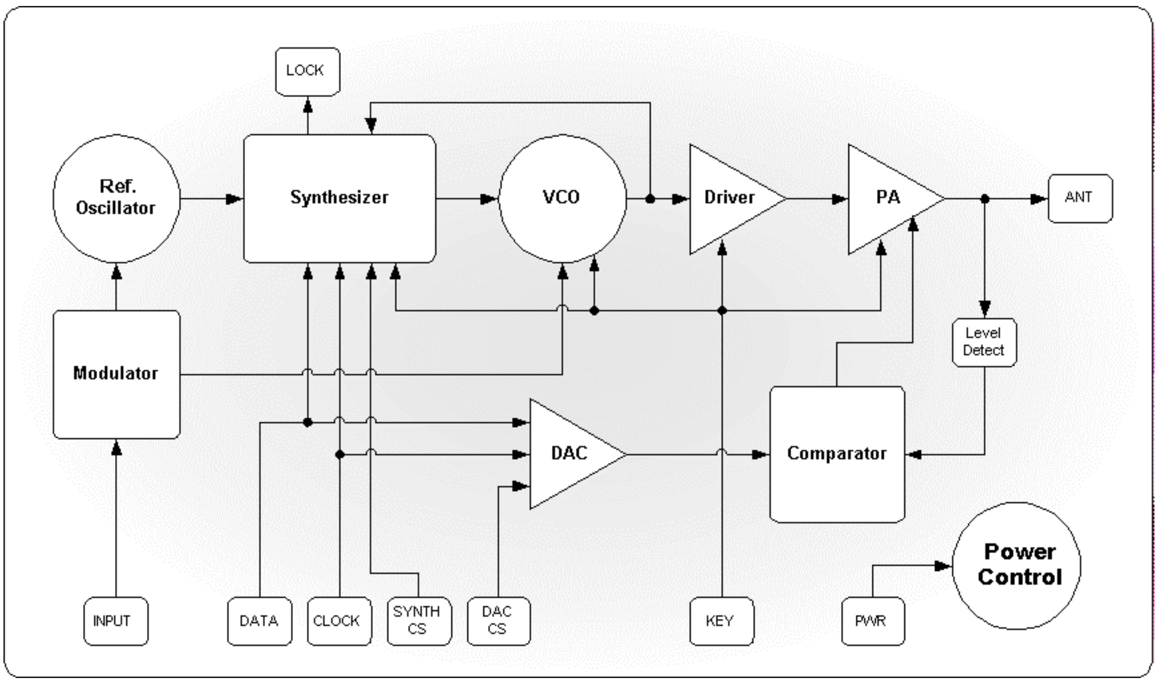


Figure 3 – The Transmitter

National Semiconductor's LMX2316

ECHO's transmitter uses National Semiconductor's LMX2316 PLLatinum® low-power frequency synthesizer. This single chip contains many of the functional blocks that used to require multiple components. This synthesizer provides a phase comparator, lock detector, frequency divider and reference divider. The reference divider is provided so that the desired frequency step size can be obtained from a standard 10 MHz or 12.8 MHz temperature-compensated crystal oscillator (TCXO).

Some basic specifications have to be provided by the transmitter designer in order for us to program up the synthesizer. Most important of those are:

- The Reference Frequency (10 MHz)
- The Frequency Step Size (2.5 kHz)
- The Transmit Frequency (435.225 MHz)
- Synthesizer hardware configuration (VCO polarity, Lock Detect pin usage, FastLock configuration, etc…) – This has to be provided by the designer!

To divide the 10 MHz reference down to a 2.5 kHz step size requires a divide ratio of 4000 (i.e. 10,000,000 / 4,000 == 2,500). To divide the desired VCO frequency of 435.225 MHz down to 2.5 kHz, we need a divide ratio of 174,090. Nothing too hard here – so far it's 6th grade arithmetic. In this transmitter, the VCO polarity is positive (i.e. as the voltage goes up, so does the frequency), the lock detect pin is high when the PLL is locked, and FastLock is disabled.

Here is where it gets tricky – because building a direct divider capable of dividing 1.2 GHz (2.8 GHz on the LMX2326) down to 2.5 kHz, and keeping it low-power and inexpensive is not possible, the engineers at National Semiconductor designed in a high speed prescaler. If they had used a simple fixed prescaler, the synthesizer step size would end up as some multiple of the prescaler value. To avoid this, the LMX2316 uses what is called a "Dual Modulus" or "Pulse Swallow" prescaler. A dual modulus prescaler just means that it divides its input by a number *N* part of the time (usually a power of 2 such as 8, 16, 32, 64 or 128), and by *N+1* for the rest of the time (9, 17, 33, 65 or 129). To start with the LMX2316 decrements both *A* (*N+1*) and *B* (*N*) counters. While *A* is greater than 0, the prescaler is set to count *N+1* counts before *A* and *B* are decremented. Once *A* reaches 0, the prescaler is switched to count *N* counts before *B* is decremented. When the *B* counter counts down to 0, it resets itself and the *A* counter, and the process restarts. The end result is a total division ratio of *BN* + *A*. Since the LMX2316 uses a ÷32/33 prescaler, and we need a divide ratio of 174,090, to set the values of the *A* and *B* counters we simply divide 174,090 by 32 and get 5440 with 10 remaining. That means we set *A* to count for 10 cycles and *B* to count for 5440. It is kind of quirky, but if you look at *B* as counting off the whole prescaler output counts, and *A* as "swallowing" the remainder, it is a little easier to work with.

Programming the LMX2316

The LMX2316 is programmed via a three-line MICROWIRE™ interface. The MICROWIRE™ interface is made up of one data line, one clock line and one Latch Enable (LE) or Strobe line. The LMX2316 can be viewed as a 21-bit shift register, where a bit is shifted in on every rising edge of the clock line. Once all 21 bits have been shifted in Most Significant Bit (MSB) first, a rising edge on the LE line copies everything from the shift register into one of three configuration registers on board the chip. The two least significant bits (C1 and C2) of the sequence determine the destination register. The interface is also compatible with the Serial Peripheral Interface (SPI). Since SPI sends data in 8-bit groups, any excess bits preceding the actual data are shifted out and ignored. Although the MICROWIRE™ and SPI differ in their interpretations of the LE or CS lines, the chip remains compatible with both by using the rising edge of LE or CS to load the given data into the desired register.

C1	C2	Register
0	0	Reference Counter
1	0	VCO Divider Counter
0	1	Function Latch
1	1	Function Latch + Reset

Table 1 - C1 and C2 Bits

Initializing the LMX2316 from power up state requires a write to the [C1, C2] == [1, 1] register to trigger an internal reset. Simultaneously, the 19 control bits are copied into the same configuration latch as does a write to the [C1, C2] == [0, 1] register. A write to the [C1, C2] == [1, 1] register must only occur once before the transmitter is keyed. Writing to this register while the transmitter is keyed will cause a glitch on the output as the PLL charge pump goes to tri-state (power down) mode, and then immediately back to normal mode. The desired mode here is powered up with FastLock disabled (FastLock is not required for this application). In addition, the lock detect (FoLD) output should follow the state of the PLL lock detect. The bits to set here are as follows:

Bit	Value	Description	State
0	1	C1	Function + Reset
1	1	C2	
2	0	Counter Reset	Reset Disabled
3	0	Power Down	Powered UP
4	1	FoLD Control	Lock Detect output follows state of PLL lock.
5	0		
6	0		
7	1	Phase Detector Polarity	Positive
8	0	CP Tri-State	Normal Operation
9	0	Fast-Lock Enable	Fast-Lock disabled
10	0	Fast-Lock Control	
11	0	Timeout Counter Enable	
12	0	Timeout Counter Value	
13	0		
14	0		
15	0		
16	0	Test Modes	Must be 0
17	0		
18	0		
19	0	Power Down Mode	Powered UP
20	0	Test Mode	Must be 0

Table 2 - Initialization/Configuration Bits

Notes:

- Bit 20 is the MSB and is shifted out first!
- [C1, C2] = [0, 1] bit settings are identical – difference is that the synthesizer is not reset when this register is written to.
- The Lock Detect line also prevents the transmitter from being keyed should the PLL lose lock – so it is imperative that it be set up properly!

Once the LMX2316 has been initialized, the Reference divider can be written. In our case we need to write 4000 to this register, or 00111110100000 binary, padded out to the required 14 bits. In addition, there are four bits that must be set to 0 and one bit of note. This last bit sets the Lock Detect precision. If it is set, the chip will not set its lock detect output high until five (normally three) internal cycles have passed with the PLL locked – since we absolutely do not want to be transmitting with an unlocked PLL, this is a good thing to set. The final bit stream looks like this:

Bit	Value	Description	State
0	0	C1	Reference Divider
1	0	C2	
2	0	Ratio Bit 0 (LSB)	4000
3	0	Ratio Bit 1	
4	0	Ratio Bit 2	
5	0	Ratio Bit 3	
6	0	Ratio Bit 4	
7	1	Ratio Bit 5	
8	0	Ratio Bit 6	
9	1	Ratio Bit 7	
10	1	Ratio Bit 8	
11	1	Ratio Bit 9	
12	1	Ratio Bit 10	
13	1	Ratio Bit 11	
14	0	Ratio Bit 12	
15	0	Ratio Bit 13 (MSB)	
16	0	Test Modes	Must be 0
17	0		
18	0		
19	0		
20	1	Latch Detect Precision	Wait 5 clocks before asserting Latch Detect output

Table 3 - Reference Divider

The final bits to set are the Programmable Divider bits, a.k.a. the A and B counters. In our case we want to set the frequency to 435.225 MHz, so the A and B counters have to be set to 10 and 5440 respectively.

Bit	Value	Description	State
0	1	C1	Programmable Divider (N Counter)
1	0	C2	
2	0	A0	A (swallow) counter == 10
3	1	A1	
4	0	A2	
5	1	A3	
6	0	A4	
7	0	B0	B counter == 5440
8	0	B1	
9	0	B2	
10	0	B3	
11	0	B4	
12	0	B5	
13	1	B6	
14	0	B7	
15	1	B8	
16	0	B9	
17	1	B10	
18	0	B11	
19	1	B12	
20	1	Go Bit	Go!

Table 4 – Programmable Divider Bits

If you were setting up the data transmitter, which operates at 435.150 MHz, all you need to change are the Programmable Divider Bits. Namely, you divide the desired frequency 435,150,000 by the step size 2,500, resulting in 174,060. Next you divide 174,060 by the prescaler 32, resulting in 5439 with 12 remaining, so the A and B counters would be set to 12 and 5439 respectively. You can actually vary the frequency even when the transmitter is keyed. Be careful not to make any sudden frequency changes though, as the PLL will lose lock, unkeying the transmitter while the PLL tunes the VCO.

At this point the synthesizer is doing its thing – all you need to do is to set the desired output power and wait for the Lock Detect line to indicate the PLL is locked. If the transmitter is left on for extended periods, these three registers (make sure you write to the function register, and NOT the initialization register) should be refreshed occasionally to guard against single event upsets (SEU) – something you don't have to worry about for ground-based transmitters!

Setting Transmitter Power Level

The last items to work with on the transmitter are power control, keying and output level. Since the transmitter is connected directly to the battery, it contains a power FET that will disconnect it from the bus when inactive. This allows us to reset the PLL in case something gets latched up. The transmitter key line is a simple logic level, where low is unkeyed and high is keyed. Setting the output level involves writing to a 12-bit DAC, which controls a variable-gain driver stage in the power amplifier. This DAC resides on the same programming lines as does the LMX2316 and is wired in parallel with it. It uses a different strobe line, so even though the DAC bits are shifted out to both devices, only the DAC actually receives the setting when its strobe line transitions from low to high.

Normally the transmitter should be powered off when not in use, but this is not really done to save power. The transmitter draws about 4.9 mA in Standby (unkeyed) mode to power the PLL, DAC and TX control circuitry. Most of the current consumed by the transmitter is by the power amplifier "brick" – but it, along with the RF driver, the VCO, and even the PLL loop drivers are powered off when the transmitter is in Standby mode. The real purpose behind completely powering down the transmitter is to clear any undetected latch-ups or bad data in the PLL or DAC.

Sample Code

What follows is some basic code that will set the transmitter to a given frequency and set its output power. This code assumes one transmitter with its control lines attached to the FPGA bits 8 – 15.

```
/******************************************************************************
 * TuneTx()
 *
 * Set the given transmitter frequency
 *
 * Inputs:
 *
 * iInit  – Will initialize (reset) the PLL if TRUE
 * lFreq  – The frequency in Hz to which the transmitter will be tuned
 * iLevel – The output level the transmitter DAC will be set to
 *
 ******************************************************************************/

/* Synthesizer Configuration */
#define SYNTH_REF        (10000000L)          /* 10 MHz */
#define SYNTH_STEP       (2500)               /* 2.5 kHz */

/* LMX2316 Control bits */
```

```c
#define CTRL_R_COUNTER   ((unsigned char)0x00) /* Load the Reference counter */
#define CTRL_MA_COUNTERS ((unsigned char)0x01) /* Load the M and A div vals */
#define CTRL_FUNCTION    ((unsigned char)0x02) /* Load the Function register */
#define CTRL_INITIALIZE  ((unsigned char)0x03) /* Initialize the chip */
#define VCO_POS          ((unsigned char)0x80) /* VCO frequency changes with voltage */
#define PRESCALER        (32)                  /* 8 for a 2306, 32 for 2316/26 */

/* Transmitter control lines */
#define TX_PORT          (0x00C1)              /* FPGA Bits 8 - 15 */
#define TX_SPI_DATA      (0x01)                /* TX SPI Data */
#define TX_SPI_CLK       (0x02)                /* TX SPI Clock */
#define TX_DAC_CS        (0x04)                /* TX DAC Chip Select */
#define TX_PLL_CS        (0x08)                /* TX PLL Chip Select */
#define TX_PTT           (0x10)                /* TX PTT – high == key */
#define TX_PWR           (0x20)                /* TX Power – high == ON */


void TuneTx ( int iInit, long lFreq, unsigned uLevel )
{
   unsigned char ucBuff[3];
   unsigned long ulDiv;
   unsigned uB, uA;

   if ( iInit )
   {
      /* Initialize the Chip */
      ucBuff[0] = (unsigned char)0;
      ucBuff[1] = (unsigned char)0;
      ucBuff[2] = (unsigned char)CTRL_INITIALIZE;

      /* Drop the PLL CS, write the data and raise PLL CS... */
      outp ( TX_PORT, inp ( TX_PORT ) & ~TX_PLL_CS );
      BitBang ( ucBuff, 3 );
      outp ( TX_PORT, inp ( TX_PORT ) | TX_PLL_CS );

      /* Allow the PLL some time to digest this */
      MsDelay ( 5 );
   }

   /* Set the function and initialization bits
    * Test modes: OFF
    * Power Down Mode: Normal Operation
    * Timeout Counter: 0 (off)
    * FastLock Modes: Disabled
    * Charge Pump Output: Normal
    * Phase Detector polarity: Positive
    * Fo/LD Pin: Digital Lock Detect
    * Counter reset: Clear bit so counter can run
    * 20 19 18 17 16 15 14 13 12 11 10  9  8  7  6  5  4  3  2  1  0
    *  0  0  0  0  0  0  0  0  0  0  0  0  0  V  0  0  1  0  0  C2 C1
    * Bits 21, 22 and 23 will be ignored by the PLL
    */

   ucBuff[0] = (unsigned char)0x00;
   ucBuff[1] = (unsigned char)0x00;
   ucBuff[2] = VCO_POS | (unsigned char)0x10 | CTRL_FUNCTION;

   outp ( TX_PORT, inp ( TX_PORT ) & ~TX_PLL_CS );
   BitBang ( ucBuff, 3 );
   outp ( TX_PORT, inp ( TX_PORT ) | TX_PLL_CS );

   /* Set the reference divider
    * Lock Detect Precision = Set LD after 5 consecutive ref cycles
    * Test modes 0
    * 20 19 18 17 16 15 14 13 12 11 10  9  8  7  6  5  4  3  2  1  0
    *  1  0  0  0  0  R  R  R  R  R  R  R  R  R  R  R  R  R  R  C2 C1
    */

   ulDiv = (SYNTH_REF / SYNTH_STEP) & 0x3FFF;  /* only 14 bits long */
   ucBuff[0] = (unsigned char)0x10;
   ucBuff[1] = (unsigned char)(ulDiv >> 6);
```

```
   ucBuff[2] = (unsigned char)(ulDiv << 2) | CTRL_R_COUNTER;

   outp ( TX_PORT, inp ( TX_PORT ) & ~TX_PLL_CS );
   BitBang ( ucBuff, 3 );
   outp ( TX_PORT, inp ( TX_PORT ) | TX_PLL_CS );

   /* Set the frequency dividers
    * We want to shift this out:
    * 20 19 18 17 16 15 14 13 12 11 10  9  8  7  6  5  4  3  2  1  0
    *  1  B  B  B  B  B  B  B  B  B  B  B  B  B  A  A  A  A  A  C2 C1
    */

   ulDiv = lFreq / SYNTH_STEP;
   uB = (unsigned)(ulDiv / (unsigned long)PRESCALER) & 0x1FFF;
   uA = (unsigned)(ulDiv % (unsigned long)PRESCALER) & 0x1F;

   ucBuff[0]  = 0x10;
   ucBuff[0] |= (unsigned char)(uB >> 9) & 0x0f;
   ucBuff[1]  = (unsigned char)(uB >> 1);
   ucBuff[2]  = (unsigned char)(uB & 0x01) << 7;
   ucBuff[2] |= (unsigned char)uA << 2;
   ucBuff[2] |= CTRL_MA_COUNTERS;

   outp ( TX_PORT, inp ( TX_PORT ) & ~TX_PLL_CS );
   BitBang ( ucBuff, 3 );
   outp ( TX_PORT, inp ( TX_PORT ) | TX_PLL_CS );

   /* Set the transmitter power level */

   ucBuff[0] = (unsigned char)(uLevel >> 8);
   ucBuff[1] = (unsigned char)uLevel;

   outp ( TX_PORT, inp ( TX_PORT ) & ~TX_DAC_CS );
   BitBang ( ucBuff, 2 );
   outp ( TX_PORT, inp ( TX_PORT ) | TX_DAC_CS );

   /* Give the PLL 20 mS to stabilize */

   MsDelay ( 20 );
}


/*------------------------------------------------------------------------*
 * BitBang()
 *
 * Bitbang a byte to the given Tx - Byte is sent MSB first!
 *
 * Inputs:
 *
 *    pucByte = Pointer at the byte(s) to send
 *    iLen    = Number of bytes to send
 *
 *------------------------------------------------------------------------*/

static void BitBang ( unsigned char *pucByte, int iLen )
{
   int ii, ij;
   unsigned char ucCur;

   /* Get the status of the control port and make sure clock is low */
   ucCur = inp ( TX_PORT ) & ~TX_SPI_CLK;
   outp ( TX_PORT, ucCur );

   for ( ii = 0; ii < iLen; ii++ )
   {
      for ( ij = 0; ij < 8; ij++ )
      {
         if ( (pucByte[ii] & (unsigned char)(0x80 >> ij)) )
         {
            /* Send a 1 */
            ucCur |= TX_SPI_DATA;
```

```
         }
         else
         {
            /* Send a 0 */
            ucCur &= ~TX_SPI_DATA;
         }

         /* Set the status of the data bit */
         outp ( TX_PORT, ucCur );

         /* Raise and lower clock */
         outp ( TX_PORT, ucCur | TX_SPI_CLK );
         outp ( TX_PORT, ucCur );
      }
   }

   /* Make sure the data line idles low */
   outp ( TX_PORT, ucCur & ~TX_SPI_DATA );
}
```

Summary

In this paper, I have attempted to provide the reader with enough understanding of the ECHO transmitter in order to set it up and actually start transmitting. I really have not gone into much depth as far as transmitter design goes, but have provided enough information for the reader to understand what the numbers being sent to the synthesizer actually do. If you are interested in more (and mathematically gory) information on synthesizers and their design, go to Zarlink's website (http://www.zarlink.com) and download application note AN182. For a truly exhaustive dissertation on this subject, see *Microwave and Wireless Synthesizers, Theory and Design* by Ulrich L. Rohde. Demonstration software for configuring any device in the LMX2306 family can be downloaded from my web site at http://www.spottydog.us. This software includes source*, which I have released in to the public domain*. The software sets up a standard PC printer port to act as an SPI interface and is written entirely in C.

References

[1] National Semiconductor, Inc, LMX2306/LMX2316/LMX2326 PLLatinum™ Low Power Frequency Synthesizer for RF Personal Communications, Datasheet DS100127, 2002.

[2] Rohde, Ulrich L. *Microwave and Wireless Synthesizers, Theory and Design*. John Wiley and Sons, Inc. 1997

[3] Zarlink Semiconductor Inc, Designing Single Loop Frequency Synthesisers, Application Note AN182, Issue 3.1, 1999

[4] SpaceQuest Ltd. TX-435 specifications – see http://www.spacequest.com/products/UHFTransmitter.pdf

Acknowledgements

My thanks go to Mark Kanawati (N4TPY) and Bob Bruhns (WA3WDR) for proofreading this paper and making sure my circuit descriptions did not veer to far into the realm of fantasy.

AMSAT Eagle Project
Fall 2004 Status Report

By Richard M. Hambly W2GPS

The Eagle satellite is the focus of AMSAT's new Vision Statement. The satellite has been in the design phase since Dick Jansson WD4FAB presented his seminal paper at the 2000 AMSAT Symposium and has been refined at meetings in Denver CO in July 2001 and Orlando FL in October 2002. Another design meeting was held this past summer. This presentation will provide the current status of the Eagle design activities.

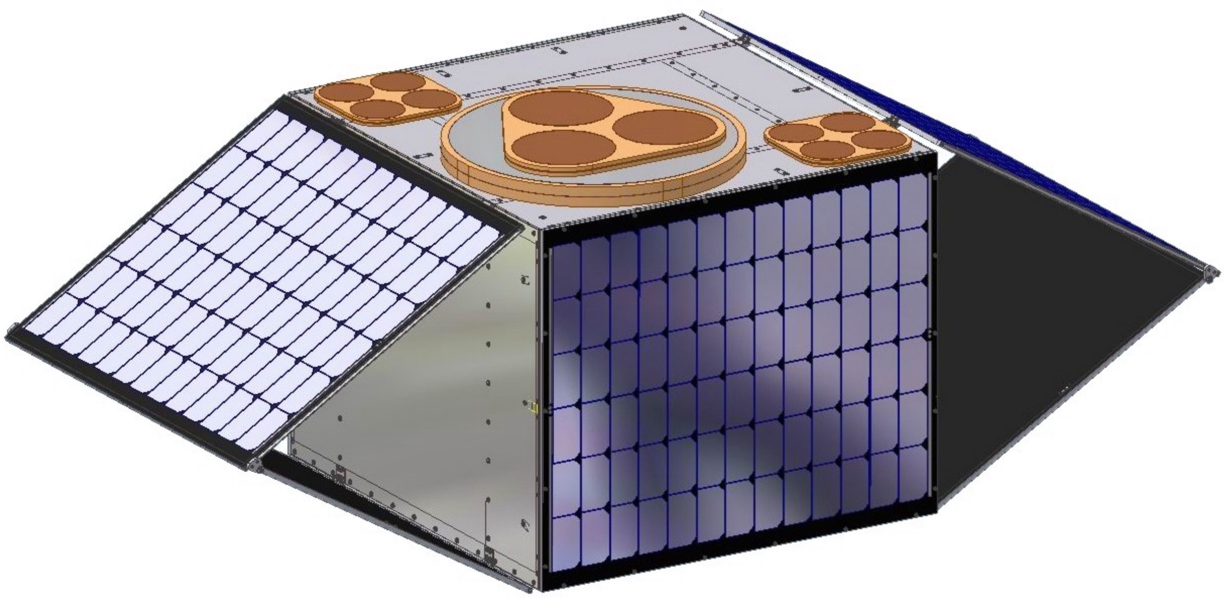


Figure 1: Eagle with Solar Panels Deployed

BACKGROUND:

The AMSAT Eagle project has been under consideration since it was originally proposed by Dick Jansson WD4FAB at AMSAT's 18th Space Symposium in Portland Maine on October 28, 2000. Dick's paper "So You Want to Build a Satellite" is published in the 2000 Proceedings

The first Eagle project design meeting was conducted July 14, 2001 at the Hilton Garden Inn in Denver, Colorado[1]. At this meeting two designs were considered and Dick's approach was selected. It was also decided to minimize propulsion by searching for a geosynchronous transfer orbit (GTO) launch and use propulsion only to stabilize the orbit by raising perigee, if necessary.

The second Eagle project team meeting was conducted September 28, 2002 at the Travelodge hotel in Orlando, Florida[2]. At this meeting the space frame, module packaging and thermal designs ware reviewed and an overall architecture considered that would accommodate a variety of popular operational modes as well as support for some of the microwave bands. Lou McFadin W5DID presented a design proposal for Sun and Earth sensors and was given the go-ahead to purchase parts and to pursue these designs in coordination with a team at Santa Rosa Jr. College in California.

A RENEWED EMPHASIS ON EAGLE

The AMSAT Board commissioned a new Strategic Planning committee consisting of board members, officers and advisors that met February 20-22, 2004 at the Airport Clarion Hotel in Orlando, Florida[3]. After an intense two days of work this committee produced new mission and vision statements for AMSAT that will guide the continuing efforts to develop a full Strategic Plan. This committee has met by teleconference every other week since the February kick-off effort to continue their work. The key result for the Eagle project is contained within the vision statement.

Our Vision is to deploy high earth orbit satellite systems that offer daily coverage by 2009 and continuous coverage by 2012…

This requires two HEO satellites by 2009 and three by 2012.

THE LATEST DESIGN MEETING

The third Eagle project design team meeting was conducted July 16-18, 2004 at the Airport Clarion in Orlando, Florida[4].This meeting was publicly announced through the AMSAT News Service (ANS) and all interested parties were afforded the opportunity to attend. Some AMSAT members availed themselves of the opportunity and were well received. They made valuable contributions and enjoyed the experience.

The primary goal of this meeting was to establish the requirements for the Eagle mission. The previous Eagle team meetings had left many unanswered questions that this group was determined to resolve. The team succeeded in achieving this goal, as will be seen in following paragraphs.

Two other important goals were achieved at this meeting:

- every aspect of Eagle's development was assigned to a working group and
- each working group was assigned an interim group leader.

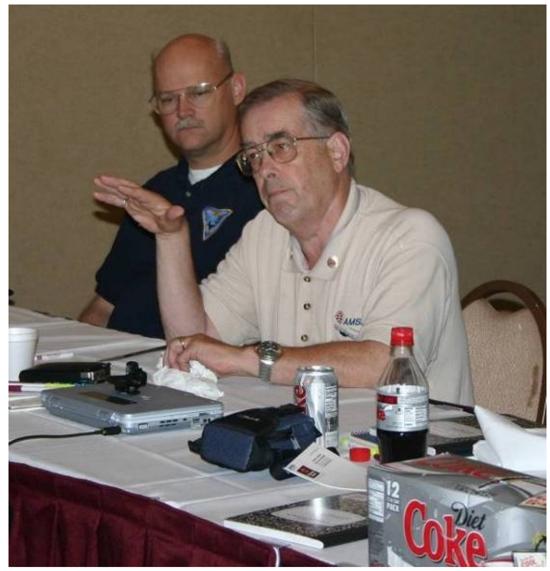


Figure 2: Robin Haighton VE3FRH making a point while Jim Sanford WB4GCS listens at the July 2004 Eagle Team Meeting

Eagle Requirements

The Eagle satellite is being built to support the AMSAT vision statement and will be designed to carry a set of payloads that will support the primary needs of the worldwide AMSAT community while providing both the builders and the users challenging, exciting, and valuable new features and technologies. The payloads will be carried by a modified version of the structure designed by Dick Jansson WD4FAB.

The requirements are summarized in the following outline.

1.0 Payloads

1.1 Transmitters

1.1.1 V band 20KHz bandwidth using SDR techniques

1.1.2 Two S Band

1.1.2.1 100KHz bandwidth

1.1.2.2 Either transmitter can be driven by SDR or analog inputs

1.1.3 C band wideband digital which includes telemetry

1.1.4 All bands should be capable of being operated simultaneously

1.2 Receivers

1.2.1 U band 100KHz bandwidth

1.2.2 L band 100KHz bandwidth

1.2.3 C band wideband digital

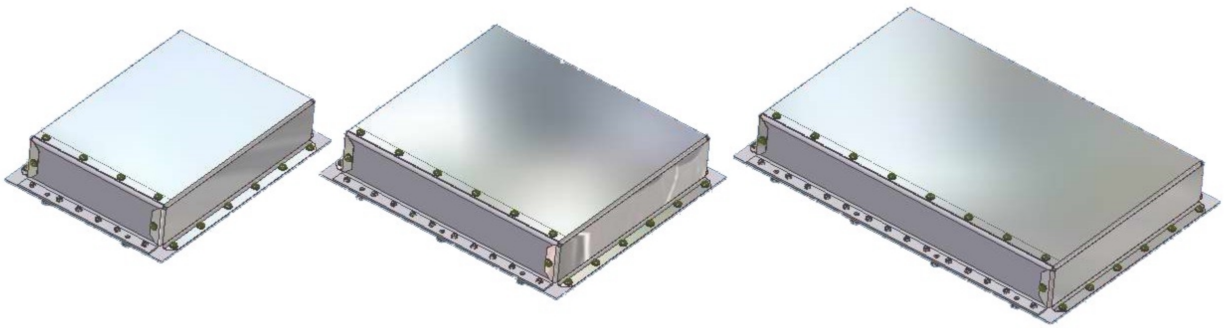


Figure 3: Payload Module Housings. The large Module will not be used in the latest design.

1.3 GPS (NASA)

1.4 CEDEX (Surrey Satellite Technology)

1.5 Cameras

1.5.1 Narrow FOV on +Z axis

1.5.2 Wide FOV on –Z axis

1.5.3 Cameras should survive all beta angles.

1.6 Telemetry beacons active on all transmitters

1.6.1 The IHU will provide digital data and clock to the transmitter. The transmitter itself is responsible for data delivery.

1.7 Command uplinks on the U and L receivers

1.7.1 Demodulation to baseband audio is in the receiver

2.0 Structure and Physical Properties

2.1 Mass

2.1.1 100Kg or less

2.2 Size

2.2.1 600mm by 600mm by 450 mm with fixed and deployable solar panels.

2.3 Stabilization

2.3.1 Spin stabilized (+ Z Nadir pointing at apogee) 1-15RPM

2.4 Orbit

2.4.1 High apogee elliptical

2.5 Attitude Control

2.5.1 Magnetorquers and nutation dampers

2.5.2 Sensors

2.5.2.1 The Sun sensors will measure the sun at all angles and attitudes

2.5.2.2 The Earth sensor will measure the attitude of the spacecraft with respect to the Earth while its distance is within two radii of the Earth's surface.

2.5.3 The satellite will stabilize to the desired attitude in 72 hours.

2.6 Propulsion

2.6.1 The simplest system that will accomplish a desirable orbit and is acceptable to the launch agency. Initial estimate is 60 meters per second delta velocity.

2.6.2 The propulsion system should be modular

Figure 4: Lou McFadin W5DID, Dick Jansson WD4FAB, and Alan Bloom N1AL at the July 2004 Eagle Team Meeting

2.7 Structure

2.7.1 Aluminum honeycomb panels forming core structure supporting internal modules and integrated with separation interface.

2.7.2 Separation interface is located on the on –Z side, and is launcher dependent.

2.7.3 Consider the possibility of side mounting

2.8 Magnetic Environment

2.8.1 Magnetically clean as practically achievable

3.0 Thermal Control

3.1 Battery temperature should not exceed a -15 to +15C range.

3.2 Electronics module environment should be from -25 to +40C

4.0 Power Generation

4.1 Two fixed and four deployable solar panels with omni coverage.

4.2 Fault tolerant BCR and battery system that fails in an operational mode.

4.3 Buss voltage is 10 to 14 volts nominal.

5.0 Housekeeping

5.1 IHU-3

5.2 CAN-Do! Information buss

6.0 Antennas

6.1 High Gain +Z

6.1.1 U (435MHz), L (1.2GHz), S (2.4GHz) and C (5.6GHz)

6.2 Omni Antennas, -Z (functional in all attitudes)

6.2.1 V (145MHz), U, L and S

6.3 Omni Antennas +Z

6.3.1 U, L and S

C-C RIDER PAYLOAD

An exciting new payload will be carried by Eagle based on a design concept first put forward by Tom Clark W3IWI that he calls C-C Rider. This has evolved based on the "Dream Payload" presentation made at the July 2004 Eagle team meeting by Rick Hambly W2GPS to include elements of four previously separate proposals, now integrated into the new C-C Rider payload. They are:

- KarnSat (~1Mbps),
- C-C Rider (5GHz Band),
- Software Defined Radio, and
- IP in Space

Figure 5: Rick Hambly W2GPS and Phil Karn KA9Q studying C-C Rider Plans during July 2004 Eagle Team Meeting

This will be a totally new technology to the Amateur Satellite Service that is directed at putting access to high orbit satellites into the hands of the average Ham even for those living in apartments and restricted communities. While the basis of this technology is a digital carrier with error correcting codes, the applications are the same as the average Ham expects, voice, data, video, and other modes in both one-on-one and round table group conversation modes. There will be much more said about this in other presentations.

"LINEAR" TRANSPONDERS

Eagle will have linear band-translating transponders that function much as those on previous high orbit satellites but are implemented in a unique new way. In particular the uplinks will be on U and L-bands with downlinks on V- and S-band. This will support the popular "Mode B" and the modes made popular by AO-40, Modes U/S and L/S, as well as other combinations.

Both uplink receivers and the S-band transmitters will support 100KHz bandwidths. The V-band transmitter will be limited to 20KHz, which will be the lower 20KHz of each of the receivers' bandwidths. It is not clear if both receivers and/or both transmitters will be able to be operated simultaneously, but that is not a requirement.

The implementation of these receivers and transmitters will use techniques developed by the world of amateur Software Defined Radios (SDR). This means digitizing the received 100KHz spectrum segments all at once at a high IF frequency and creating the 100KHz and 20KHz transmit spectrums similarly at a high IF frequency. The traditional IF matrix found in analog designs will be replaced with a digital matrix. There will be much more to say on this subject as the design develops.

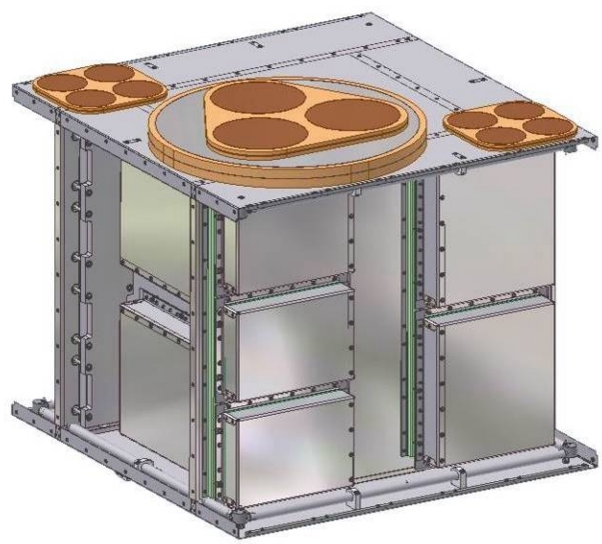


Figure 6: Eagle with Solar Panels Removed.

To provide a safe backup system in case of a failure in the digital implementation of the linear transponders there will be two S-Band transmitters and either of them will be capable of being driven by the SDR driver or by a traditional analog linear driver. One or more of the receivers will also be capable of analog operation.

ASSIGNMENTS

At the conclusion of the Eagle team meeting assignments were made so that all subsystems groups and management assignments now have individual points of contact so everyone will know who to contact on any issue. Some of these assignments are of an interim nature and those people will be actively looking for their replacements while other assignments will be more long lasting. The assignments as made during the meeting are as follows.

- Project Manager: Jim Sanford WB4GCS
- Chief Technical Officer: Rick Hambly W2GPS (acting)
- Secretary: Stephen Diggs W4EPI
- Structure and Thermal: Dick Jansson WD4FAB
- Launch: Lee McLamb KU4OS (lead), Tom Clark W3IWI (Russian launches)
- Guidance and Control - Ken Ernandes N2WWD
- Sensors: Alan Bloom N1AL
- Power Generation and Distribution: Lou McFadin W5DID
- Propulsion: Stan Wood WA4NFY (lead), Daniel Schultz N8FGV, Ken Ernandes N2WWD
- Housekeeping: Bdale Garbee KB0G (data interface), Chuck Green N0ADI, Lyle Johnson KK7P (IHU-3)
- Antennas: Stan Wood WA4NFY
- Payloads: Bob McGwier N4HY, Daniel Schultz N8FGV, Tom Clark W3IWI
- GPS: Lou McFadin W5DID
- CEDEX: Robin Haighton VE3FRH
- Cameras: Gunther Meisse W8GSM
- Command and Control/Telemetry: Stephen Diggs W4EPI, Stacy Mills W4SM

DESIGN APPROACH

Each of the three Eagle team meetings discussed the viability of using open design techniques. It has been decided to attempt to design Eagle in the open. To the extent possible, all drawings, schematics, software source code and other design materials will be made available to the AMSAT membership, probably by placing the materials on the Web site. Membership input and feedback will be encouraged through forms provided on the Web site.

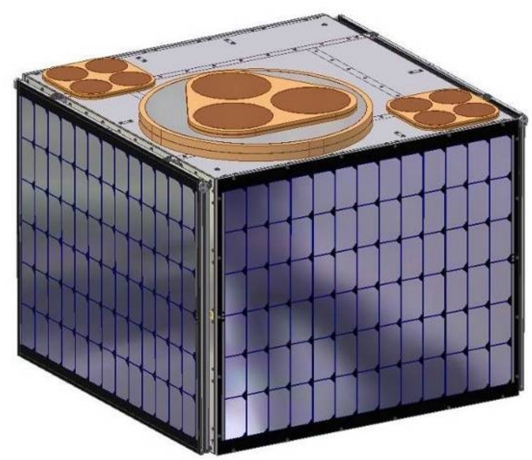


Figure 7: Eagle with Solar Panels in Launch Configuration

There are certain considerations that could limit or prevent the implementation of such an open design environment. They are as follows.

- The security of the satellite, especially issues of certain command and control codes.
- The use of commercial or other proprietary designs and products.
- The desire of a designer to maintain his or her designs as private

intellectual property as has been the tradition at AMSAT.

- The International Traffic in Arms Regulations (ITAR), U.S. Government Subchapter M, Title 22, Code of Federal Regulations, Parts 120 through 130 (22 CFR 120-130).

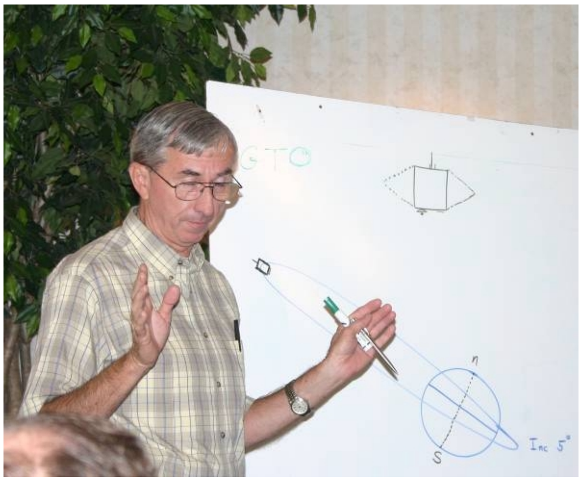


Figure 8: Stan Wood WA4NFY explaining orbital dynamics at the July 2004 Eagle Team Meeting

It remains to be seen to what extent we can make Eagle an open project but the team will be encouraged to pursue open design techniques wherever practical.

Figure 9: Gunther Meisse W8GSM coming up with another idea at the July 2004 Eagle Team Meeting

REFERENCES

So You Want to Build a Satellite, Dick Jansson WD4FAB, Proceedings of the AMSAT-NA 16th Space Symposium, October 27-29, 2000.

---

[1] Present at the July 2001 Eagle design meeting were Russ Tillman K5NRK, Chuck Green N0ADI, Stan Wood WA4NFY, Lou McFadin W5DID, Jim White WD0E, Lyle Johnson KK7P, Paul Williamson KB5MU, Bdale Garbee KB0G, Phil Karn KA9Q, John Connor NJ0C, Art Feller W4ART, Mike Kingery KE4AZN, Rick Hambly W2GPS, Ed Collins N8NUY, Mark Kanawati N4TPY, Robin Haighton VE3FRH, Dick Jansson WD4FAB, Tom Svitek, Dan Schultz N8FGV, and Brian Straup N5YC.

[2] Present at the September 2002 Eagle design meeting were Shea Ferrin, Bdale Garbee KB0G, Chuck Green N0ADI, Robin Haighton VE3FRH, Rick Hambly W2GPS, John Isella WA1ZVZ, Dick Jansson WB4FAB, Lyle Johnson KK7P, Lou McFadin W5DID, Russ Tillman K5NRK, Jim White WD0E, Stan Wood WA4NFY, and George (?).

[3] Present at the February 2004 Strategic Planning meeting were Robin Haighton VE3FRH, Rick Hambly W2GPS, Tom Clark W3IWI, Barry Baines WD4ASW, Lou McFadin W5DID, Stan Wood WA4NFY, Martha Saragovitz, Art Feller W4ART, Jim Jarvis N2EA, Bill Birden WB1BRE, Gerald Youngblood AC5OG, Dick Jansson WD4FAB, Lee McLamb KU4OS and Stephen Diggs W4EPI. Gunther Meisse W8GSM was unable to attend due to sudden illness.

[4] Present at the July 2004 Eagle design meeting were Ken Ernandes N2WWD, Bdale Garbee KB0G, Chuck Green N0ADI, Robin Haighton VE3FRH, Rick Hambly W2GPS, Dick Jansson WD4FAB, Lyle Johnson KK7P, Phil Karn KA9Q, Lou McFadin W5DID, Tom Clark W3IWI, Bob McGwier N4HY, Lee McLamb KU4OS, Karl Sandstrom K5MAN, Jim Sanford WB4GCS, Dan Schultz N8FGV, Stan Wood WA4NFY, Alan Bloom N1AL, Lynnette Evans W3GZZ, Paul Tabatschkow N3UD, John Conner NJ0C, Stephen Diggs W4EPI and Gunther Meisse W8GSM.

AMSAT Eagle Project

By: Dick Jansson, WD4FAB

Abstract

The AMSAT Eagle Project has evolved from the continuing interests of member's, for a "replacement" for the popular High Earth Orbit (HEO) Amateur radio communications satellite AMSAT OSCAR 13 (AO-13), and now for AO-40. These interests resulted in an effort to create a universally applicable spaceframe and earlier presentations.[i,ii] To this date the spaceframe design has reached a degree of maturity, but we are still lacking the necessary payload modules. This presentation will revisit the features of a spaceframe design that has yet to achieve a fully defined mission.

Eagle Objectives

The needs of the Amateur radio community are for a simple, low-cost HEO (High Earth Orbit) satellite that will provide reliable, wide-area coverage and long distance communications. We have seen that having low-power microwave links are not only possible, but are very practical, thanks to AO-40. While having microwave RF links is a major goal for Eagle, it is still seen to be very desirable to include VHF (2m) and UHF (70cm) receiving and/or transmitting equipment as a part of the mission.

At this moment, AMSAT-DL is constructing a P3-E spacecraft for this purpose. P3-E is, however, a satellite design that requires a significant propulsion effort to increase the orbital inclination to a high value, targeting for inclinations up to 63°. The original design concept for Eagle was for ***no*** propulsion. That would have been possible by using one of the earlier Ariane 5 launchers, which provided GTO[iii] launches with a perigee of 500+km. Unfortunately, we cannot guarantee the use one of these launchers, as the updated Ariane 5 launchers now have perigee values in the 200+km range, making it most necessary that we must plan to have a minimum propulsion system to lift the initial perigee up to about 800km.

Other objectives of the Eagle Project are for a program length of no more than three years, with costs, outside of launch costs, not more than $500,000. We will also reuse as much prior design technology as possible, following the KISS[iv] principle that is AMSAT's trademark. Finally, one of the original objectives is be less than a 50kg launch mass, making it easier to find a suitable launch.

AMSAT Vision

In 2004 the AMSAT Strategic Planning Committee and the Board of Directors met to examine the forward-looking goal and vision for the organization. The major goal is to provide continuous HEO communications coverage by 2012. This includes AMSAT-DL's P3-E satellite followed by a succession of two Eagle satellites, providing daily coverage anywhere in the World. These goals are to also encourage technical and scientific innovations and to promote the training and development of skilled satellite and ground systems designers and operators.

Eagle Initial Design Objectives

In examining the opportunities for a secondary launch payload, we felt that a spacecraft design that was inside of a 600mm cube would permit us greater launch possibilities.

Taking advantage of using only a minimum propulsion effort means that we will be placed in a low-inclination GTO orbit. This means that we will experience operating sun angles (Beta or β) of all values from 0° to 360°. Earlier satellites, designed for high inclinations, often ended up in low inclinations and as a result needed an operating "sleep" period to reorient the satellite for useable solar angles to provide for optimum battery charging, rather than optimum antenna pointing angles. This meant that operating "seasons" were experienced, unfortunately. Accordingly, an initial design objective for Eagle was to be able to operate at any Beta angle and thus the removal of the need for operating seasons.

Other initial objectives for the Eagle design are to have a simple core structure to handle the launch loading of the payload. At the same time we needed to maintain a light-weight design using low-cost structural elements.

Initial Goals vs. Real World

It became clear, early-on, that being able to avoid a propulsion system was unrealistic. We will need to be able to lift our 200km launch perigee to about 800km for a long-life stable orbit. However keeping a KISS propulsion system does seem possible, through the use of a mono-propellant such as hydrogen peroxide, H_2O_4. While any energetic propellant can be hazardous to handle, some propellants, such as H_2O_4, can be handled without the need for exotic materials and handling systems. As the design has evolved, we see some of these possibilities evolve into real hardware features.

A View of the Hardware

Fig. 1 shows the Eagle design as it has evolved. Shown is the 600mm cube with the Y-side solar panels latched down in the launch position. The view of the top of Eagle, the +Z side, with the U, L, and S band gain antennas mounted with room left for the C band array. Not shown are the V, L and S pop-up omni antennas on the bottom (-Z side), needed for initial commanding of the satellite.

The current antenna designs are shown in this view, with a parasitic gain patch antenna for U band, 435 - 438 MHz. This is composed of the reflector (the spacecraft skin), a driven element disc and a director disc. For L (1268 – 1270 MHz) and S (2400 – 2402 MHz) bands, arrays of patch elements are shown for increased gains. All of these antennas are designed for right hand (clock-wise) circular polarization, RHCP. This polarization has been the common standard used on AMSAT satellites.

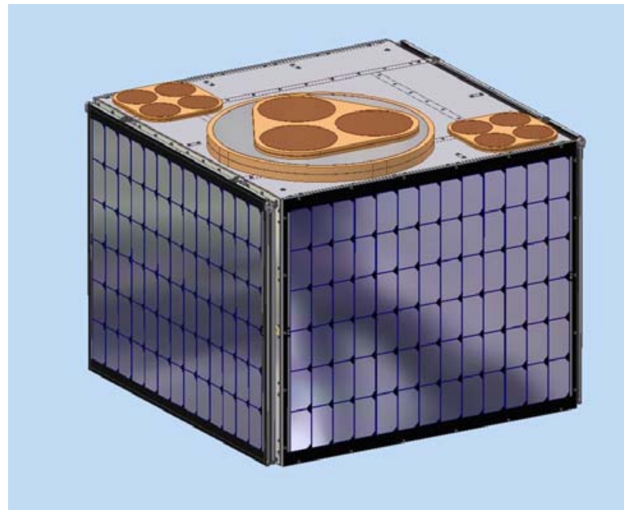


Fig. 1: Eagle shown in its launch position

Now we get into some action, Fig. 2 shows Eagle following its launch separation with the Y-side solar panels deployed. This geometry provides Eagle with its operating capability for any, and all, solar β angles. The solar panels facing the viewer are on the +X side.

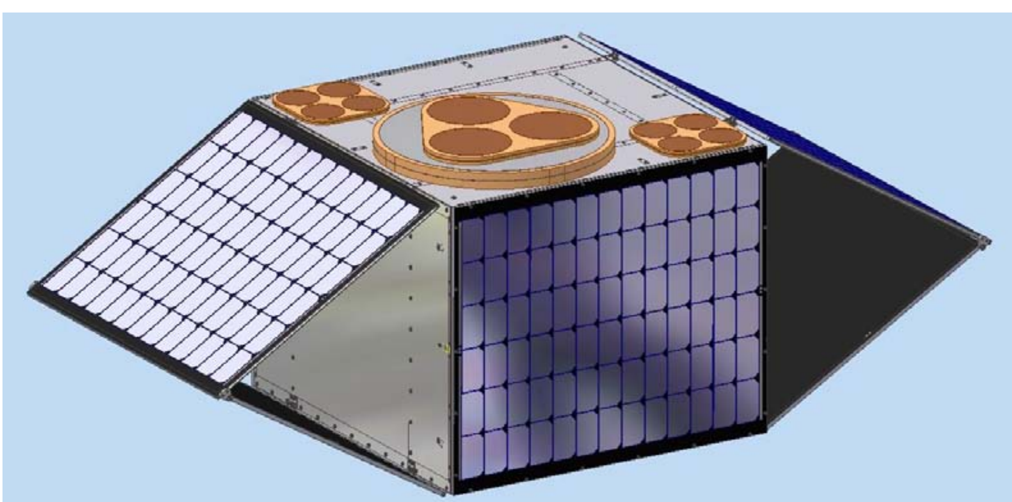


Fig. 2: Eagle after launch with Y-side solar panels deployed

Of engineering interest are such matters of the stability of the spin motion about the Z axis. The CAD program used for this effort, Autodesk's Inventor 8, provides for an examination of the mass distribution of the design, and thus a determination of the spin stability. We are assured that it will be a stable spin.

Another matter of engineering interest is that of the simplicity and robustness of the core structure of the design. Fig. 3 shows this core structure composed of 0.5 inch thick aluminum honeycomb panels. Shown on the face of the panes are the fiberglass module-mounting rails. These are taken from the AO-40 design.

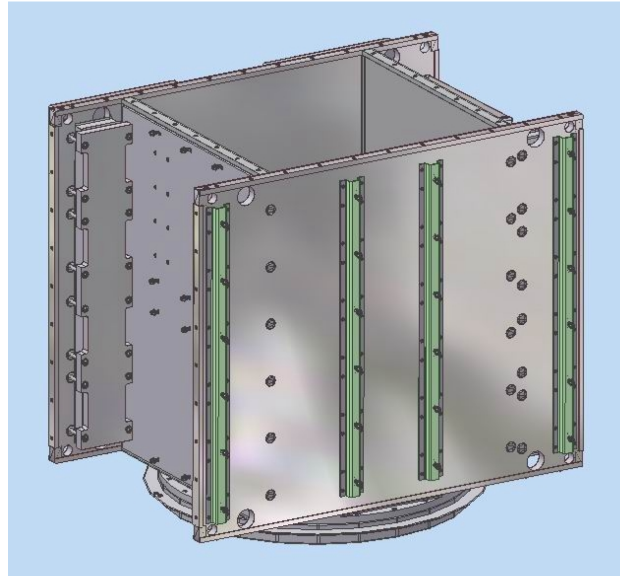


Fig. 3: Eagle core structure, on left is a Li-Ion battery

One of the early design features of Eagle is that of the module housings for the system electronics. A considerable amount of design effort was expended in this design, even before the spacecraft design reached any degree of maturity. This module design was created to get past the design problems experienced with those of AO-40. Fig. 4 shows three sizes of modules, based on the size of the main PCB mounted inside. As a result, we have modules designated "125x180mm", "200x180mm" and "275x180mm", following the 75mm size incrementing that was used on AO-40.

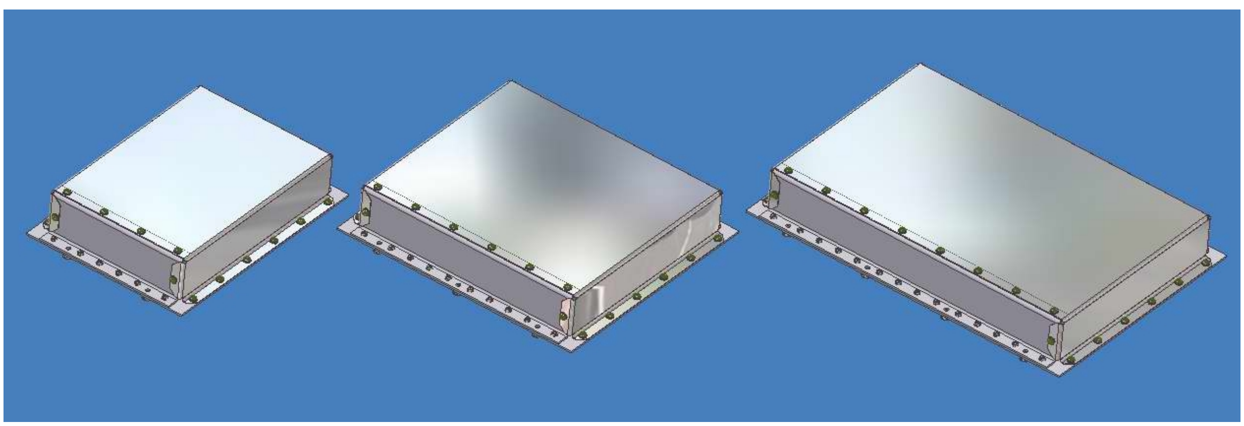


Fig. 4: Electronic modules for Eagle; L-R: 125x180mm, 200x180mm, and 275x180mm

Power System

The power system for Eagle has not yet been fully defined. These discussions center about the use a 14VDC or a 24VDC main bus power system. While these discussions continue, battery designs for either bus voltage have continued. If we use the cylindrical cell NMH batteries that were incorporated into AO-40 as the Auxiliary Battery, they require a somewhat massive clamping system to contain the cylindrical cells, a difficult geometry to deal with. If we proceed to examine newer technologies we are quickly presented with the quite high power density cells of the Lithium-Ion (Li-Ion) systems. In addition to the higher power densities of Li-Ion the cell geometries are rectangular, making them very much easier to mount and clamp into the spacecraft.

Fig. 5 shows a partially assembled spacecraft with modules mounted and also showing one of the NMH battery cell strings mounted on the Y side next to some transmitter modules.

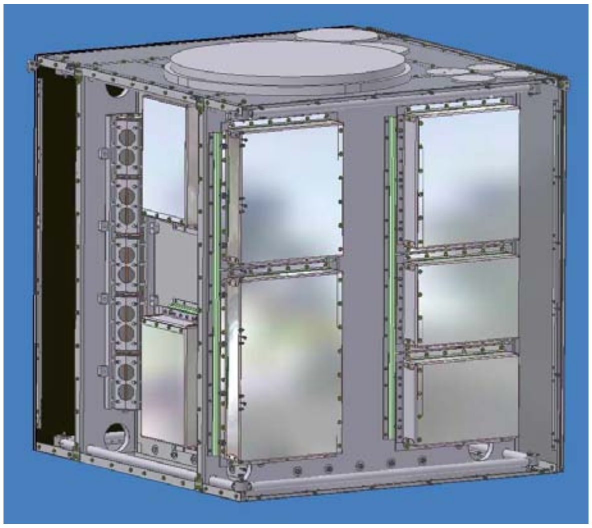


Fig. 5: Modules mounted in spacecraft with NMH cell string mounted on the left side.

Fig 6 shows another partially assembled view of Eagle, this time showing a propellant tank mounted in the center and also a Li-Ion cell assembly mounted in the Y-side compartment. The clamping bar on the Li-Ion cells is made of a piece of aluminum honeycomb panel, a relatively light weight clamp.

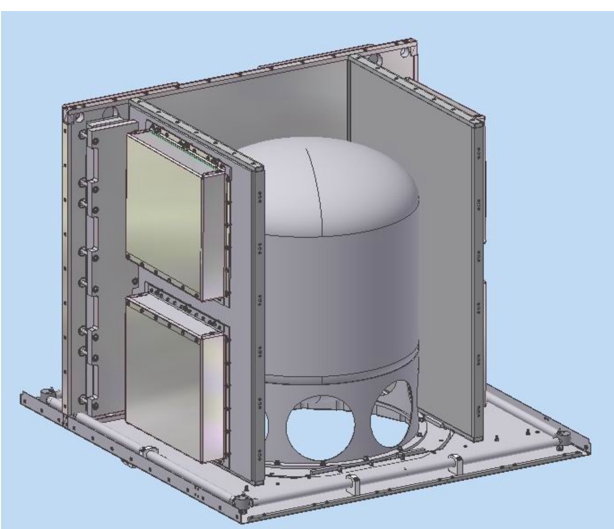


Fig. 6: Partial assembly of Eagle, showing a Li-Ion cell unit on left side

Navigation System

Navigation systems for Eagle have had several levels of consideration. The designs of the detection elements of Earth Sensor and Sun Sensor have had only early efforts. The elements that are of the “large hardware” components that can be easily copied from AO-13 and AO-40 have been designed into Eagle. These are the Nutation Damper, a design that has been used on all P3 spacecraft since 1980. The other element that has been incorporated is the magnetic torquing rings that provide for a computer controlled torquing against the Earth’s magnetic field when the satellite is near its perigee. This torquing system allows the computer control of satellite pointing and spin rate. Fig. 7 shows these navigation system elements.

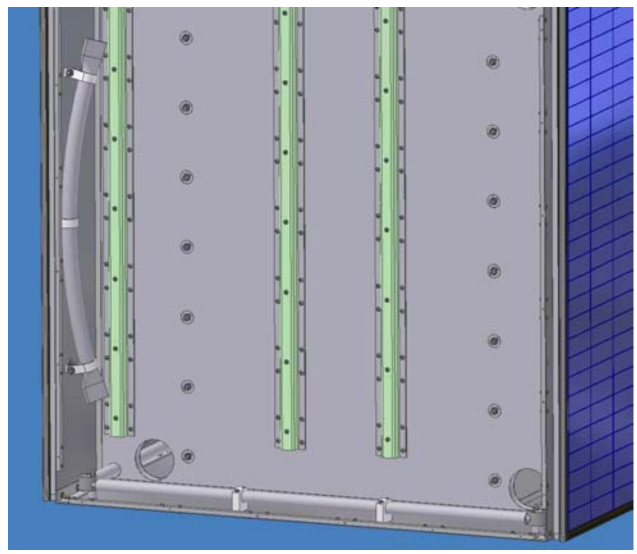


Fig. 7: The curved Nutation Damper shown on left side; Torque Ring shown mounted to bottom panel. Top Torque Ring is similarly mounted to top panel.

Thermal System

Early thermal analytic examinations of the Eagle spacecraft design have been conducted, see Fig. 8. These analyses have shown that the desired operational concept, of being able to operate at any β angle, is valid. This analytic work has also shown that the power generation plan is also very valid.

The thermal analytic work has shown that suitable temperatures can be achieved for Eagle through only the use of thermal control tapes, and that thermal insulating blankets will not be needed.

For the higher power dissipation modules, a specially designed module has been created, providing for a “heat sink” to which are mounted the high-power devices. These modules, in turn, will need to be specially mounted to the Y-side panels, to which a 3mm thick aluminum skin has been provided. This thick skin will allow the dissipated heat to be “spread” over the expanse of the panel, thus providing for radiative heat dissipation.

For a reference on module power dissipations, the AO-40 spacecraft had transmitter modules with much higher power dissipations, requiring that the module heat sinks had to be mounted to the heat pipe system built into the spaceframe. The Eagle RF amplifier power dissipations are considerably lower than in AO-40, allowing for a less rigorous thermal system for these dissipations.

One concept that has been carried forward from all P3 designs since before 1980 is that of mounting of the low power modules that are of great importance to the command and control (C&C) of the spacecraft, such as the command receivers, flight control computer (IHU), and other command devices. These units must be protected from the excessive temperatures that can be experienced during solar eclipses. The duration of a solar eclipse can be up to three hours, during which spaceframe temperatures can drop to as low as -100°C or lower. The critical C&C modules can be protected from these low temperatures through the use of very low emittance thermal coatings on the modules and also providing for insulated mounting of the modules, hence the use of the fiberglass module mounting rails, a concept that has been incorporated in all P3 spacecraft since 1980. Telemetry data from AO-10 spacecraft, and later, have proven these concepts. Fig. 8 illustrates the results of the early thermal and power analyses.

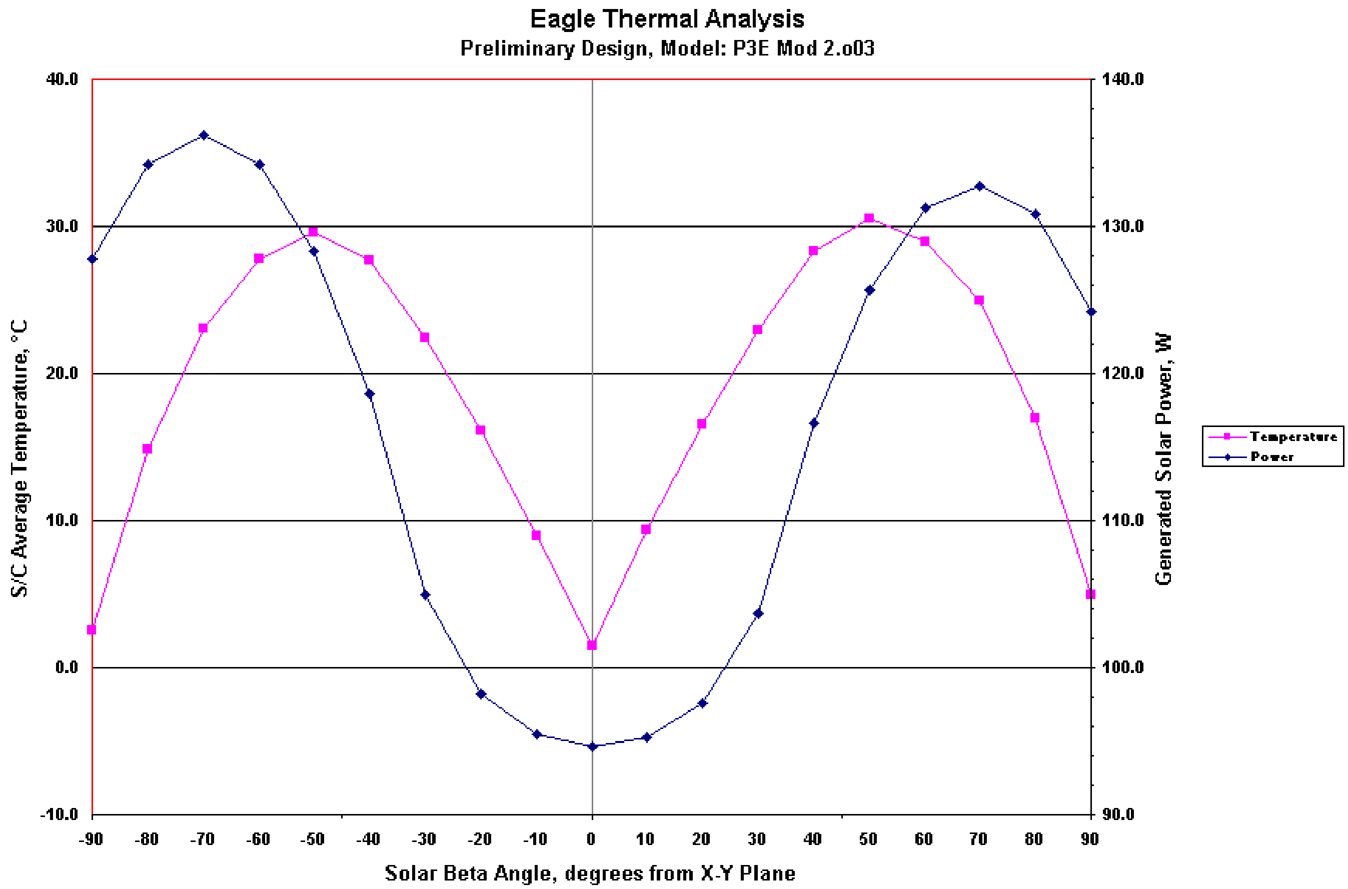


Fig. 8: Eagle preliminary Thermal and Power analyses

The final flight temperatures will probably be set to a little lower temperature than shown in Fig. 8. The power analysis shows that even with the 18% solar cells, an ample power generation is available. It is expected that higher efficiency cells will be used for the final flight solar panels.

Antenna Performance Analysis

The following information was created for the Eagle project by Ken Ernandes, N2WWD. This effort was done to illustrate antenna performance over the whole orbit and, as a result, defining the desirable antenna gains.

The first chart is to show the "squint" angle as a function of the MA count of the orbit. Squint angle is defined here as the angle between the bore-sight of the antenna and the Earth station antenna. Thus with the Eagle antennas pointed at the center of the Earth at apogee, the squint angle will be zero with the satellite at apogee with the station located at the satellite subpoint. If a station is located away from the subpoint, then the squint will be at a minimum at some other MA count, see Fig. 9. Operating experience with earlier satellites show that workable antenna pointing conditions can be achieved with squint angles out to 30°.

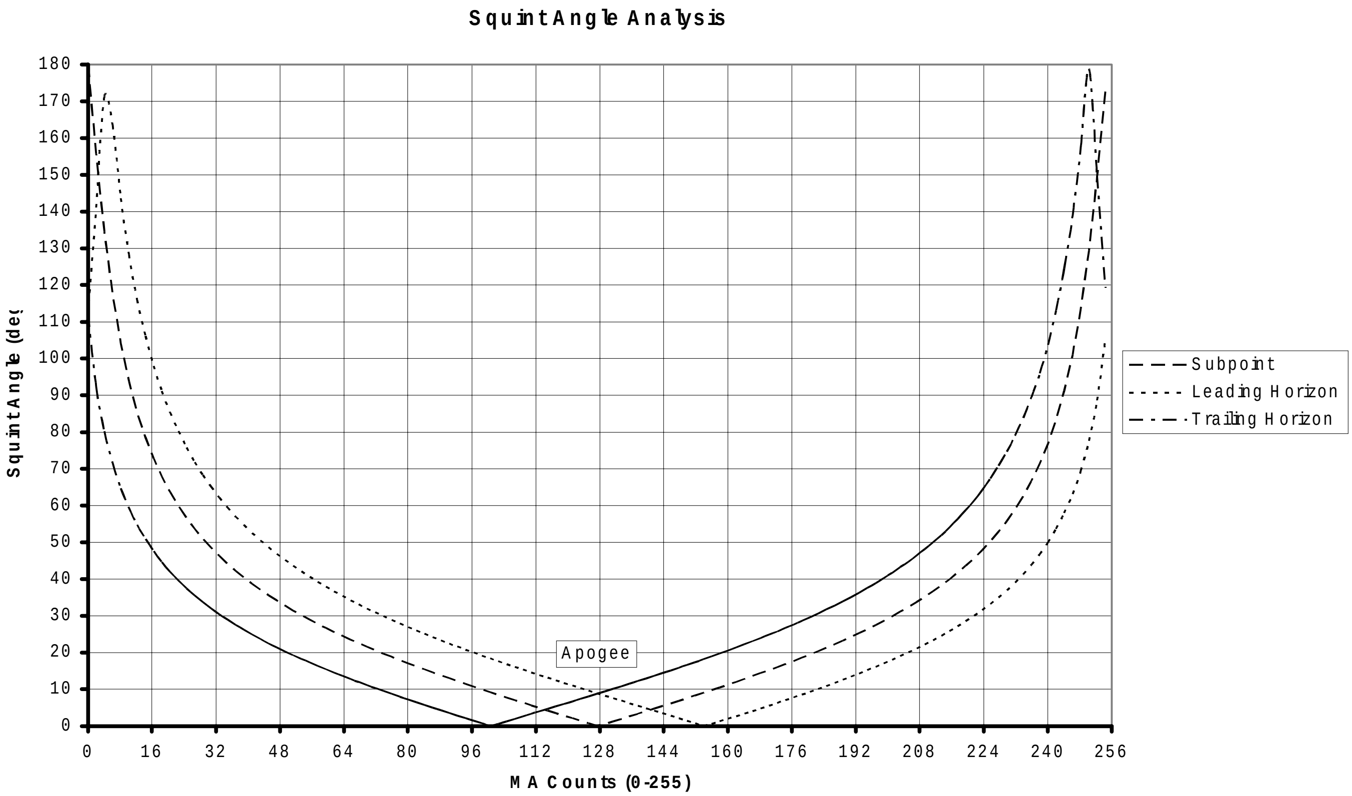


Fig. 9: Eagle Squint Angle analysis

A close look at Fig. 9 shows that at the Squint = 30°points there is about 146 MA counts, or 6.0hr of operating time out of the total of 10:27hr orbital period. This is about ≈ 57.5% of the orbit. That is a lot of operating time!

Fig. 10 shows the free space path loss of Eagle's antennas. This path loss is:

$$\text{Path Loss} = 20 \cdot \log_{10} \cdot \text{Range}$$

This element of path loss is based upon Eagle's orbit of 35,000km apogee x 800km perigee. The other gains and losses, e.g.: antennas, frequencies, etc., will need to be modeled separately and added to the path loss to determine the total path loss.

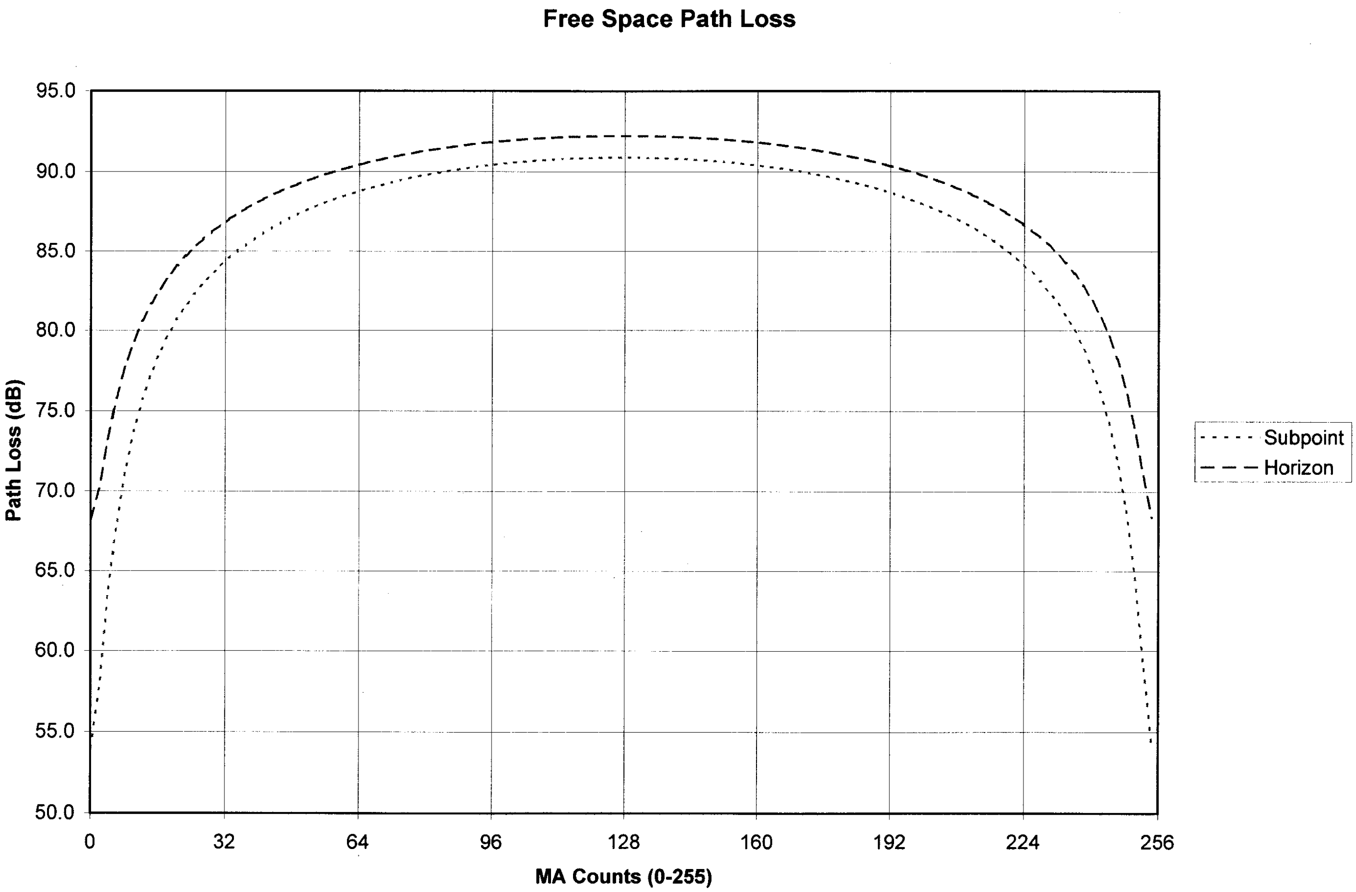


Fig. 10: Eagle Free Space Path Loss

Conclusions

By far the largest difficulty for bringing Eagle to completion is the generation of the mission description and then a commitment by AMSAT engineers for the design and fabrication of the electronics for that mission.

On the mechanical side, the basic 3D geometry has been established for the Eagle spaceframe, allowing us to show geometry suitable for a HEO Ham radio communications mission. The 2D drawings for this fabrication are only 10% complete, but this is not seen as a hindrance for completing the fabrication. A number of mechanical support equipment designs have been created and are ready to be fabricated.

The antenna designs need to be completed and evaluated. The navigation design needs a lot of work, but some of the key hardware is in hand. The propulsion system needs a lot of work to bring a flight suitable design to completion. We have a negotiated separation interface with the needed hardware available.

With the recently committed Vision statement of AMSAT's, it is encouraging that Eagle will "come to life" as a work-horse satellite design for the enjoyment of all the users across the globe.

Footnotes:

[i] "So You Want to Build a Satellite", Dick Jansson, WD4FAB; Proceedings of the AMSAT-NA 18th Space Symposium 27-29 October 2000

[ii] "So You Want to Build a Satellite! – Revisited", Dick Jansson, WD4FAB; AMSAT Journal, Sept./Oct. 2002

[iii] Geosynchronous Transfer Orbit, the standard intermediate launch orbit used for synchronous orbiting satellites. Apogee of 36,000km with perigee of ≈200km.

[iv] *Keep It Simple Stupid*, a rather crass, but basic guidance tenant used to keep the minds of the designers on engineering fundamentals, rather than allow them to be drawn to exotic, but not necessarily proven concepts.

Making Sense of Sensors

Alan Bloom, N1AL
n1al@amsat.org

Abstract: *Eagle will probably have a highly-elliptical equatorial orbit with apogee at about 36,000 km and perigee below 1000 km. The satellite will be spin-stabilized with the "Z" spin axis aligned with the earth at apogee. The high path loss at apogee is compensated by high-gain antennas pointing in the +Z direction. The Eagle sun sensors help determine the spacecraft's orientation in space so that the spin axis can be correctly aligned. When the satellite approaches perigee, the earth moves out of the high-gain antennas' field of view. A primary task of the earth sensors is to help determine when to switch to the omnidirectional antennas.*

There are two types of sun sensor. The dual-slit type determines the sun's elevation and azimuth by detecting the sun crossing time as a function of the satellite rotation. The staring type does not depend on satellite rotation, but reads out the elevation and azimuth directly. Two sensors of each type are included, oriented to give full 180-degree elevation, 360-degree azimuth coverage.

The earth sensors also depend on the satellite rotation for their operation. Each includes an infrared-sensitive horizon-crossing indicator (HCI) that senses the transition between cold space and relatively warm earth when the field of view crosses the earth's horizon. Two earth sensors at opposite corners sweep out two cones in space, at least one of which will intersect the earth as the satellite approaches perigee.

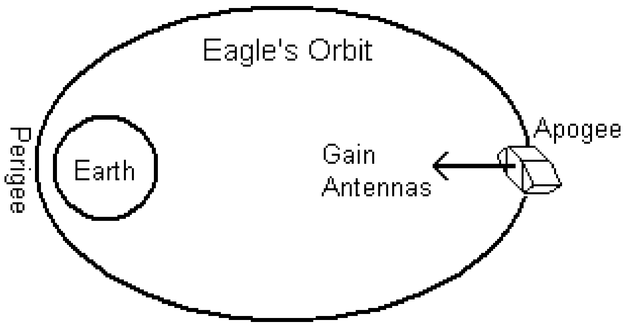
As an experiment, we are also considering a magnetic field detector to sense the direction and strength of the earth's magnetic field when at low elevations, to complement the data from the sun sensors. This should help in determining spacecraft orientation and magnetorquer timing. Since the field strength varies as the inverse cube of the distance, it should provide a sensitive indication of the distance to the earth.

All sensors communicate with the IHU (internal housekeeping unit) processor via Eagle's CAN bus, similar to the one flown on AO-40. CAN is an industry-standard serial communications bus originally developed for the severe mechanical and electrical environment of automobiles. A standard CAN interface board will be used by most subassemblies in Eagle, simplifying both design and testing.

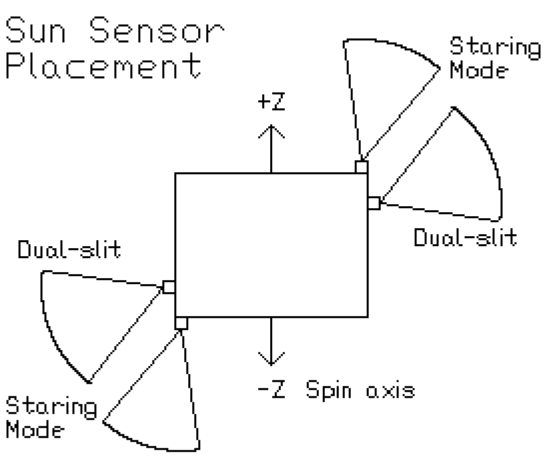
Introduction

While Eagle's exact orbit will depend on available launch opportunities, it will surely be a highly-elliptical high-earth orbit (HEO) of some type.[1] Most likely it will be a geosynchronous transfer orbit (GTO) which typically has an apogee of approximately 36,000 km and a perigee on the order of 200 km. At 200 km, atmospheric drag is strong enough to de-orbit the satellite within a few days, so an on-board rocket motor is required to raise the perigee after launch. Perhaps the most important task of the sun and earth sensors is to determine the direction of the spacecraft spin axis (the attitude) so that it can be re-oriented for the rocket firings.

The large path loss at apogee requires gain antennas on the satellite. Once a stable orbit has been achieved, Eagle's spin axis will be oriented so that the gain antennas point directly to the earth at apogee. Again, the sensors are key to that task.



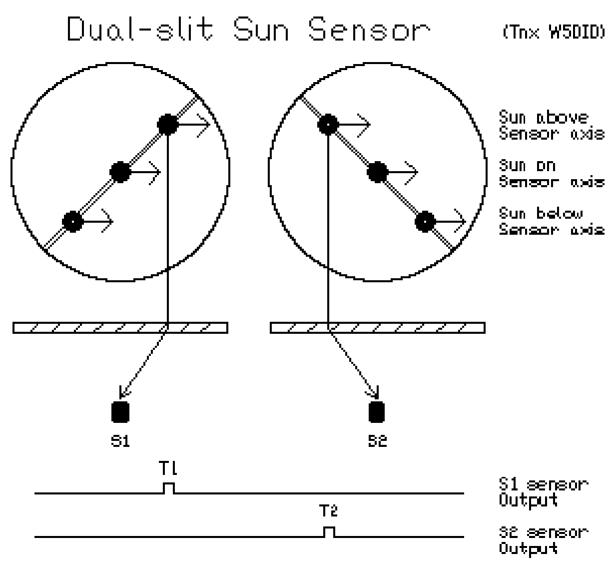
When near perigee, the gain antennas point in the wrong direction so the transmitters and receivers must switch to omnidirectional antennas. This must be done at the correct mean anomaly (MA), the fraction of the orbital period since perigee. The earth sensors provide a sensitive indication of MA once the orbital parameters are known.



Eagle will have two types of sun sensor. The dual-slit sensors depend on the sun moving past their field of view due to satellite rotation. They cover directions roughly perpendicular to the spin axis. When the sun is near the spin axis, it appears motionless from the satellite's frame of reference. That is the purpose of the staring-mode sensors which do not depend on satellite rotation for their operation. The four sun sensors (two of each type) are arranged with overlapping fields of view that cover the entire sky so the sun can be located at any spacecraft attitude.

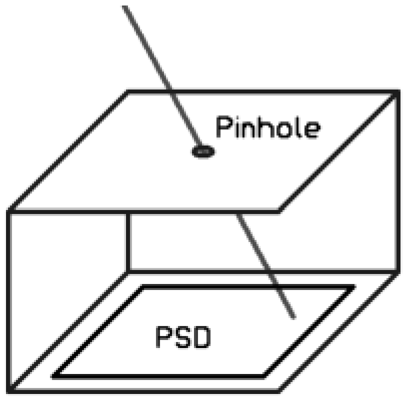
Dual-Slit Sun Sensors

Each dual-slit sensor contains two cavities containing a photodetector mounted behind a slitted opening oriented at an angle to the spin axis. One slit slants to the right, the other to the left. If the sun is exactly perpendicular to the spin axis, both detectors will detect the sun at the same time and both will output identical voltage pulses. In the diagram below, the right slit will detect the sun first if the sun is above the center line. If the sun is below the center line, the left slit will pulse first. If the spin period is known, the sun's elevation angle can be computed from the time between pulses.



Of course, the spin period is simply the time between successive pulses from the same slit. The azimuth can be computed by measuring the time from a known time reference to the average of the two pulses. So the dual-slit sun sensor can determine spin rate, azimuth and elevation whenever the sun is within its field of view during part of the rotation.

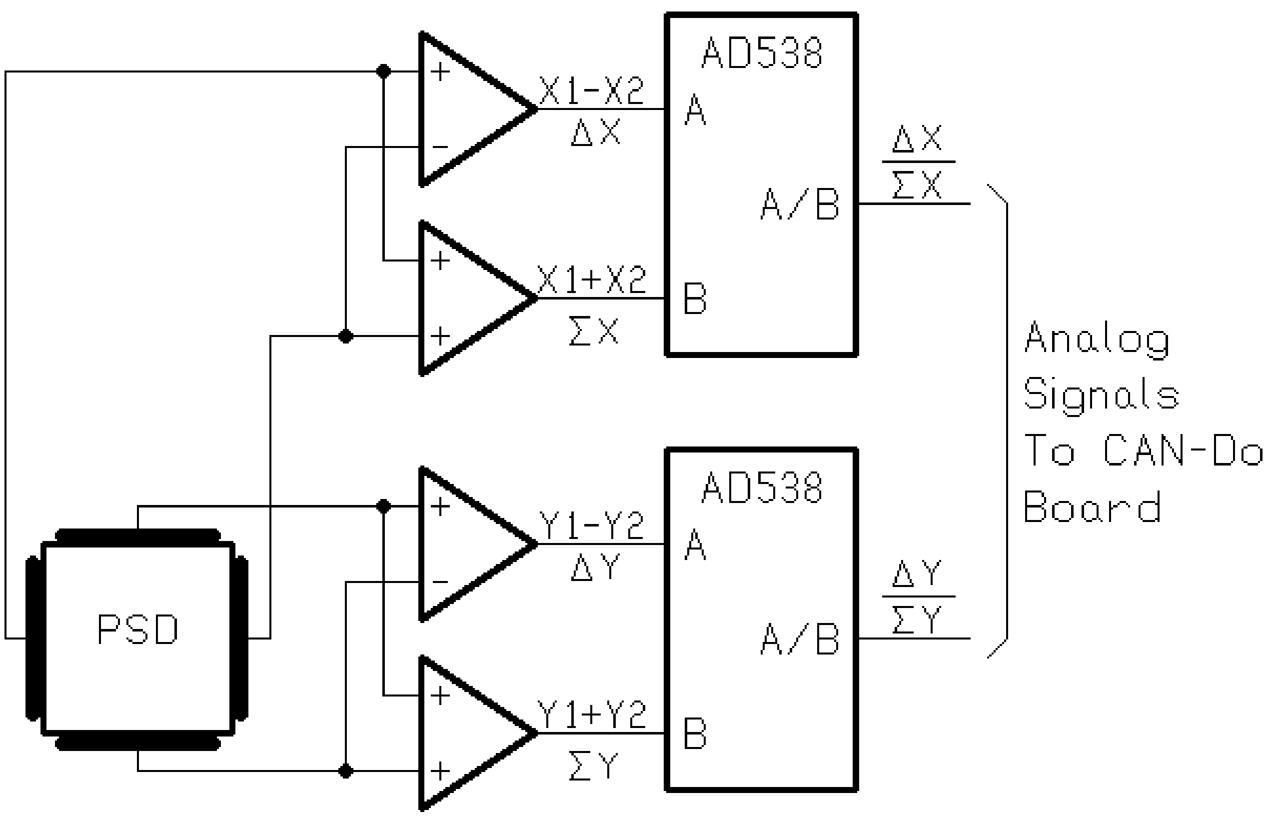
Staring-Mode Sun Sensors



The staring sensors are used to fill in directions not covered by the dual-slit sensors. They do not require the satellite to be rotating; they give the current sun direction whenever it is within the field of view. Each sensor consists of a light-tight box with a small hole. It is like an old-fashioned pinhole camera with the film replaced by a silicon photodetector chip from Hammamatsu, called a "position-sensitive detector" (PSD).

There are four electrical contacts on the PSD, one on each edge. When a spot of light falls on the chip, a current is generated, which flows into a transparent resistive coating on the chip's surface. The current will tend to flow in the path of least resistance, which is toward the edges that are closest. The difference in current between opposite edges is proportional the X and Y position of the spot, from which elevation and azimuth can be calculated. If the sun is not too close to the Z axis, the satellite's rotation rate can also be determined.

The analog processing circuitry is copied from the AO-40 sensors.[2] Differential amplifiers connected to opposite sides of the PSD calculate the sum and difference of the currents from each opposing pair of contacts. An analog multiplier/divider chip from Analog Devices takes the ratio of those two numbers. Dividing by the total current makes the X and Y position outputs independent of solar intensity.

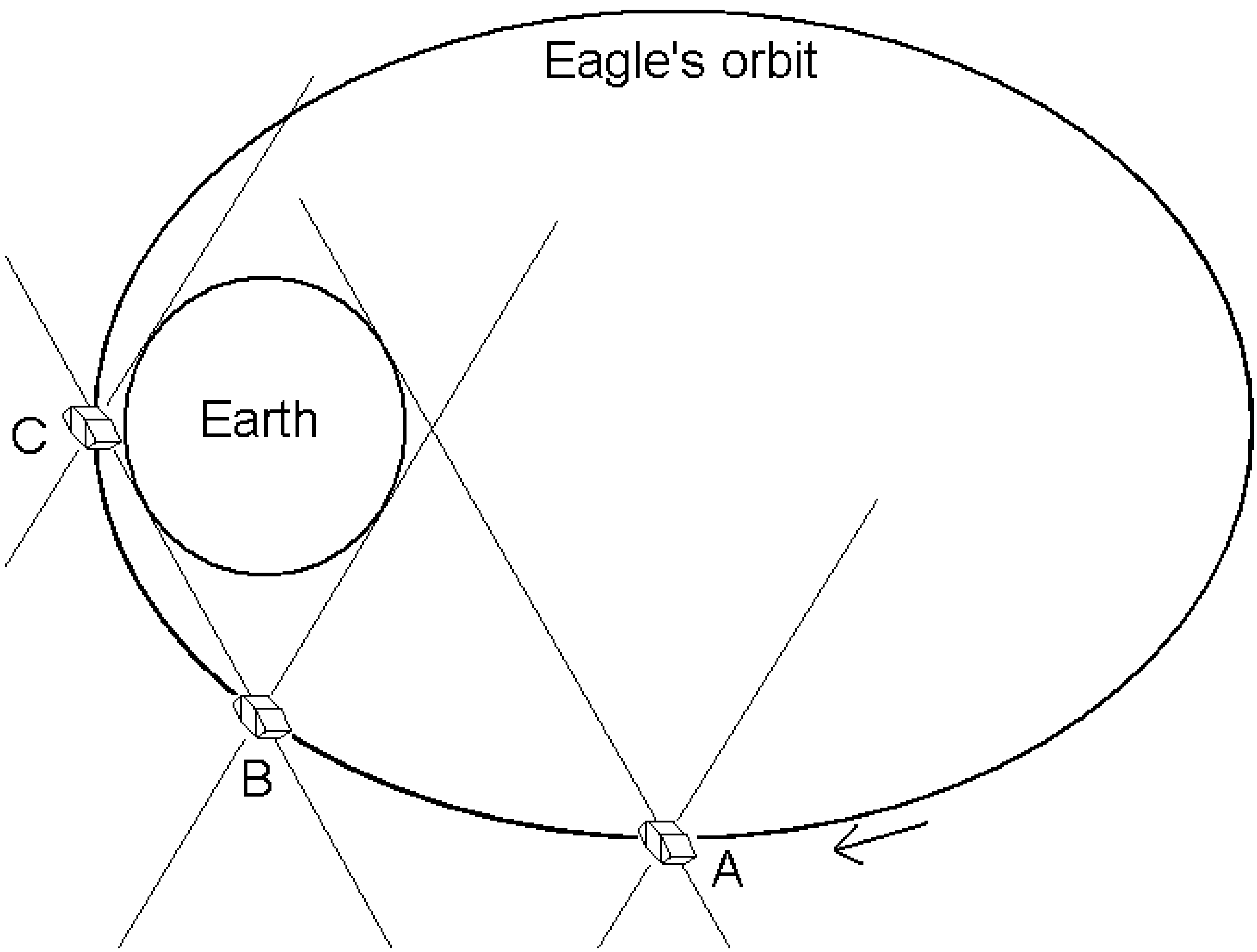


Earth Sensors

The purpose of the earth sensors is to help determine the position of the Earth when Eagle is near perigee. There are two sensors at opposite corners of the spacecraft pointed at approximately 60 degrees from the spin axis. As the satellite rotates, the two sensors sweep out two cones in space. Once the proper spin-axis orientation is achieved, at least one of the cones will intersect the earth whenever the satellite is in the half of the orbit closest to perigee.

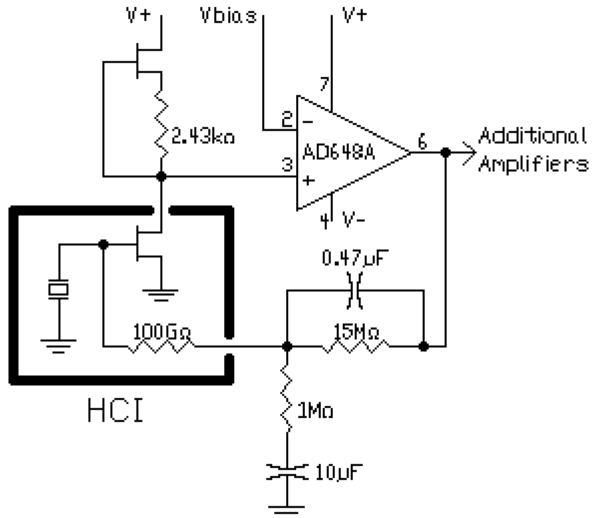
In the diagram below, when the satellite is to the right of point A, the earth is not in view of either of the earth sensors. Between points A and B, the sensor on the +Z axis (to the left) can see the earth during a portion of the satellite rotation. Between points B and C, earth is in view of the -Z sensor. The 60-degree sensor angle is just right for an orbit with 1000-km perigee and 36,000-km apogee. If perigee is higher than 1000 km, the earth will be out of view near point C. If apogee is higher than 36,000 km, there will be a blind spot in the vicinity of point B.

The earth sensors are based on an infrared-sensing "horizon-crossing indicator" (HCI) manufactured by Servo Corporation.[3] These parts normally cost $20,000 each and we need two of them. However they offered us a special deal at $4000 each and the money was raised through a special AMSAT challenge

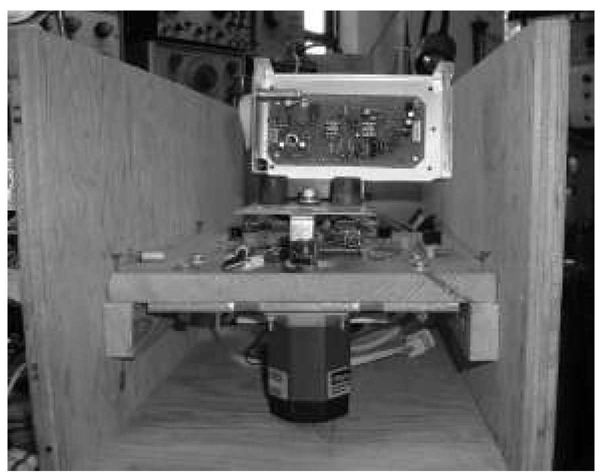


grant, matched by two anonymous donors. Each sensor consists of a lithium tantalate pyroelectric detector mounted in an aluminum housing. It includes a lens designed for use in the 14 µm to 16µm spectral band. The sensors have a narrow 4-degree field of view (FOV). Because they respond to infrared radiation, they detect heat. As the satellite rotates and the FOV sweeps across the earth's horizon, the transition between warm earth and cold space produces a voltage pulse which can be detected by sensor electronics.

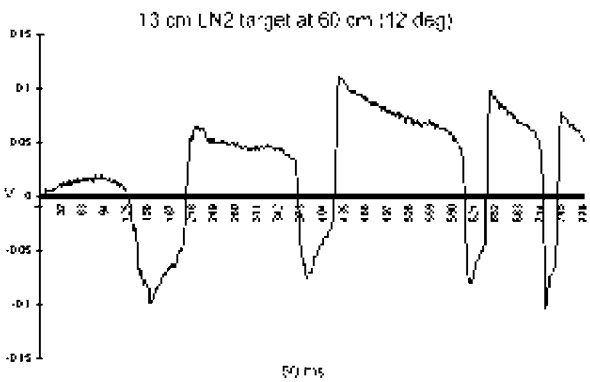
Sensor operation is similar to an electret microphone which consists of two parallel plates charged to a high voltage. Movement of one plate changes the capacitance which generates a small change in voltage. The pyroelectric sensor contains a lithium crystal that holds a permanent charge. When heated, it produces a small voltage proportional to the change in capacitance. The impedance is very high; it can source only a few picoamps. An internal 1 x 10^{11}-ohm resistor acts as a load and the low-level signal is buffered by a low-leakage-current FET. These parts are all located inside the evacuated aluminum sensor housing to avoid stray leakage current caused by humidity and contamination.



The circuit for the earth sensor is similar to the one shown in Servo's documentation. An external JFET provides a constant current source for the JFET that is built into the sensor housing. Because of the phase inversion in the internal JFET, the non-inverting op-amp input is a virtual ground using the internal 10^{11}-ohm resistor in the feedback path. Since we are only interested in the transitions between warm and cold, the amplifiers may be AC-coupled to eliminate thermal drift in the sensor and circuitry.



Since we only have two of the Servo devices and both are required for the mission, we have been reluctant to take chances with them. All of our testing at the time of writing has been performed with infrared detectors salvaged from defunct motion-sensing burglar alarms. We use a vat of liquid nitrogen to simulate the cold of space and the interior of the room to simulate the warm earth. To simulate satellite rotation, a Compumotor stepper motor driven by a model OEM750 microprocessor-based controller sweeps the sensor FOV past the liquid nitrogen. Data is collected by a National Instruments Lab-PC+ data-acquisition card using LabView software written by team member Mike Miller WB6TMH. The figure below shows some preliminary data using a varying rotation rate with the sensor mounted 60 cm above the nitrogen vat. The transitions between the cold and hot environment are readily visible. The droop after each transition is caused by the AC-coupled amplifiers.



The motion-detector devices actually have two sensors pointed in slightly different directions. Their electrical outputs are normally connected opposing each other in differential fashion. That cancels out the average-temperature signal from each detector resulting in a sensitive indication of temperature difference. It seems like that feature would work well for a horizon-crossing indicator, if this type of device could be shown to operate and survive in a space environment. We would like to do further research and testing to try to answer that question.

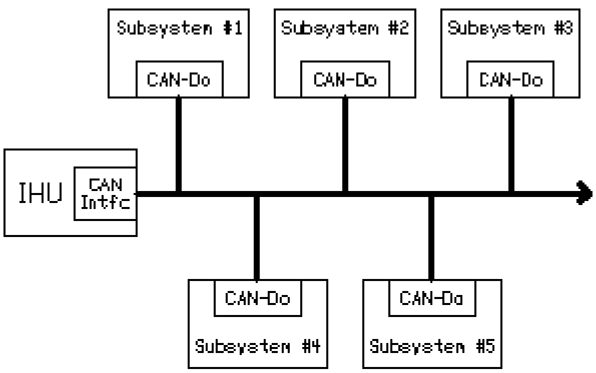
Magnetic Earth Sensors

As an experiment, we are considering including a three-axis magnetic field sensor on board. By measuring the direction of the earth's magnetic field as well as the direction of the sun (using the sun sensors), the spin axis direction can be determined even when the earth is not in view of the earth sensors. Also, since the magnetic field strength is inversely proportional to the cube of the distance to the earth's center, it provides a sensitive indication of altitude. For example, if the perigee is at an altitude of 1000 km (7378 km from the earth's center), the field is nearly 200 times stronger than at an apogee of 36,000 km. Once the orbital parameters are known, the position in the orbit (MA, or mean anomaly) can be calculated from the altitude.

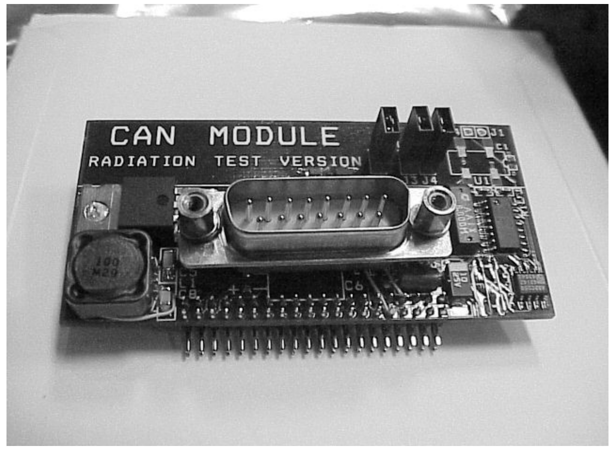
One potential problem is stray magnetic fields in the satellite itself. Obviously the magnetic sensor is useless when the magnetorquers are energized. Even when they are turned off again, there will be residual magnetization in the rods. In general that stray field will be different after each magnetorquing session. However stray fields caused by objects in the satellite will rotate with the satellite and thus be static from the frame of reference of the magnetic sensor. The earth's field, however, will appear to rotate at the satellite's spin rate. By measuring the phase, direction and magnitude of the AC component, it should be possible to determine the earth's magnetic field vector fairly accurately. The Philips model KMZ51 magnetic field sensor we plan to use includes integrated compensation and set/reset coils to compensate for sensitivity drift. Preliminary experiments by John Mock KD6PAG show good repeatability.

Sensor Interfaces

The Controller Area Network (CAN) is an industry-standard serial bus specification originally designed for the harsh mechanical, thermal, and electrical environment of automotive applications. The first amateur satellite to fly a CAN bus was AO-40, where it interfaced the on-board controller, called the Internal Housekeeping Unit (IHU), to the SCOPE cameras and several other experiments. In Eagle, nearly all the sub-systems on board the spacecraft will talk to the IHU through the CAN bus



A standard interface board called "CAN-Do" has been developed by a team of AMSAT volunteers.[4] In addition to Eagle it will be used in P3E and probably future satellites as well. The CAN bus connection is via a 15-pin D-subminiature connector that bolts to the outside wall of the subsystem chassis. A 40-pin connector interfaces to the subsystem electronics board. Each CAN-Do board has 5 analog inputs available as well as digital inputs and outputs. The six sensors in Eagle have a total of 10 analog outputs. By splitting the sensors into two groups (each with one of each type of sensor), two CAN-Do modules can handle them all.



Unlike most CAN bus nodes in the satellite, sensor readings must be timed accurately. Calculating the correct sun and earth azimuth requires knowledge of the rotational phase of the satellite at the time the readings were taken, and the calculation of the solar elevation using the dual-slit sun sensor depends on the accuracy of the time difference between the two pulses. Normally the IHU simply polls every CAN bus node 50 times per second and stores those values in memory so they are available to any software routine that needs the data. However that results in a 20 ms uncertainty in the time the measurement was taken. If the satellite is rotating at 15 rpm, that results in a resolution of almost two degrees, which is not sufficient.

One solution is to modify the firmware in the CAN-Do's on-board processor to time the measurements, process the data, and report the results back to the IHU. However that means the CAN-Do modules for the sensors would be different from all the others in the spacecraft, which breaks the CAN-Do paradigm that all nodes are identical. Another possibility is to include a second processor in each sensor housing to do the measurements. That issue is still under discussion at the time of this writing.

Where Are We?

The sensor team, located in Sonoma County California, includes several people who worked on the staring-mode sun sensors for AO-40, as well as some new faces. In addition to local radio amateurs, we hope again to enlist the help of some electronics students at the Santa Rosa Junior College under the direction of instructor (and sensor team leader) Herb Sullivan K6QXB. So far we have built a test fixture and data acquisition system for the earth sensor and have begun learning what is required for that part of the project. Preliminary experiments with magnetic sensors look promising. We have some staring-mode sun sensor electronics boards left over from the AO-40 project that we will use for breadboarding the Eagle units. We are still determining the requirements for the mechanical housings and exactly where and how they mount on the spacecraft.

Testing Eagle subsystems should be much simpler than on previous satellites because of the standard CAN-Do interface. John Connor NJ0C has written "UHU", a software program that runs under Linux or Windows and simulates the IHU driving the CAN bus. A "CAN-232" widget connects between the RS-232 port on the PC and the CAN-Do module. The software can set digital outputs, read digital inputs and read voltages on the analog inputs. We have obtained the necessary hardware and software and have started experimenting with them.

I would like to thank Jim Hill K6UUW who contributed much of the material on the earth sensors. Also thanks to the Santa Rosa Junior College and Agilent Technologies which have generously allowed us to use their facilities for this project.

1. G. Gould Smith, WA4SXM. "Amateur Satellite Launch Sites, Launches and Orbits." *Proceedings of the AMSAT-NA 21st Space Symposium and AMSAT-NA Annual Meeting*, pp 124-149.

2. A description of the AO-40 staring sun sensor project, including a technical analysis and schematic diagrams, is available on the AMSAT-NA web site: http://www.amsat.org/amsat/sats/phase3d/sun_sensor.html

3. A similar part is shown on the manufacturer's web site: http://www.servo.com/minihci.htm

4. Bdale Garbee, KB0G et al. "Doing More with Fewer Wires in the Harness: A New Approach to Spacecraft On-Board Command and Telemetry Interfacing." *The AMSAT Journal*, 26:6, Nov/Dec 2003, pp 11-15.

Eagle’s Radiation Environment
By Steven R. Bible, N7HPR

Introduction

Eagle’s estimated orbit will depend on available launch opportunities, but it will probably be a Geosynchronous Transfer Orbit, (GTO) which is a near-equatorial orbit with apogee about 36,000 km and final perigee between 500 and 1000 km. This orbit places Eagle in a high radiation environment of the Earth’s inner Van Allen and outer radiation belts. The goal of this paper is to introduce radiation basics, the Earth’s radiation environment, and put them in the context of Eagle’s orbit and radiation effects to Eagle’s designers to aid them in design decisions.

This paper is a collection of information and notes from the Internet. References are made in each of the sections to allow the reader to study more in depth.

Radiation Basics

Ion

[G] An ion is an atom or group of atoms with a net electric charge. A negatively charged ion, which has gained one or more electrons, is known as an anion, for it is attracted to anodes, and a positively charged ion, which has lost one or more electrons, is known as a cation (pronounced cat eye on), for it is attracted to cathodes.

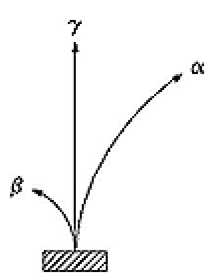
[F] Ion - Atomic particle, atom, or chemical radical bearing an electrical charge, either negative or positive.

[G] The word "ion" is from Greek ion, present participle of ienai "go", thus "a goer". "Anion" and "cation" mean "up-goer" and "down-goer", and "anode" and "cathode" are "way up" and "way down" (hodos = road, way).

Ionization

The process by which a neutral atom or molecule acquires a positive or negative charge.

Radioactivity was discovered in 1895, when it was found that heavy elements such as uranium emitted "rays" which could ionize air and fog photographic film. In 1898 Ernest Rutherford noted that the radiation seemed to contain two electrically charged components of opposite signs, steered by a magnet in opposite directions--positive "**alpha rays**" and negative "**beta rays**."



Ultimately beta rays were identified as electrons and "**alpha particles**" as completely ionized helium nuclei; a third component, "**gamma rays**" unaffected by magnets, turned out to be related to light and X-rays. For his work on radioactivity, Rutherford was awarded a Nobel prize in 1908.

[C] When an atom is hit by a fast-moving particle, like those emitted by radioactive materials, or absorbs light, an **electron** may be torn off. What is left is an electrically charged atom or "**ion**," carrying a positive charge, and the process is known as "**ionization**."

Ionizing Radiation

Radiation that has enough energy to eject electrons from electrically neutral atoms, leaving behind charge atoms or ions. There are three basic types of ionizing radiation:

- Alpha particles (helium nuclei),
- beta particles (electrons),
- gamma rays (high frequency electromagnetic waves, x-rays, are generally identical to gamma rays except for their place of origin.)

Neutrons are not themselves ionizing but their collisions with nuclei lead to the ejection of other charged particles that do cause ionization.

[E] Ionization is the process in which a charged portion of a molecule (usually an electron) is given enough energy to break away from the atom. This process results in the formation of two charged particles or ions: the molecule with a net positive charge, and the free electron with a negative charge.

Each ionization releases approximately 33 electron volts (eV) of energy. Material surrounding the atom absorbs the energy. Compared to other types of radiation that may be absorbed, ionizing radiation deposits a large amount of energy into a small area. In fact, the 33 eV from one ionization is more than enough energy to disrupt the chemical bond between two carbon atoms. All ionizing radiation is capable, directly or indirectly, of removing electrons from most molecules.

Ion types

Hydrogen, the simplest atom, has one electron. When that electron is removed, we get the simplest positive ion, the "**proton**"; like the electron, it is a fundamental particle, but 1836 times heavier. The chemical symbol for hydrogen is H, but for the proton it is H^+.

The next heavier atom is that of helium (chemical symbol He) and it contains two electrons. Its nucleus consists of two protons and also two neutrons, particles similar to the proton but with no electric charge. The Sun gets its energy by combining protons (some of which convert to neutrons in the process) into helium, deep in the Sun's core; since the helium nucleus is an unusually stable combination of particles, energy is released in the process.

The completely ionized helium atom He^{++}, missing both electrons, is also known as the "**alpha particle**". Just as in the Sun and in most stars, hydrogen is the most abundant element with helium next, so <u>the solar wind consists mostly of protons, with 5% alpha particles and small numbers of heavier ions.</u>

Alpha Particles

[E] Alpha particles (symbol α) are a type of ionizing radiation ejected by the nuclei of some unstable atoms. They are large subatomic fragments consisting of 2 protons and 2 neutrons.

An alpha particle is identical to a helium nucleus having two protons and two neutrons. It is a relatively heavy, high-energy particle, with a positive charge of +2 from its two protons. Alpha particles have a velocity in air of approximately one-twentieth the speed of light, depending upon the individual particle's energy.

[B] Alpha particles have the least penetrating power. They come to a complete halt within forty microns (or micrometers, μm) in soft tissue. This stopping distance is equivalent to a few cell diameters; thus, most alpha particles can't penetrate an ordinary sheet of paper. Nevertheless, when alpha emitters are in direct contact with living cells, they are among the most damaging of all radionuclides, apparently because they deliver more energy over a shorter distance. The exact reason for their greater effectiveness remains unknown.

Beta Particles

[E] Beta particles are subatomic particles ejected from the nucleus of some radioactive atoms. They are equivalent to electrons. The difference is that beta particles originate in the nucleus and electrons originate outside the nucleus.

Beta particles have an electrical charge of -1. Beta particles have a mass of 549 millionths of one atomic mass unit, or AMU, which is about 1/2000 of the mass of a proton or neutron. The speed of individual beta particles depends on how much energy they have, and varies over a wide range.

While beta particles are emitted by atoms that are radioactive, beta particles themselves are not radioactive. It is their energy, in the form of speed, which causes harm to living cells. When transferred, this energy can break chemical bonds and form ions.

[B] A beta particle is much less penetrating than a gamma ray. A typical beta particle may travel tens of centimeters in air, but only a few millimeters in soft tissue. A more energetic beta particle will penetrate further, on the average. As it interacts with matter, liberating orbital electrons and ionizing the medium, a beta particle loses energy, slows down, and eventually comes to rest. [10] The stopping distance depends on the initial velocity of the beta particle as well as on the nature and density of the medium. Many radiation monitors, used to measure incoming ionizing radiation, have a mica "window" which, when closed, can stop beta rays without significantly affecting gamma rays. If a radioactive source is emitting both beta and gamma rays, then by taking two readings (one with the window closed, one with it open) the relative contributions of beta and gamma can be calculated. Similarly, most protective clothing can stop beta rays, but not gamma rays.

High Energy Photons (X-Ray and Gamma Ray)

[E] A gamma ray is a packet of electromagnetic energy – a photon. Gamma photons are the most energetic photons in the electromagnetic spectrum. Gamma rays (gamma photons) are emitted from the nucleus of some unstable (radioactive) atoms.

Gamma radiation is very high-energy ionizing radiation. Gamma photons have about 10,000 times as much energy as the photons in the visible range of the electromagnetic spectrum.

Gamma photons have no mass and no electrical charge--they are pure electromagnetic energy.

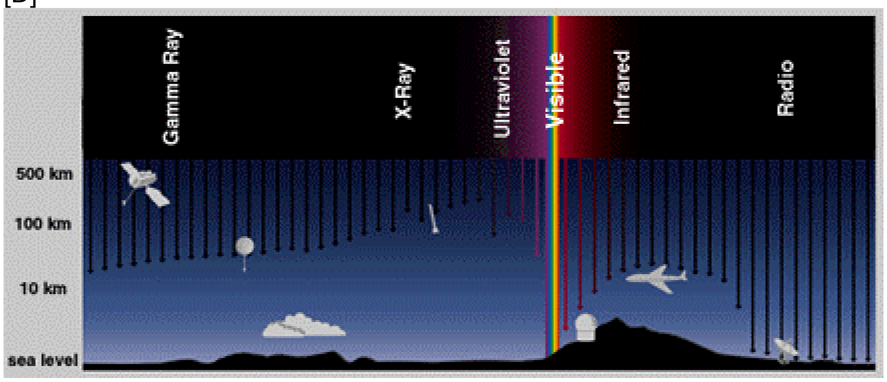
Because of their high energy, gamma photons travel at the speed of light and can cover hundreds to thousands of meters in air before spending their energy. They can pass through many kinds of materials, including human tissue. Very dense materials, such as lead, are commonly used as shielding to slow or stop gamma photons.

Their wavelengths are so short that they must be measured in nanometers, billionths of a meter. They range from 3/100ths to 3/1,000ths of a nanometer.

Gamma rays and x-rays, like visible, infrared, and ultraviolet light, are part of the electromagnetic spectrum. While gamma rays and x-rays pose the same hazard, they differ in their origin. Gamma rays originate in the nucleus. X-rays originate in the electron fields surrounding the nucleus.

[B] x-rays and gamma rays consist of high-energy photons. Photons travel at the speed of light, and each photon has its own "wavelength". When these photons lose energy by ionizing the medium, they change wavelength, but not velocity. Consequently, there is no absolute stopping distance for photons. Some of them are absorbed or scattered as they interact with matter, but a photon may also pass right through matter without being affected at all, and without causing any effects either. More energetic photons will penetrate more readily than less energetic ones. The thickness of a given material which will allow half of the incident photons to get through can be measured. If this thickness is doubled, one quarter of the photons will get through. If it is increased tenfold, one in a thousand will penetrate. Shielding against x-rays or gamma rays is therefore never perfect. To protect workers or other individuals from undesirable exposures, some decision must be made as to what an "acceptable" exposure ought to be.

[D]

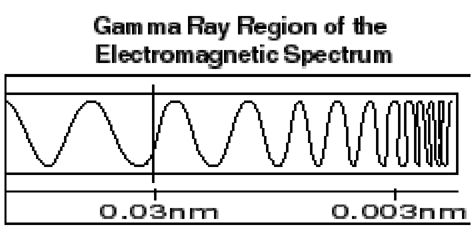


[D] Gamma-rays have the smallest wavelengths and the most energy of any other wave in the electromagnetic spectrum.

Gamma-rays travel to us across vast distances of the universe, only to be absorbed by the Earth's atmosphere.

Gamma-rays are the most energetic form of light and are produced by the hottest regions of the universe. They are also produced by such violent events as supernova explosions or the destruction of atoms, and by less dramatic events, such as the decay of radioactive material in space. Things like supernova explosions (the way massive stars die), neutron stars and pulsars, and black holes are all sources of celestial gamma-rays.

Unlike optical light and X-rays, gamma rays cannot be captured and reflected in mirrors. The high-energy photons would pass right through such a device. Gamma-ray telescopes use a process called Compton scattering, where a gamma-ray strikes an electron and loses energy, similar to a cue ball striking an eight ball.



X-rays - As the wavelengths of light decrease, they increase in energy. X-rays have smaller wavelengths and therefore higher energy than ultraviolet waves. We usually talk about X-rays in terms of their energy rather than wavelength. This is partially because X-rays have very small wavelengths. It is also because X-ray light tends to act more like a particle than a wave. X-ray detectors collect actual photons of X-ray light - which is very different from the radio telescopes that have large dishes designed to focus radio waves!

Electrons

Matter is made up of atoms, each consisting of electrically charged parts: a central nucleus, charged positively, surrounded by one or more negative electrons. The nucleus contains most of the mass, whereas the electrons are lightweight, nimble and relatively easy to separate from the rest of the atom.

Short electromagnetic waves carry enough energy to eject electrons from matter, in particular ultra-violet light and x-rays. A near vacuum is necessary for any such procedure to be effective, because in ordinary air free electrons collide with molecules, lose their energy and are recaptured. In most of space however matter is so rarefied and encounters are so few that free electrons persist for a long time.

As we climb upwards through the atmosphere, space conditions begin at about 70 km or 45 miles, where electrons liberated by sunlight last long enough to allow air to conduct electricity to a significant degree. That is the beginning of the ionosphere, a layer with enough free electrons (and ions) to play an important role in radio communications. At sunset the electrons of the lowest part of the ionosphere are quickly recaptured and that layer disappears. However, at about 200 km (120 miles), where the density of free electrons is the greatest (up to a million in each cubic centimeter), collisions are so few that the ionosphere persists day and night.

Positive Ions

When one or more electrons are torn off an atom, the remaining atom becomes positively charged and is known as a positive ion. Positive ions carry most of the energy and electrical current in the magnetosphere, and are the main component of both the inner and the outer radiation belts. Fast ions are also produced by the Sun as a continuous outflow in all directions, known as the solar wind, which initiates and powers magnetic storms and similar phenomena.

The simplest atom is the one of hydrogen, with just one electron. Tearing off that electron gives the simplest ion, the proton. The proton has a close relative, the neutron--nearly the same mass, but no electric charge.

Most of the fast ions in the magnetosphere and in the solar wind are protons.

Comic Radiation

Cosmic rays, a very thin drizzle of ions moving close to the speed of light and bombarding the Earth from all directions; they probably fill our galaxy and their origin is uncertain.

http://www-istp.gsfc.nasa.gov/Education/wcosray.html
Cosmic ray particles to be ions of a familiar sort--mostly hydrogen, some helium, diminishing amounts of carbon, oxygen etc. and even a few atoms of iron and of heavier elements, to all intents proportions similar to those found on the Sun. The conclusion seems to be that here is ordinary matter, which had undergone some extraordinary process to gain huge energies.

Those energies are indeed huge. The atmosphere shields us from cosmic rays about as effectively as a 13-foot layer of concrete, yet a large proportion of cosmic ray particles manages to send fragments all the way through it. Some have much, much higher energies, though as one goes up in energy, the numbers drop drastically. Cosmic ray ions at the top of the energy range produce in the atmosphere showers of many millions of fragments, covering many acres, and their more energetic fragments register even in deep mines, a mile underground. Relatively few of the particles are so energetic--an experiment might register them once a week--but their existence is a real riddle. How can a single atomic nucleus gain such extreme energies?

See also http://www.oulu.fi/~spaceweb/textbook/crays.html

Plasma

Plasma is sometimes called "the fourth state of matter", beyond the familiar three--solid, liquid and gas. It is a gas in which atoms have been broken up into free-floating negative electrons and positive ions, atoms that have lost electrons and are left with a positive electric charge.

The topside ionosphere extends many thousands of km into space and merges with the magnetosphere, whose plasmas are generally more rarefied but also much hotter. The ions and electrons of the magnetospheric plasma come in part from the ionosphere below, in part from the solar wind (next paragraph), and many details of their entry and heating are still unclear.

Finally, there exists the interplanetary plasma--the solar wind. The outermost layer of the Sun, the corona, is so hot that not only are all its atoms ionized, but those which have started off with many electrons have several of them (sometimes all of them) torn off, including deeper-lying electrons which are more strongly attached. For instance, characteristic light has been detected in the corona from iron which has lost 13 electrons.

This extreme temperature also prevents the plasma of the corona from being held captive by the Sun's gravity, and instead it flows out in all directions, filling the solar system far beyond the most distant known planets. Through the solar wind the Sun shapes the Earth's distant magnetic field, and the wind's fast flow (~400 km/s) supplies the energy which ultimately powers the polar aurora, the radiation belts and magnetic storm phenomena.

Ions and electrons in space are usually intimately mixed, in a "soup" containing equal amounts of positive and negative charges. Such a mixture is known as **plasma**. In many respects it behaves like a gas, but when electric and magnetic forces are present, additional properties come to light, quite unlike those of ordinary gases.

At Earth, however, a strong magnetic field confronts the solar wind, forming a much bigger obstacle than the Earth itself. Because the solar wind is a plasma, it is forced to detour around the Earth's field, creating a large shielded cavity around the Earth--the magnetosphere.

The explanation of space phenomena thus requires a good understanding of plasma physics. Unfortunately, no laboratory can duplicate the large dimensions and the very low particle collision rates found in space plasmas. The behavior of such plasmas can be sometimes simulated by computers, but ultimately, to figure what actually happens, one needs to send instruments into space and study their observations.

Measuring Ionization

[B] There are two kinds of ions, namely the "atomic" and "molecular" ions:

If an atomic nucleus is orbited by too many or too few electrons, in comparison with the number of protons in the nucleus, the resulting charged atom is called an "**ion**" (it is an "atomic ion");

if one of the chemical bonds connecting atoms in a molecule is broken, the electrically charged molecular fragments are also called ions, or "free radicals" (these are "molecular ions").

Ions are far more reactive, chemically, than uncharged atoms or molecules. Whenever a particle (or photon) of ionizing radiation penetrates matter, thousands of highly reactive ions are created all along its trajectory. Indeed, the electromagnetic energy of such a subatomic projectile is so great that orbital electrons from nearby atoms are ripped from their orbits and sent showering among the surrounding molecules, causing a series of random electronic interactions, breaking thousands of chemical bonds, and leaving behind a trail of newly formed ions.

The ionizing ability of any ionizing projectile depends on its energy. The basic unit of energy at the atomic level is the ELECTRON-VOLT (eV). This is the energy acquired by one electron when it is accelerated by an electrical potential of one volt. As usual, the prefixes "kilo" and "mega" are used for "thousand" and "million" respectively. Thus

1,000 eV = 1 keV (kilo-electron-volt), and

1,000 keV = 1,000,000 eV = 1 MeV (mega-electron-volt)

A **beta particle**, emitted from within an unstable nucleus, typically has an energy of several tens or even hundreds of keV. Some **beta particles** carry more than a thousand keV (i.e. more than a MeV). A typical **gamma ray photon** carries an amount of energy in the same general range, that is, between 10 keV and 2,000 keV (= 2 MeV). Note that most **beta particles** and **gamma rays** are far more energetic than x-rays (which seldom exceed 150 keV). And in most cases, **alpha particles** are even more energetic than gamma rays or beta particles, having energies between 1 MeV and 10 MeV.

Such energy is enormous in comparison with the energy that binds molecules together. Indeed, no molecular bond can withstand such a jolt.

The energy binding the atoms together in a molecule is generally between 5 and 7 electron-volts. Thus a single beta particle with an energy of 100 keV could theoretically break between 14,000 and 20,000 of these bonds. Likewise, a single alpha particle with an energy of 4 MeV could break between 50,000 and 800,000 such bonds. However, since much of the energy is actually spent in "exciting" the molecules rather than ionizing them, the number of bonds broken (and the number of ions formed) is only about one-sixth of the number theoretically possible. It is still a large number.

See also http://www-istp.gsfc.nasa.gov/Education/wenpart1.html

0.03 eV
The energy of a molecule of oxygen or nitrogen in the air we breathe. It moves as fast as a speeding bullet, but is still rather low on the scale of energies.

0.5 eV
An atom or molecule at the temperature of the Sun's surface.

0.67 eV
The energy needed by a proton or neutron to escape the Earth's gravity.

1000 - 15,000 eV
Typical energy of an electron in the polar aurora.

40,000 eV
Energy required by an electron to penetrate a thin-wall Geiger counter like that of Explorer 1.

50,000 eV
Typical energy of an ion in the ring current.

1.4 MeV
The energy of electrons from radioactive potassium, a major source of the Earth's internal heat.

4.2 MeV
The energy of alpha particles from radioactive uranium 238, another source of the Earth's heat (and of its helium as well--see positive ions, history).

10-100 MeV
Typical proton energies in the inner radiation belt.

10-15,000 MeV
Range of energies in solar outbursts (see Sun).

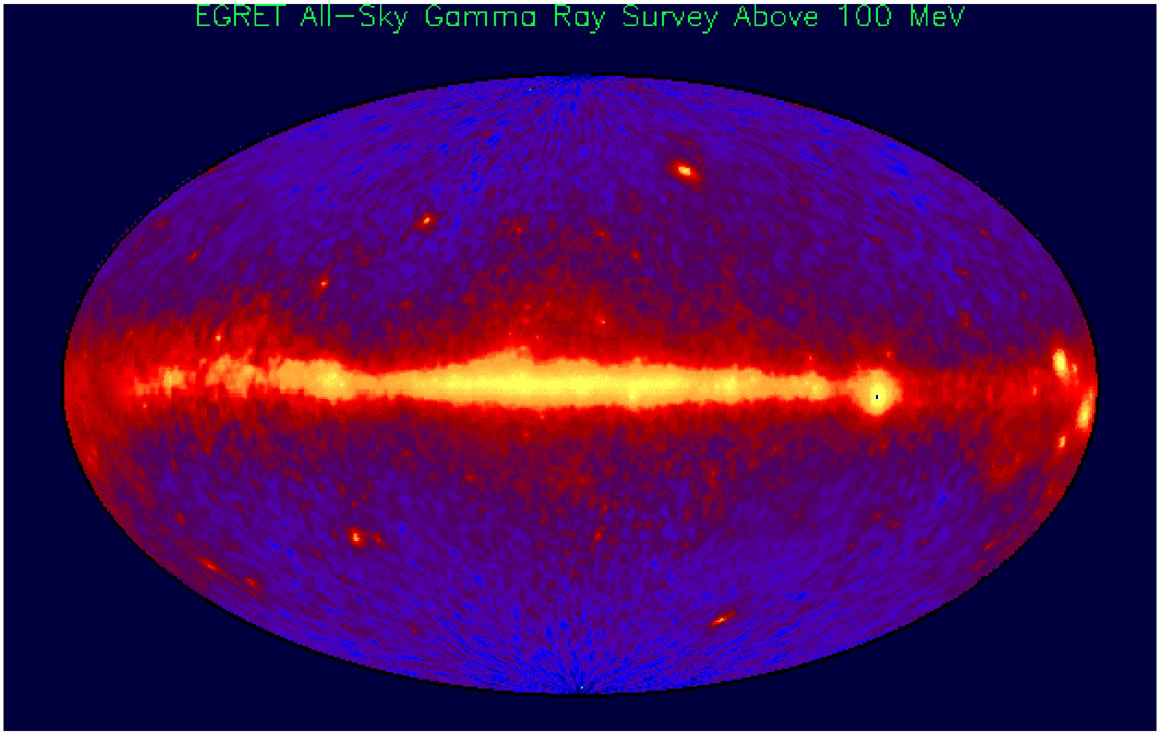
1-100,000,000,000 GeV
Range of energies among cosmic ray ions. However as their energy goes up, their intensity goes way down, so that ions at the high energy end are quite rare.

[C] Energy of individual ions and electrons, which often move at a respectable fraction of the velocity of light (an upper limit which they can never reach). The faster the particle moves, the higher its energy and the greater is the thickness of material needed to stop it. Energies like these are measured in electron volts (eV): auroral electrons have 1000-15,000 eV, protons in the inner belt perhaps 50 million eV, while the energy of cosmic ray ions may reach many billions. In contrast, air molecules in the atmosphere only have about 0.03 eV, raising what could be the most fundamental question in space research--how come a few particles get so much?

[B] Although radioactivity was first discovered in the nineteenth century, it is not a new phenomenon. Every living thing is subject to a certain unavoidable level of exposure to ionizing radiation, called "background radiation". Trace amounts of uranium and thorium can be found everywhere on earth: in soils, in building materials, even in seawater. Consequently, uranium and thorium decay products have existed in the natural environment since the dawn of time.

There are a handful of other primordial radionuclides of terrestrial origin. The most important of these, biologically, is potassium-40 (K-40), with a half-life of 1.3 billion years. It can be found, in minute amounts, in all blood samples.

In addition, extremely energetic ions, neutrons and photons are continually impinging on the earth in all directions from outer space, creating (by activation) a number of radioisotopes in the upper atmosphere. This radiation from outer space is called "cosmic radiation", and the radioisotopes that it creates are called "cosmogenic radionuclides". These include tritium (half-life 12.3 years) and carbon-14 (half-life 5,370 years).



[H] Image of entire sky in 100 MeV or greater gamma rays as seen by the EGRET instrument aboard the CGRO spacecraft. Bright spots within the galactic plane are pulsars while those above and below the plane are thought to be quasars.

Radiation Measurement

[I] Scientists have devised a system for measuring the amount of energy that is transferred from radiation to an object as well as for estimating the relative damage that a particular kind of radiation can cause.

The basic unit of measurement for the amount of radiation is the roentgen. Second, a dose measurement depends on the medium the radiation is penetrating. The medium is the material receiving the radiation. For instance, the medium may be a human being, a spacecraft, or a house here on Earth. Each medium's reaction to radiation differs based on its physical structure and what it is made of. In the past, scientists have described radiation exposure to humans in units of rem (roentgen equivalent, man). More recently, a special unit has been developed to describe the biologically effective radiation to humans, and it is called the sievert (Sv). The relationship between rem and sievert is:

1 Sv = 100 rem

Roentgen

[I] The roentgen is defined as the amount of x-ray or gamma ray radiation (electromagnetic radiation) that produces 1/3 x 10-9 coulomb of electric charge in one cubic centimeter of dry air at standard conditions.

The roentgen is a unit used to measure a quantity called exposure. This can only be used to describe an amount of gamma and X-rays in the air. One roentgen is equal to depositing in dry air enough energy to cause 2.58E-4 coulombs per kg. It is a measurement of molecular ionization in one mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only measures deposits in air, and only for radiation in the form of gamma and x rays.

RAD

(radiation absorbed dose) One rad equals the absorption of 100 ergs in every gram of tissue exposed to radiation.

To show biological risk, rads are converted to rems. The rem is adjusted to take into account the type of radiation absorbed and the differences in likelihood of damage from the different

Rad is a measure of the dose of any ionizing radiation to body tissues in terms of the energy absorbed per unit of mass of the tissue. One rad is the dose corresponding to the absorption of one-hundred (100) ergs per gram of tissue (1 milli-rad [m-rad] = zero point zero-zero-one (0.001) rad).

The rad (Radiation Absorbed Dose) is a unit used to measure a quantity called absorbed dose. This relates to the amount of energy actually absorbed in some material, and is used for any type of radiation and any material. The difference between a rad and a rem is a rad is a measurement of radiation absorbed by the material not the potential affect of the radiation. One rad is defined as the absorption of 100 ergs per gram of material. The unit rad can be used for any type of radiation, but it does not describe the biological effects of the different radiations.

REM

REM is a measure of the dose of any ionizing radiation to body tissue in terms of its estimated biological effect relative to a dose of one (1) roentgen (r) of x-rays (one (1) milli-REM [m-REM] - zero point zero-zero-one (0.001) REM).

The rem (Roentgen Equivalent Man) is a unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the biological damage by the radiation. Rem is a measurement of potential damage done by radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms milli-rems. To determine equivalent dose (rem), you multiply absorbed dose (rad) by a quality factor (Q) that is unique to the type of incident radiation. Every year the average person is exposed to 360 milli-rem annually. This means we are exposed to about 1 milli-rem on a daily basis. At the website www.epa.gov/radiation/students/calculate.html there is a neat little survey you can fill out that gives your annual radiation expose and tells what factors its due to. High levels of rem cause radiation sickness.

Gray

[I] The gray describes an objective property of radiation that can be expressed in simple terms: the amount of energy transferred by radiation to an object. An absorbed dose of one gray is equal to the absorption of one joule of radiation energy by one kilogram of matter. For example, the average person absorbs about 450 micrograys of cosmic radiation in the course of a year. The gray was adopted internationally as a unit of absorbed dose in 1976. Prior to the gray, there was the rad, short for radiation absorbed dose. The difference between the rad and the gray is a proportionality factor: 100 rads equals one gray. Finally, prior to either of these units, there was another measure of radiation absorption called the roentgen.

Sievert

[I] An estimate of this damage is embodied in the unit sievert, which measures the radioactive dose equivalent. One sievert is equal to one gray multiplied by a relative biological effective factor, Q, and a factor that takes into account the distribution of the radiation energy, N.

Specifically, if E represents the radioactive dose equivalent in sieverts, and D is the absorbed dose in grays, then E = QND. The factor Q varies from 1 for electromagnetic radiation to 20 for radiation consisting of high-energy charged particles. Suppose that the distribution of energy of cosmic radiation is identical for both charged particles and electromagnetic energy and is equal to one: N = 1. If the 450 micrograys of absorbed cosmic radiation consist solely of gamma rays (high energy electromagnetic radiation), then Q = 1, and the average person absorbs 450 microsieverts of radiation in one year. Alternatively, suppose that the 450 micrograys of absorbed cosmic radiation consists solely of alpha particles (helium nuclei) with energies of 10 million electron volts. In this case, Q = 20, and the average person absorbs 9,000 microsieverts of radiation in one year.

The sievert is the correct unit to use when you wish to monitor the biological danger of radiation. The gray is the correct unit to use when you wish to monitor energy absorbed per unit mass. Prior to the sievert, the unit used to monitor the biological effectiveness of radiation was called the rem, short for roentgen equivalent man. Similar to the difference between the rad and the gray, the difference between the rem and the sievert is a proportionality factor: 100 rems equal one sievert.

Dose and Dose Rate

[G] Dose

- Only the amount of energy of any type of ionizing radiation that imparted to (or absorbed by) the human body can cause harm to health.
- To look at biological effects, we must know (estimate) how much energy is deposited per unit mass of the part (or whole) of our body with which the radiation is interacting.
- The international (SI) unit of measure for absorbed dose is the gray (Gy), which is defined as 1 joule of energy deposited in 1 kilogram of mass. The old unit of measure for this is the rad, which stands for "radiation absorbed dose." - 1 Gy = 100 rad.
- Equivalent dose – the biological effect depends not only on the amount of the absorbed dose but also on the intensity of ionization in living cells caused by different type of radiations.
- Neutron, proton and alpha radiation can cause 5-20 times more harm then the same amount of the absorbed dose of beta or gamma radiation.
- The unit of equivalent dose is the sievert (Sv). The old unit of measure is the rem. - 1 Sv = 100 rem.

Earth's Radiation Belts

[C] The Earth actually has two radiation belts of different origins. The inner belt, the one discovered by Van Allen's Geiger counter, occupies a compact region above the equator (see drawing, which also includes the trajectories of two space probes) and is a by-product of cosmic radiation. It is populated by protons of energies in the 10-100 MeV range, which readily penetrate spacecraft and which can, on prolonged exposure, damage instruments and be a hazard to astronauts. Both manned and unmanned spaceflights tend to stay out of this region.

The outer radiation belt is nowadays seen as part of the plasma trapped in the magnetosphere. The name "radiation belt" is usually applied to the more energetic part of that plasma population, e.g. ions of about 1 MeV of energy (see energy units). The more numerous lower-energy particles are known as the "ring current", since they carry the current responsible for magnetic storms. Most of the ring current energy resides in the ions (typically, with 0.05 MeV) but energetic electrons can also be found.

The Inner Radiation Belt - http://www-istp.gsfc.nasa.gov/Education/winbelt.html

The Earth has two regions of trapped fast particles. The inner radiation belt discovered by Van Allen is relatively compact, extending perhaps one Earth radius above the equator (1 RE = 6371 km or about 4000 miles). It consists of very energetic protons, a by-product of collisions by cosmic ray ions with atoms of the atmosphere. The number of such ions is relatively small, and the inner belt therefore accumulates slowly, but because trapping near Earth is very stable, rather high intensities are reached, even though their build-up may take years.

Further out is the large region of the ring current, containing ions and electrons of much lower energy (the most energetic among them also known as the "outer radiation belt"). Unlike the inner belt, this population fluctuates widely, rising when magnetic storms inject fresh particles from the tail of the magnetosphere, then gradually falling off again. The ring current energy is mainly carried by the ions, most of which are protons.

However, one also sees in the ring current "alpha particles," atoms of helium which have lost their two electrons, a type of ion that is plentiful in the solar wind. In addition, a certain percentage are O+ oxygen ions, similar to those in the ionosphere of the Earth, though much more energetic. This mixture of ions suggests that ring current particles probably come from more than one source.

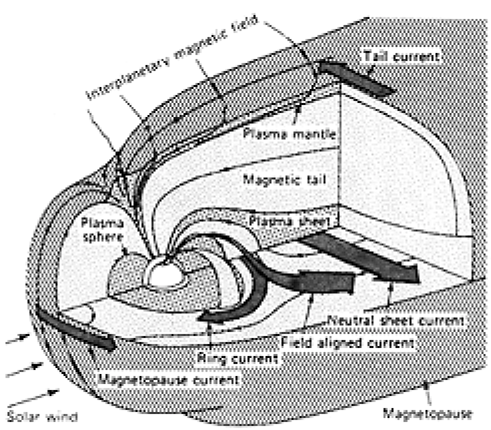
Outer Radiation Belt - http://www-istp.gsfc.nasa.gov/Education/woutbelt.html

The outer radiation belt is nowadays seen as part of the plasma trapped in the magnetosphere. The name "radiation belt" is usually applied to the more energetic part of that plasma population, e.g. ions of about 1 MeV of energy. The more numerous lower-energy particles are known as the "ring current", since they carry the current responsible for magnetic storms. Most of the ring current energy resides in the ions (typically, with 0.05 MeV) but energetic electrons can also be found.

Whereas the inner belt is marked by great stability, the ring current and outer belt constantly change. Sooner or later the particles are lost, e.g. by collision with the rarefied gas of the outermost atmosphere, and on the other hand, new ones are frequently injected from the tail. The electric fields that inject the new particles can also draw oxygen ions upwards from the ionosphere, and the ring current contains such ions, typically a few percent of the total, more during magnetic storms.

The magnetic boundary between the Earth's field and the solar wind, named the magnetopause, has a bullet-shaped front, gradually changing into a cylinder. Its cross-section is approximately circular. http://www-istp.gsfc.nasa.gov/Education/wmpause.html

http://www-istp.gsfc.nasa.gov/Education/Iexplore.html



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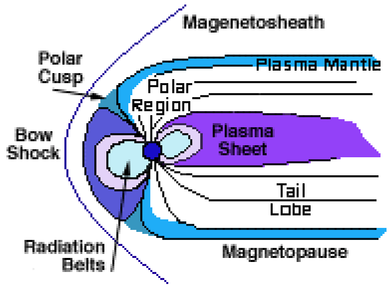

See also http://www.oulu.fi/~spaceweb/textbook/magnetosphere.html

Eagle's Orbit

[A] The main sources of energetic particles that are of concern to spacecraft designers are:

1) **protons** and **electrons** trapped in the Van Allen belts,
2) **heavy ions** trapped in the magnetosphere,
3) **cosmic ray protons** and **heavy ions**, and
4) **protons** and **heavy ions** from solar flares.

Protons (Van Allen Belts, Solar Flares)
Electrons (Van Allen Belts)
Heavy Ions (Earth's Magnetosphere, Solar Flares)
Cosmic Ray Protons (Solar Flares)

Van Allen Belts (protons, electrons)
Solar Flares (protons, heavy ions, cosmic ray protons)
Earth's Magnetosphere (heavy ions)

NASA test components see: NASA/GSFC Radiation Effects & Analysis Home Page
http://radhome.gsfc.nasa.gov/top.htm

[A] Experience has shown that the most effective means of reducing uncertainty factors and design margins in particle predictions, is to define for the mission:

1. When the mission will fly,
2. Where the mission will fly,
3. Mission duration,
4. When the systems will be deployed,
5. What systems must operate during worst case environment conditions
6. What systems are critical to mission success, and
7. The amount of shielding surrounding the SEE sensitive part(s).

Estimates that include only worst case conditions lead to over-design and should be used only in the concept design phase of a mission when the actual launch date and length have not been defined. After the launch date and duration are defined, it is possible to estimate how long the spacecraft will be in each phase of the solar cycle. These estimates should consider the impact of a launch delay of one year. Mission scenario definition is especially important for solar flare particles where the number of events is highly dependent on the amount time that the satellite spends in solar maximum conditions.

Eagle's exact orbit will depend on available launch opportunities, but it will probably be a GTO (geosynchronous transfer orbit), which is a near-equatorial orbit with apogee about 36,000 km and final perigee between 500 and 1000 km.

Project Eagle Specifications R5, as of October 3, 2002:
4.0 Orbit:
4.1 Initial orbit GTO (200km perigee)
4.2 Final orbit GTO with perigee greater than 500 km

Comparison – Synchronous orbit - 42,000 km or 26,000 miles, some 6.6 Earth radii

The levels of all of these sources are affected by the activity of the sun. The solar cycle is divided into two activity phases: the solar minimum and the solar maximum. An average cycle lasts about eleven years with the length varying from nine to thirteen years [1, 2, 3]. Generally, the models of the radiation environment reflect the particle level changes with respect to the changes in solar activity.

Space ENVironment Information System (SPENVIS)

ESA has a free radiation simulation tool used to estimate what would be seen in a specific orbit: http://www.spenvis.oma.be/spenvis/intro.html

[A] Low Earth Orbits (LEOs)

The most important characteristic of the environment encountered by satellites in LEOs is that several times each day they pass through the proton and electron particles trapped in the Van Allen belts. The level of fluxes seen during these passes varies greatly with orbit inclination and altitude. The greatest inclination dependencies occur in the range of $0° < i < 30°$. For inclinations over 30°, the fluxes rise more gradually until about 60°. Over 60° the inclination has little effect on the flux levels. The largest altitude variations occur between 200 to 600 km where large increases in flux levels are seen as the altitude rises. For altitudes over 600 km, the flux increase with increasing altitude is more gradual. The location of the peak fluxes depends on the energy of the particle. For trapped protons with $E > 10$ MeV, the peak is at about 4000 km. For normal geomagnetic and solar activity conditions, these proton flux levels drop gradually at altitudes above 4000 km. However, as discussed above, inflated proton levels for energies $E > 10$ MeV have been detected at these higher altitudes after large geomagnetic storms and solar flare events.

The amount of protection that the geomagnetic field provides a satellite from the cosmic ray and solar flare particles is also dependent on the inclination and to a smaller degree the altitude of the orbit. As altitude increases, the exposure to cosmic ray and solar flare particles gradually increases. However, the effect that the inclination has on the exposure to these particles is much more important. As the inclination increases, the satellite spends more and more of its time in regions accessible to these particles. As the inclination reaches polar regions, it is outside the closed geomagnetic field lines and is fully exposed to cosmic ray and solar flare particles for a significant portion of the orbit.

Under normal magnetic conditions, satellites with inclinations below 45° will be completely shielded from solar flare protons. During large solar events, the pressure on the magnetosphere will cause the magnetic field lines to be compressed resulting in solar flare and cosmic ray particles reaching previously unattainable altitudes and inclinations. The same can be true for cosmic ray particles during large magnetic storms.

[A] Highly Elliptical Orbits (HEOs)

Highly elliptical orbits are similar to LEO orbits in that they pass through the Van Allen belts each day. However, because of their high apogee altitude (greater than about 30,000 km), they also have long exposures to the cosmic ray and solar flare environments regardless of their inclination. The levels of trapped proton fluxes that HEOs encounter depend on the perigee position of the orbit including altitude, latitude, and longitude. If this position drifts during the course of the mission, the degree of drift must be taken into account when predicting proton flux levels.

Radiation Effects

NASA/GSFC Radiation Effects & Analysis Home Page
http://radhome.gsfc.nasa.gov/top.htm

Single Event Effect Criticality Analysis
http://radhome.gsfc.nasa.gov/radhome/papers/seecai.htm

The systems engineer must make decisions within a trade space including availability, performance, schedule, and cost risk associated with single event effects

Systems engineers have a sometimes incomplete understanding of the exact nature of the risk. For example, experts are familiar with the details of single event effects, particle environments, and radiation hardness issues at the component level but have an incomplete picture of the risk-cost-performance trade space comprising mission reality.

The possibility exists to launch with unforeseen and unacceptable risk, or conversely to be overly conservative and lose the battle in terms of the component costs, power requirements, or system complexity through poorly planned actions aimed at controlling these risks.

Radiation damage to on-board electronics may be separated into two categories: total ionizing dose and single event effects. **Total ionizing dose (TID)** is a cumulative long-term degradation of the device when exposed to ionizing radiation. **Single event effects (SEEs)** are individual events which occur when a single incident ionizing particle deposits enough energy to cause an effect in a device [A].

Two types of SEEs: soft errors and hard errors. **Soft errors** are nondestructive to the device and may appear as a bit flip in a memory cell or latch, or as transients occurring on the output of an I/O, logic, or other support circuit. Also included are conditions that cause a device to interrupt normal operations and either perform incorrectly or halt. **Hard errors** may be (but are not necessarily) physically destructive to the device, but are permanent functional effects. Different device effects, hard or soft, may or may not be acceptable for a given design application.

Unlike TID degradation, SEE rates are not evaluated in terms of a time or dose until failure, where the stopwatch begins at launch, but a ***probability that an SEE will occur within a known span of time***. Devices are tested in ground test facilities to characterize the device in a radiation environment. Calculations are also performed to predict the radiation environment for a particular mission orbit. Environment predictions are used with the experimental device data to calculate the probability of occurrence of SEEs in the device for the mission.

The effects of propagation of SEEs through a circuit, subsystem, and system are also often of particular importance. The level of impact on the affected circuit, box, subsystem, etc. depends on the type and location of the SEE, as well as on the design. Evaluating the severity of the single event effect hazard involves knowledge from several technical fields including radiation physics, parts engineering, solid state physics, electrical engineering, reliability analysis, and systems engineering.

Both the functional impact of an SEE to the system or spacecraft and the probability of its occurrence provide the foundation for setting a design requirement. System-level SEE requirements may be fulfilled through a variety of mitigation techniques, including hardware, software, and device tolerance requirements. The most cost efficient approach may be an appropriate combination of SEE-hard devices and other mitigation. However, the availability, power, volume, performance, and cost of radiation-hardened devices prohibit their use. Hardware or software design also serves as effective mitigation, but design complexity may present a problem. A combination of the two may be the selected option.

Terms and Definitions

Single Event Upset (SEU) - a change of state or transient induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are "soft" errors in that a reset or rewriting of the device causes normal device behavior thereafter.

Single Hard Error (SHE) - an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.

Single Event Latchup (SEL) - a condition which causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.

Single Event Burnout (SEB) - a condition which can cause device destructiondue to a high current state in a power transistor.

Single Event Gate Rupture (SEGR) - a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.

Single Event Effect (SEE) - any measurable effect to a circuit due to an ion strike. This includes (but is not limited to) SEUs, SHEs, SELs, SEBs, SEGRs, and Single Event Dielectric Rupture (SEDR).

Multiple Bit Upset (MBU) - an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.

Linear Energy Transfer (LET) - a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV*cm2/mg of material (Si for MOS devices, etc...).

LET Threshold (LETth) - the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm2. Typically, a particle fluence of 1E5 ions/cm2 is used for SEB and SEGR testing.

Cross section (sigma) is the device SEE response to ionizing radiation. For an experimental test for a specific LET, sigma = #errors/ion fluence. The units for cross section are cm2 per device or per bit.

Asymptotic or saturation cross section (sigmasat) is the value that the cross section approaches as LET gets very large.

Sensitive volume refers to the device volume affected by SEE-inducing radiation. The geometry of the sensitive volume is not easily known, but some information is gained from test cross-section data.

Function Analysis and Criticality

The function the device performs is critical to the analysis. For example, memories will exhibit different conditions than power converters.

Functional analysis is an effective method for the consideration of a design for single event effects.

Criticality lends itself well to the assessment of the impact of a specific effect.

Error propagation analysis

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A Simulator for the AMSAT Eagle Spacecraft

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ABSTRACT
The ability to simulate a spacecraft functioning in its orbital environment has several useful applications. These include evaluating engineering design concepts and configurations, spacecraft commanding event rehearsal and Command Station operator training. The cost involved in developing vehicle-specific spacecraft simulators has been historically prohibitive. However, a new lower cost concept providing high fidelity and facilitating rapid development on a modest budget was developed and implemented for the NAVSTAR Global Positioning System (GPS) Launch and early orbit, Anomaly resolution and Disposal Operations (LADO) program. This approach is hierarchical, beginning with a generic simulation engine upon which base functionality for celestial bodies (i.e., Sun, Moon, Earth), Ground Station and Spacecraft components are modeled. Tailoring to a specific spacecraft design involves developing the functionality of components and subsystems to form a vehicle, followed by modeling the vehicle's interactions with the celestial environment (i.e., orbital and attitude dynamics), as well as its Telemetry, Tracking and Commanding (TT&C) interactions with the Ground Stations. This method has been used to develop simulators for multiple types of GPS spacecraft. Further, it has produced interactions with the Ground Station (TT&C) software, which experienced operators are unable to distinguish from actual GPS spacecraft.

SIMULATION ARCHITECTURE
The AMSAT Eagle Spacecraft Simulator is being adapted from the GPS spacecraft baseline. It has a three-tier architecture comprising: (1) the Commercial Off-the-Shelf (COTS) Simulation Engine; (2) the COTS spacecraft and ground system base-level modules and (3) the top-level system-specific (tailored) modules; each is described in the sections below.

Simulation Engine
The Simulation Engine is COTS software package developed by Braxton Technologies, Inc (http://www.braxtontech.com) and provides the core capability to develop simulations of any kind (i.e., it is not limited only to satellite system simulations). The Simulation Engine has three key features facilitating simulation development:

- Data Nodes
- Simulation Workspaces
- Event Sequencer

Data Nodes

A unique feature of this Simulation Engine is its data nodes, which transfer both parameters and event triggers across individual simulation modules. The data nodes mimic a wiring and switching network, enabling in effect each subsystem module or other entity to function independently, except for accepting data and event triggers from other modules. Therefore, subsystem experts can develop algorithms to model their module's behavior using only data node interface requirements established between the other subsystems. Since data nodes have a standard structure, interfacing between modules is defined through an established template.

Simulation Workspace

The Simulation Workspaces allow the user to define initial simulation conditions, such as simulation date/time, spacecraft orbit and attitude states, system and subsystem modes, and individual data node values. The workspace also allows interactive display of data nodes, whereby the simulation operator is able to modify parameters in real time. Data node display may be made by parameter value lists or by a variety of graphic widgets. **Figure 1** is an example of a workspace with various data node access.

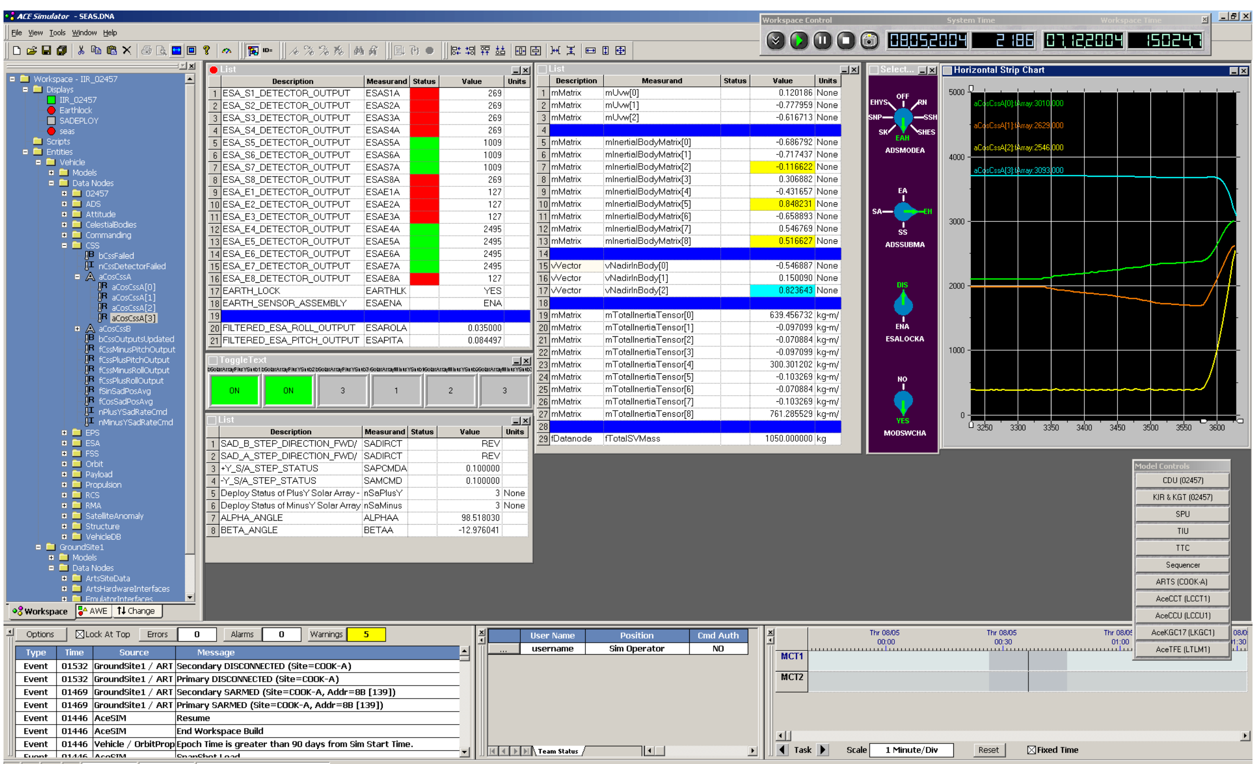

FIGURE 1. SIMULATION WORKSPACE USER INTERFACE

Event Sequencer

The Event Sequencer allows the simulation operator to execute a pre-defined sequence of events in a script, such as data node value changes or timeline triggers. It also allows acquisition of reproducible results and/or controlled variations to the simulation, as well as repeated error-free execution of complex event sequences.

Base-Level Modules

The Simulation Engine has a set of base-level modules that are invariant for any satellite system simulation. These include the Sun/Moon/Earth [environmental], Spacecraft Orbit and Attitude Propagation modules. The base modules also include generic spacecraft components and algorithms, such as telemetry sensors (temperature, voltage, current, tank pressure, etc), electronics boxes (power consumption and heat generation), propulsion system (solid or tanks, lines, valves, manifolds and thrusters), heater elements and logic for electrical power distribution, and heat conduction buses that interface with other components.

Eagle-Specific Tailored Modules

Due to the simulator's Object Oriented Programming (OOP) development approach, the Eagle spacecraft simulation can leverage, to a large degree, off the base modules and even the developed GPS simulations. This capability excludes, however, any GPS modules containing third-party proprietary information or other restricted data.

It is within these tailored modules that Eagle design team members may develop their own simulation modules. The least simulation required is power consumption, heat generation and conduction, and any changes to the spacecraft's mass properties (due to events such as deployments or propellant consumption).

Design team members may also opt to provide algorithms that model their component's behavior or otherwise code their components module themselves. In either case, the input and output will be data node parameters and events.

Component simulation modules may be developed using the Microsoft Visual C++ .NET framework, wherein software developers may join the Eagle team and work one-on-one with hardware developers. This is also an area where AMSAT may promote educational outreach with Universities for mutual benefit.

TOP-LEVEL MODELING

Figure 2 is a generic top-level block diagram illustrating a satellite simulation. The spacecraft environmental interactions with the Earth, Sun and Moon are depicted at the top, while the major components of the spacecraft simulation,

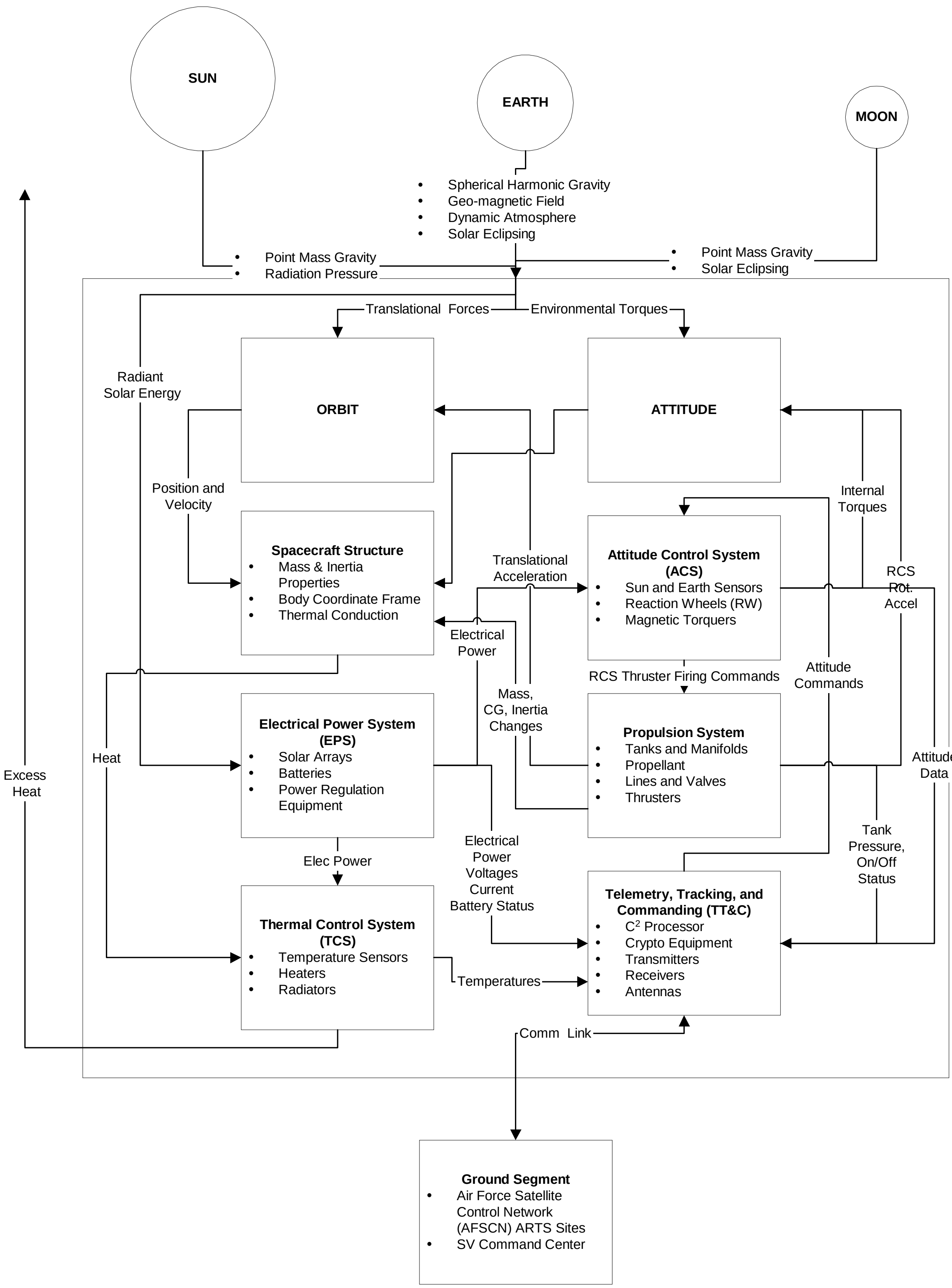

FIGURE 2. SIMULATION TOP-LEVEL BLOCK DIAGRAM

which to a large extent parallels the spacecraft's major subsystems, are shown in the center portion. Lastly, the spacecraft interaction with Ground Control stations over the Command Link is presented at the bottom.

Environmental Interactions

Environmental interactions are effects on a spacecraft induced by the Earth, Sun and Moon as principal celestial bodies. (Note: other bodies may be added if needed.) This module contains propagation algorithms that compute the geometric arrangement of these celestial bodies as required for a given simulation. The spacecraft's environmental interactions fall into the general categories of illumination, gravitation, atmospheric and magnetic.

Spacecraft illumination, in addition to being a critical factor in electrical power generation, affects the spacecraft's orbit, attitude and thermal balance. The solar flux is calculated based on the inverse square of spacecraft's distance and its direction relative to the Sun, and whether or not the spacecraft has an unobstructed line-of-sight to the Sun or is in partial (penumbra) or total (umbra) eclipse when occluded by either the Earth or Moon. The solar flux density and direction are considered when modeling the solar array output, as well as for radiation pressure acceleration on the orbit and torques on the attitude. A portion of the incoming sunlight also heats the spacecraft (depending on the properties of the illuminated surfaces) and the space environment serves a heat sink for energy radiated based on spacecraft temperature.

Gravitational perturbations originate from both the Earth's aspherical mass arrangements and gravitational disturbances, in addition to concurrent effects due to the Sun and Moon masses; gravitation provides translational disturbances affecting the orbit.

The Earth's atmosphere affects spacecraft in which at least a portion of the orbit is below an altitude of 2500 km (as will be the case for Eagle). Atmospheric drag decelerates the spacecraft thus affecting its orbit, as well as affecting the vehicle's attitude, if the center of mass is offset from the vehicle structure's center of pressure.

Marked effects on the spacecraft's attitude may be induced intentionally via the interaction of the electromagnetic torque rods with the Earth's magnetic field.

Spacecraft Subsystem Simulation

Spacecraft subsystem simulation is structured so as to maintain the vehicle's mass and inertial properties, as well as the component-relative locations and their orientations relative to the space environment. An existing power bus is responsible for collecting electrical power from solar arrays, controlling battery charging and discharging, and distributing power throughout the spacecraft based on component demand versus availability. There is in addition a thermal bus, which induces conductive heat flow between the components and structure.

The Orbit propagator considers the effects of all external (environmental) and internal (i.e., thrust) translational forces imparted on the body when updating the spacecraft's orbital position and velocity. Similarly, the Attitude propagator considers the effects of all externally and internally generated rotational forces (thruster, reaction wheel, magnetorque rod, deployment – i.e., torques) imparted on the body when updating the spacecraft's orientation in space.

The Telemetry Tracking and Commanding (TT&C) subsystem is responsible for collecting health and status measurements (temperature, voltage, current, tank pressure, processor state, etc.), formatting and relaying them to ground as telemetry measurements. This subsystem must also accept, decrypt, validate and employ commands received from authorized Command Stations. It is anticipated that this particular subsystem will require the most extensive development and tailoring for the Eagle simulation.

Ground Control

The Ground Stations interact with the Eagle spacecraft's TT&C subsystem using the RF command link as interface. Signal strength received by both the spacecraft and ground station considers the inverse square of the distance between the spacecraft and ground station (i.e., free space "path loss"), as well as the antenna gain. The latter in turn considers the spacecraft's attitude and the antenna gain patterns. The command link model computes the probability of a data packet (command or telemetry) dropping out based on the actual link margin versus the system threshold. This probability may range from virtually no dropping out of data packets (such as for link margin surplus), to some dropping out of packets (borderline link margin) to the dropping out of nearly all data packets (in the event of a link margin deficit).

APPLICATIONS

The Eagle simulator has applications for engineering design, spacecraft integration, commanding rehearsal and possibly for on-orbit trouble-shooting. The simulator's level of modeling sophistication (i.e., fidelity) determines its usefulness in these areas.

Engineering Design

The simulator's initial usefulness is to support system-level engineering. Candidate architectures may be evaluated during detailed design, simulating operation various orbital conditions. These may include variations in parameters, such as illumination and attitude (for antenna pointing and signal strength) to represent both best and worse cases and typical conditions. Information from these studies will help refine and optimize the baseline to determine necessary compromises, as well as the best overall design that is ultimately consistent with the stated goals.

Spacecraft Integration

The simulator may be set up to facilitate hardware-in-the-loop via CAN bus interfaces. In this manner, a partially assembled spacecraft may be connected to the simulator that uses models for the remaining components and thus develop a virtually completed vehicle (and may be done at all stages of assembly, up to and including the completed vehicle). The environmental models may be used at any stage to drive external conditions, depending on the complexity of the laboratory equipment.

Commanding Rehearsal

The simulator enables the Command Team to rehearse commanding sequences using a platform in which even serious errors shall not represent a catastrophic outcome. It is thus a convenient tool with which strategies, command plans and checklists may be developed, tested and refined without jeopardizing the Eagle spacecraft.

On-Orbit Troubleshooting

The simulator's greatest design challenge is to develop component models having sufficient fidelity so as to facilitate on-orbit troubleshooting. The closer that models parallel actual subsystem physical characteristics and operation, the greater the probability of their usefulness as on-orbit troubleshooting tools. However, since the time required for developing such sophisticated system models will likely be deferred in order to meet program schedule, such models will require adequate initial fidelity for engineering, integration and commanding rehearsal, while permitting higher fidelity enhancements to be added at a later date.

SUMMARY

The Eagle simulator is under development as a tool for both Design and Command Teams. It provides high fidelity modeling of the spacecraft's subsystem interactions and the interaction with both the space environment and ground stations. The simulator's engine's three-tier architecture allows each subsystem to be developed and operated independently, where each interaction between modules is carried out by data node event triggers and parameter transfers. Since simulations occur over an existing COTS simulation engine, using base class spacecraft and space environment components, the development schedule can be accelerated by leveraging off experience gained in developing simulations for several types of GPS spacecraft.

C-C Rider Revisited

Tom Clark (W3IWI), Bob McGwier (N4HY), Phil Karn (KA9Q) and Rick Hambly (W2GPS)

Abstract: At last year's AMSAT Annual meeting, W3IWI presented the concept of a C-band in-band transponder[1], dubbed "C-C Rider". This was based on the fact that the C-band satellite frequency allocation has matched pair of 20 MHz wide allocations: 5650-5670 MHz uplink, paired with 5830-5850 MHz downlink.

The status of the 5650-5670 MHz uplink band has changed since last year; the FCC has adopted an industry proposal for expanded 802.11a spectrum, and a world-wide allocation was made at WARC 2003. In this paper we speculate on the QRM level that might exist 5-10 years from now as seen by a C-band receiver on a HEO satellite. We will also discuss the RFI environment to be expected by a typical user at the C-band downlink frequency.

Many of the options that were presented in the previous paper have been considered in the context of a significant part of AMSAT's HEO (High Earth Orbit) EAGLE Project. Recent advances in SDR (Software Defined Radio) technology have led to the concept of a modular transponder that can be easily re-configured in orbit.

Since there is little suitable C-band hardware available for the amateur community, we will discuss the idea that the spacecraft RF and SDR modules can be "dual use" with low-cost compact user terminals developed as a system, in parallel with the spacecraft development.

The C-Band Radio Spectrum: Let us begin by examining the amateur frequency allocations between 1 and 10 GHz in Table 1[1,2]:

Table 1: United States Microwave Allocations

Amateur Service		Amateur-Satellite Service	
Band (MHz)	**Bandwidth (MHz)**	**Band (MHz)**	**Bandwidth (MHz)**
1240-1300	**60**	**1260-1270 ↑**	**10**
2300-2310 **2390-2450**	**10** **60**	**-** **2400-2450**	**-** **50**
3300-3500	**200**	**3400-3410**	**10**
5650-5925	**275**	**5650-5670 ↑** **5830-5850 ↓**	**20** **20**
10000-10500	**500**	**10450-10500**	**50**
24000-24250	**250**	**24000-24050**	**50**

↑ means Earth-to-space (uplink) direction only
↓ means space-to-Earth (downlink) direction only

With AO-40's S-Band downlink, many amateurs have experienced serious QRM from unlicensed (Part 15) 2.4 GHz wireless devices including cordless telephones, 802.11b/g and Blue Tooth wireless LANs, in-home video monitors and microwave ovens.

These same wireless interests have expansion plans involving the 5-6 GHz C-band spectrum. 802.11a "WiFi" and 802.16 "WiMax" LAN devices and cordless telephones are already on the market. Can we, as

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[1] see W3IWI paper in AMSAT Space Symposium 2003 Proceedings, also reprinted in AMSAT Journal, August 2004.
[2] Thanks to Paul Rinaldo, W4RI for supplying an early version of this table.

amateurs, build a technology-based “brick wall” to protect these valuable frequencies? In Figure 1, we take a look at the 2004 view of the 5600-5900 MHz spectrum:

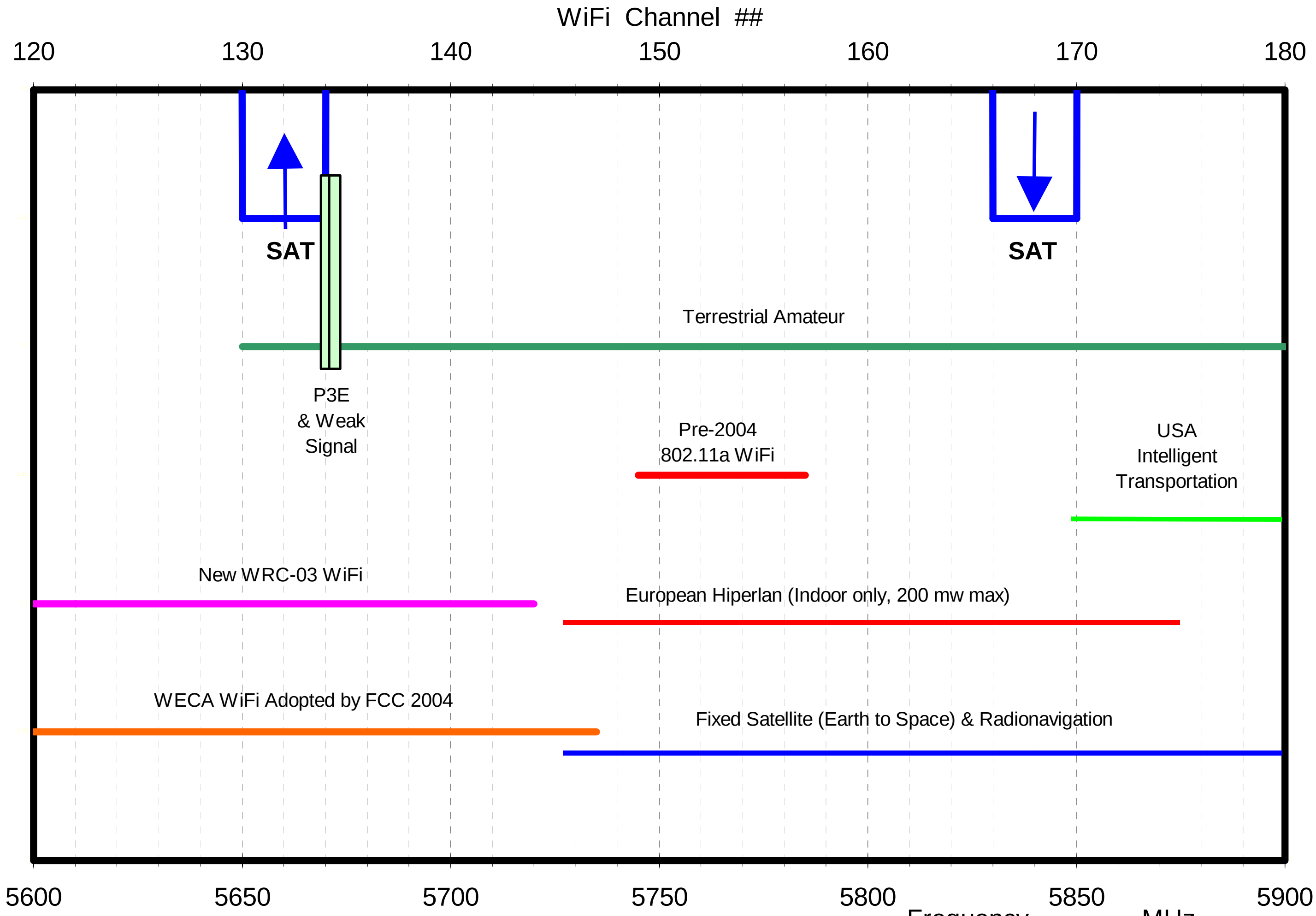

Figure 1

From this figure, we see that the 802.11a WiFi world has moved in to share the 5650-5670 MHz satellite uplink band. Let’s make some estimates concerning the QRM situation that might exist at the satellite.

The WiFi definition calls for the use of CDMA techniques, with a maximum thruput of 54 Mb/sec (just like 802.11g on 2.4 GHz). The total bandwidth available to WiFi is 550 MHz (5150-5350 MHz and 5450-5800 MHz – the 5350-5450 MHz chunk is reserved for Radio Navigation).

- Let’s assume that the WiFi users fill their allocation uniformly. The signals from the many users will be noncoherent, so their signals add as wide-band noise.
- The population of the USA is 294 million, and Canada is 32 million. As a conservative estimate let’s assume one C-band transmitter per person, operating 16 hours/day. This means that at any time there might be 217 million transmitters.
- Most 802.11a transmitters have low gain antennas and attenuation through trees and buildings affect the signal seen at a satellite. So we assume that each transmitter transmits 1 mW EIRP. This means that the 326 million transmitters will be a noise-like 326 kW transmitter spread uniformly over 550 MHz, equivalent to

$$(217 \bullet 10^6 \text{ transmitters}) \bullet (1 \text{ mW/transmitter}) / (550 \text{ MHz}) = 0.39 \text{ mW/Hz radiated}$$

- The path loss from the earth to a HEO satellite at ~40,000 km distance is ~196 dB. Assume an earth-pointing spacecraft antenna gain of ~19 dB. A loss of 177 dB is equivalent to a factor of $2 \bullet 10^{-18}$.

Putting these numbers together:

$$(0.39 \text{ mW/Hz}) \bullet (2 \bullet 10^{-18} \text{ Path Loss}) = (7.8 \bullet 10^{-22} \text{ Watts/Hz}) \text{ at the input of the receiver.}$$

This worst-case power can be converted into an equivalent 802.11a noise temperature of

$$T_{802.11} = (7.8 \bullet 10^{-22} \text{ Watts/Hz}) / k = 57\ °K$$

where k = Boltzman's Constant = $1.38 \cdot 10^{-23}$ W/Hz/°K.

We will return to this topic later when we discuss system link performance.

Some Aspects of System Design: In the previous paper, we outlined some possible design alternatives. In the last year we have refined our thinking on several topics, including:

1. **HEO vs. LEO (Winner = HEO)**: An attractive feature of C-C Rider for Low Earth Orbit (LEO) was the partial cancellation of Doppler with an inverting "bent-pipe" transponder, as well as the sharing of a single antenna for up- and down-link. Link budget calculations for the LEO case indicated the need for ~26 dBiC of antenna gain; this in turn necessitated antenna pointing accurate to a few degrees while the satellite can move at angular speeds up to ~½°/sec. This seems to be a bit beyond the capability of the average amateur.

   However a High Earth Orbit (HEO) satellite offers the user a slow-moving target. Combining this with AMSAT's plans for the HEO EAGLE satellite as it's next project led to our proposing C-C Rider as a main payload at the recent EAGLE design meeting[3]. The concepts presented in the rest of this paper are the result of enthusiastic endorsement of the concept by all the developers present at the meeting.

   The rest of this paper assumes a HEO EAGLE mission with a perigee height ~1000 km and apogee height ~40,000 km.

2. **"Bent-pipe" Transponder vs. Digital Regenerator (Winner = A New Idea!)**: The previous paper described the simple "bent pipe" transponder implementation of the C-C Rider concept reproduced in Figure 2. An addition to the concept was introduced (Figure 4 in the previous paper) discussed the desirability of providing alternative digital "demod-remod" capability as has been espoused by Phil Karn.

   As we prepared for the Orlando meeting, we developed an alternate implementation. The past two years have seen a revolution in amateur radio technique with the use of Software Defined Radios (SDRs). The receiver portion of an SDR is implemented by converting the desired RF signal to a convenient IF, and then digitizing the signal with an analog-to-digital converter (ADC). Final bandpass filters and signal processing is then accomplished in signal processing software. In this paper we will denote the receive side of an SDR as an SDRX.

   The transmit function in an SDR is accomplished by generating the desired signal in software and then converting to analog with a digital-to-analog converter (DAC). This analog signal is then heterodyned up to the desired RF signal frequency. We adopt the notation SDTX for the transmit part of an SDR.

   In most amateur implementations to date, the ADC and DAC functions of the SDR have been implemented in a "Sound Blaster" sound card running in a consumer-grade PC. This includes all the audio baseband PSK31 implementations (like MixW) and real SDR's like LINRAD and SDR-1000. Sound Blaster performance limits these implementations to bandwidths < ~50 kHz.

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[3] Held in Orlando, Florida in July 2004.

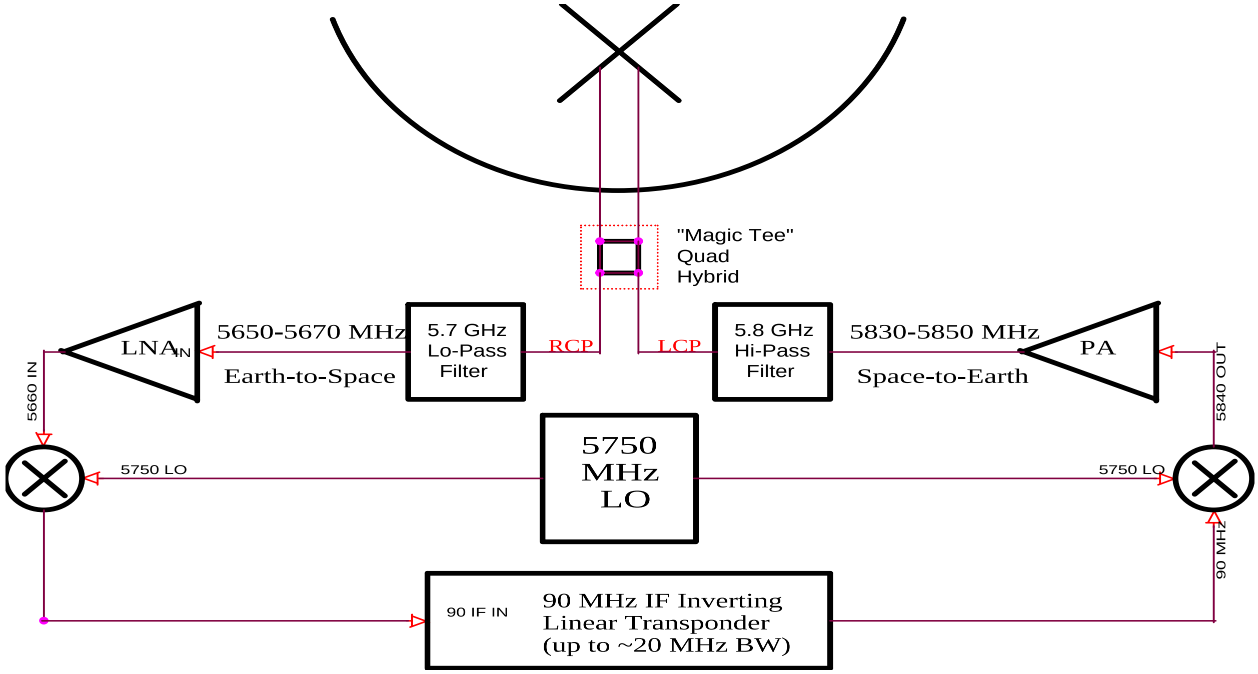

Figure 2: Simple "Bent-Pipe" idea for C-C Rider Spacecraft Transponder

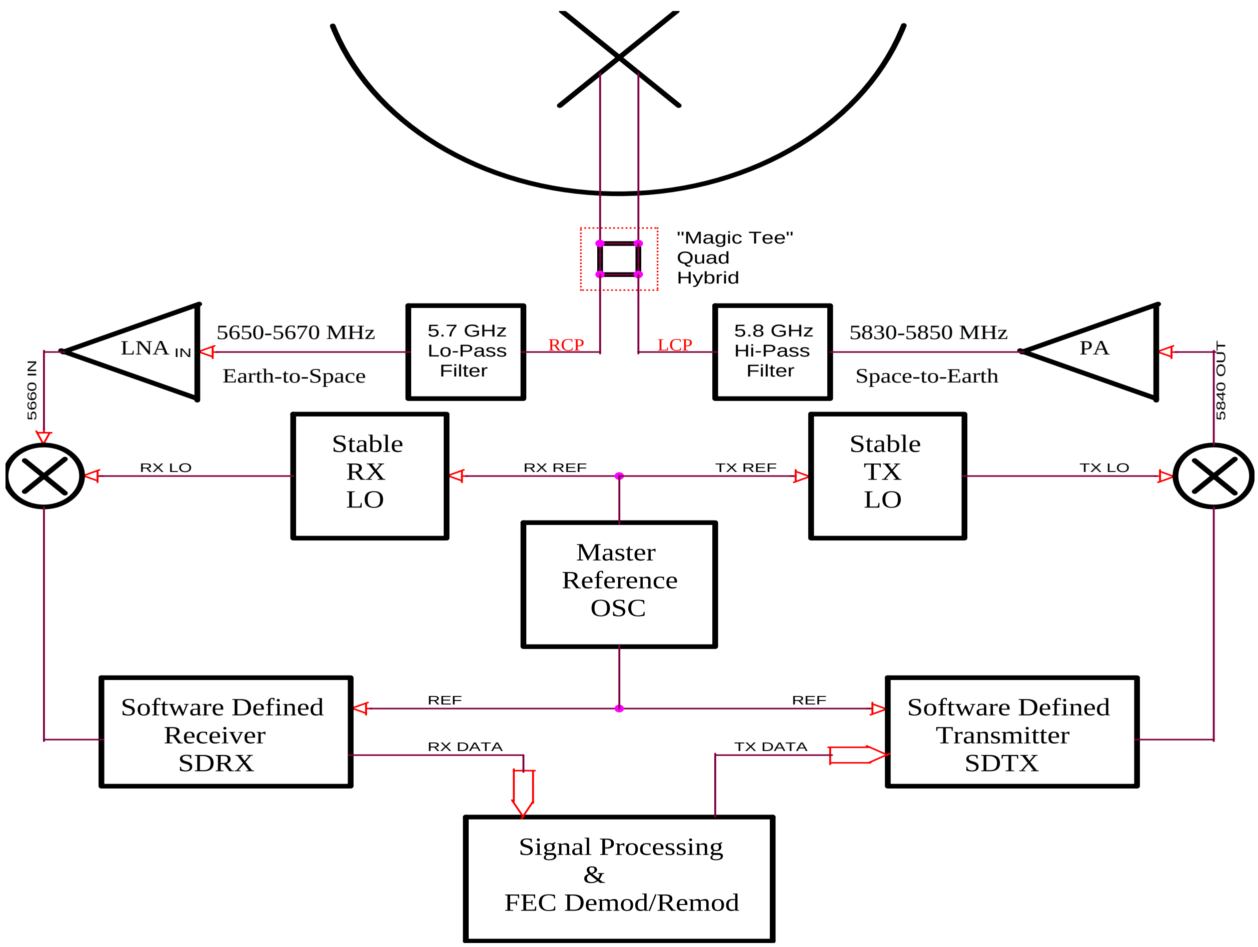

Figure 3: "Universal" Transponder using Software Defined Radio (SDR) Concepts

Thus in Figure 3, we see the C-C Rider concept "morph" into the idea of the universal SDR-based transponder. In order to optimize performance, we see that all Local Oscillators (microwave and SDR) are all derived from a single low-noise master oscillator.

Let's think about a linear transponder implemented in SDR. The signal processor could

- Remove gross Doppler offsets (less knob twiddling!)
- Apply suitable AGC to each individual signal (no alligators!)
- Optimize band utilization by suppressing unused parts of the band
- Allocate proper user vs. beacon power sharing

If a linear transponder was used for digital signals, the uplink and downlink Signal-to-Noise Ratios (SNRs) would be multiplied (making the link degrade as distance like R^4). Instead of taking this "hit", we would demodulate the digital signals at the spacecraft, applying error correction. The digital downlink signal get "fresh" FEC coding added and the links perform as a pair of R^2 paths.

3. <u>Dish Antenna vs. Array of Patch Antennas (Winner = Patches)</u>: Last year's paper offered the two possibilities. At the Orlando EAGLE meeting it became apparent that an array of patches has a lot to offer. Dick Jansson, WD4FAB has prepared an extensive drawing package for the ~60 x 60 x 45 cm EAGLE satellite. In Figure 4 we begin with Dick's drawing of the EAGLE "antenna farm" which shows a large 70 cm patch antenna in one corner. On top of the 70 cm patch is an array of three patch antennas for the 23 cm uplink. In diagonal corners are two separate arrays of four patches each for use on 13 cm.

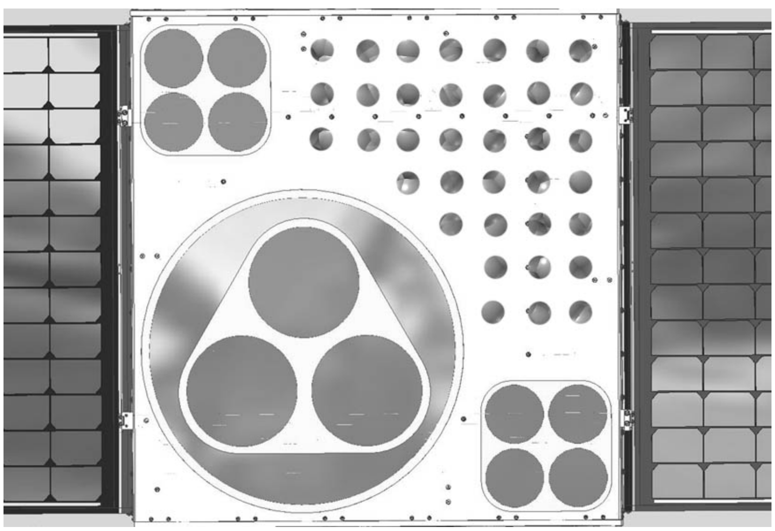

FIGURE 4. <u>Array of 36 C-Band Patches on the EAGLE Satellite.</u>

As seen in this sketch, we fill the remaining area with an array of 36 circular polarized patch antennas for C-Band (5.7 GHz) on a 50 mm (one wavelength) grid. Each patch element would be a complete C-band micro-wave system as shown in Figure 5. This circuitry would be developed using modern microstrip development soft-ware (like Ansoft's HFSS package.[4])

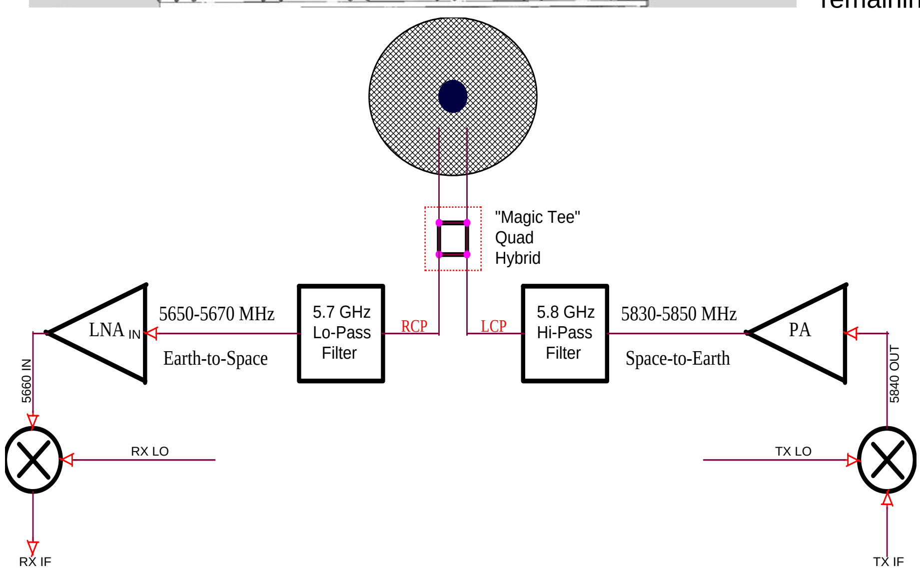

FIGURE 5. <u>Micro-wave components in each C-band array element.</u>

[4] See <u>http://www.ansoft.com/products/hf/hfss/.</u>

As mentioned in the first paper, each Power Amplifier would be a ½ - 1 watt output integrated amplifier designed for C-band wireless LAN use [5]. The LNA would be a low-noise PHEMT unit. The use of a distributed array of power amplifiers and microwave front-ends affords a unique level of redundancy. The failure of any one of the N elements would only degrade performance by a factor 1/N.

Let's look at the operation of this array on the receive side first. In Figure 6 we show a ground-based beacon transmitter provides a pointing reference for the C-band system. In this example, EAGLE's spin axis makes an angle α with respect to the signal from the beacon. Onboard the spacecraft, the signal from each of the antenna elements (after conversion to a convenient IF) is digitized in a separate SDRX channel[6].

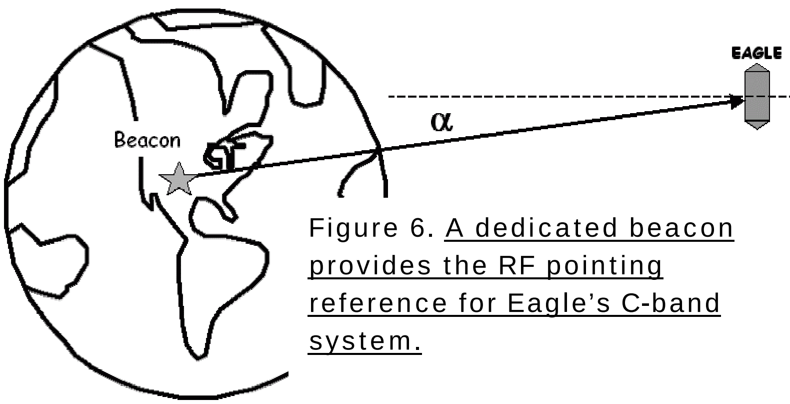

Figure 6. A dedicated beacon provides the RF pointing reference for Eagle's C-band system.

The phase data from pairs of SDRXs are combined to extract the phase difference Φ. As we see in Figure 7, the phase difference is related directly to the pointing offset α.

When projected onto the sky, the phase of the interferometer is periodic, with sinusoidal "fringes" that are spaced $2\pi B/\lambda$. The longer the baseline B, the finer is the scale of the interferometer fringes; but when B is longer than one wavelength, the phase becomes ambiguous. The array sketched in Figure 4 has the patch antennas placed on a one-wavelength grid to resolve so that the close pairs resolve fringe ambiguities, and also has spacings as long as ~9 wavelengths to improve the accuracy of position determination.

We plan that the beacon signal will be strong enough so that the beacon's pointing can be easily determined. Then, knowing the position of the earth relative to the spacecraft, the signals from all 36 antennas can be added to obtain a collecting area equivalent to ~30 cm dish. Since the array "pointing" is done electronically, the dish can be slewed to point at the earth even when the spacecraft's spin vector is off-pointed. This in turn means that the spacecraft will be useful through a larger portion of the orbit.

Once the spin axis is located with respect to the beacon on the earth, the positional data can also be applied to the SDTX transmitter elements so that the transmitting gain is comparable to the receiving gain. The array shown in Figure 4 is a bit larger than is needed to fill the earth at a 40,000 km apogee. The excess can be used to "trim" the shape of the beam to better "light up" the limb of the earth, improving DX performance.

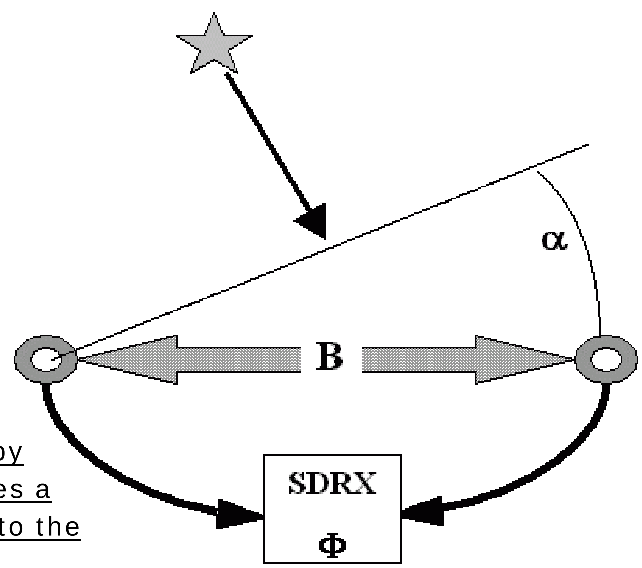

Figure 7. The interferometer formed by combining a pair of elements produces a phase measurement directly related to the pointing reference.

Interferometer Phase $\Phi = 2\pi B/\lambda \bullet \cos(\alpha)$

[5] For one possibility, see http://www.hittite.com/product_info/product_specs/amplifiers/hmc408lp3.pdf

[6] Lest you become too concerned with the complexity of this operation, realize that your typical 12-channel handheld GPS receiver contains a separate SDRX for each of the 12 channels!

The gain of each individual patch antenna element should be ~5 to 6 dBiC. If the 36 element array is used on-axis, the arraying gain should be about 10 • log(36) = 15.6 dB, the total gain should be in the 20 to 21 dBiC range, corresponding to a beamwidth ~19^0. This nicely matches the size of the earth, 15.7^0 as seen from a 40,000 km altitude.

4. Some Estimates of uplink performance: To make estimates of the link performance for C-C Rider flying on EAGLE, we make use of an Excel spreadsheet developed by Jan King, W3GEY/VK4GEY[7].

First, let's consider the uplink; the performance is critically dependent on the noise level that the spacecraft will see. Earlier we made an estimate that the worst-case noise contribution from 802.11a WLANs on the earth would be 57^0K. To this we add estimates of other contributions that we may experience:

Sky Noise	3 °K
LNA	40 °K
Antennas and Feedlines	50 °K
802.11a	< 57 °K
Transmitter (est.)	400 °K
TOTAL ESTIMATE	**550 °K**

The dominant term in this estimate is "Transmitter". In order to function as a transponder, the transmitter and receiver need to operate "full duplex" – receiving while transmitting. It is likely that each of the transmitter elements will generate some wideband noise that will be coupled into the receiver through the circular polarizing hybrid and antenna elements. Since the transmitter has not yet been developed, we can only flag this item as a serious worry!

To continue the uplink analysis, we note that we have an earth-to-space one-way path loss of –196 dB. If the user on the ground can develop 30 watts of power into a 20-21 dBiC gain antenna, his signal at the spacecraft will be about –129 dBm. If the spacecraft's antenna has a gain of 20 DbiC, the receiver will see a signal of about –109 dBm. Finally, if the receiver has a bandwidth of 100 kHz, this results in a S/N ratio of +12 dB.

If C-C Rider is used as a digital transponder that employs FEC, this performance implies a usable channel capacity in the 100-200 kb/sec range. Digital voice sounds very good with data rates of 10 kb/sec, so this link could support 10-20 noise-free voice channels. Each channel would support a two-way QSO or an n-way roundtable, so upwards of 50 simultaneous voice users can enjoy the EAGLE/C-C Rider combination.

This number can be increased if more robust uplinks can be developed. This might be done by

- Developing user terminals with transmitters bigger than 30 watts, or
- Developing user antenna systems with more than 20 dB gain, or
- Making the spacecraft transmitter have less noise in the uplink frequency band.

5. Estimates of Downlink Performance: Throughout the design, we have assumed that the spacecraft and ground-based user terminals are nearly identical. Microwave hardware developed for the spacecraft could be re-used on the ground by merely swapping the TX and RX ports. The SDRX and SDTX software would be developed with a GNU-like Open Source model; while the actual computer hardware on the ground and in space may be different, much of the intellectual property investment is reused. Therefore it is quite likely that uplink and downlink system performance will be the same, with one major difference. The spacecraft needs to operate full-duplex, so TX noise leaking into the RX becomes a dominant noise contribution. But the user will likely operate half-duplex, turning off the transmitter when not needed. The result is that the large TX noise contribution (estimated above to be 400 °K) doesn't apply. But this may trade off against localized C-band noise sources (cordless phones, "sloppy 802.11a devices, etc) in the downlink band. So, until we know a bit more about the 5830-5850 MHz spectrum, we assume that the downlink can support the uplink.

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[7] Available at http://www.amsat.org/amsat/ftp/software/spreadsheet/AMSAT-IARU_Link_Budget_Rev1.xls

Some Concluding Comments: As amateur radio enters the 21st Century, we face significant pressure on our most important resource, ***the Radio Spectrum***, especially in the 1-10 GHz range. Our allocations are precious to us, but we ***will*** lose them if we don't use them. And our usage needs to make significant contributions in advancing the state of the art.

AMSAT is now planning its next major satellite in the project that had been dubbed EAGLE which includes the C-C Rider concept discussed in this paper. We hope that it proves to be a challenging project that will inspire the participation of some new, talented people.

The ideas expressed here are far from final. Here are some areas that can challenge new blood:

- Can we really cram a one-watt C-Band PA, patch antenna, circular polarization combiner, bandpass filters and LNA into the 50 mm (~2 inch) space shown in figure 4? What DC-to-RF power efficiency will we able to achieve? How do we get rid of the heat that doesn't make its way into RF energy?

- How quiet will the TX be in the RX band? Link performance is critically dependent on this.

- How much will these modules weigh? Will they upset the spacecraft's 3-axis moment of inertia that allows the satellite to spin smoothly?

- The design of the multi-channel SDRX and SDTX will be challenging! How much computing horsepower is needed? What's the mix between general purpose CPUs vs. DSP CPUs vs. Programmable Gate Arrays?

- What communication protocols will we use (Time slotted TDMA? CDMA? FDMA? ???)? What is the ratio of Error Correction bits to Data Bits?

- How much does all this weigh? How much power is needed? What temperature range can be tolerated by the hardware?

- How do raise enough money to fund the development of the payload, the EAGLE satellite and the launch? Can we find (and afford) a suitable launch?

The way for you to become involved is to volunteer. AMSAT is an **Equal Opportunity Exploiter!**

Starting AMSAT's Lessons Learned Process

Lee McLamb, KU4OS, ku4os@amsat.org

Background:
During the February 2004 Strategic Planning meeting the "need for a thorough after action review of AMSAT projects" was identified and assigned as a top priority by the committee.

This paper will introduce the process for conducting those reviews and provide examples of some of the "lessons learned". This process is modeled after one already being used in the launch industry. The essential premise is that there are always things that can be learned regardless of the outcome of any specific mission. As a result, a review of lessons learned and how to apply them is conducted for every mission including those that were completely successful. For the Eastern Range (Cape Canaveral AFS) this has lead to a five year period including 150 countdown attempts and 103 actual launches without a scrub due to an instrumentation failure. Instrumentation includes all the tracking, communications and data processing systems from Cape Canaveral to Argentia, Newfoundland in the North and Ascension Island in the South Atlantic.

The lessons learned process also looks at AMSAT as a whole. While some of the initial focus has been on technical issues to support early work on the Eagle project, there are also lessons to be learned in the areas of organization, finance, communication, and promotion. These will also be addressed as the process continues.

Goals:
There are three primary objectives that AMSAT is looking to achieve from this effort:

1. To make sure that the information is readily available to the teams involved in current and future AMSAT projects.

2. To openly demonstrate to the membership that we are learning and making provisions to avoid problems in the future.

3. Ensure that things which are found to be particularly effective are captured as well.

Guidelines:
With the goals established, the next step was to put in place some general guidelines for soliciting input. The guidelines were made intentionally broad so that the scope of the inputs would not be limited unintentionally.

The first guideline is that ALL inputs from ALL sources are welcome. An initial request for input was sent to a large group of AMSAT members who participated in projects from the Microsats in the 1990's through AO-40 and Echo. In addition to actual problems that arose, they were also asked to consider the "near-miss". What were the things that were caught late in the process that should be noted for the future?

The second guideline addressed availability for input. It is important to recognize in a process like Lessons Learned that there is a great deal of variability in the methods through which people feel comfortable communicating. Some people are quite comfortable providing input by email while others prefer the give and take of interaction on the telephone. In some cases it has also been possible to meet for face-to-face discussions. All the methods have been used and all have proven to be very beneficial.

The third guideline states that requests not to be identified as the source of certain information will be honored. The focus of the Lessons Learned process is to make sure that the information gets captured and analyzed. In some cases people may not feel comfortable making comments that could be perceived as negative or blaming. Since everyone involved is a volunteer, there is no means to compel anyone to share information. The result is that a great deal of the success of the Lessons Learned process depends on an unshakable commitment that all inputs will be handled fairly. The goal of learning and applying the lessons must take precedent.

The fourth guideline is that suggestions and ideas are welcome. This guideline is based on the observation that sometimes good ideas or observations are made by those people with a little distance from the immediate problem. Specifically it is designed to encourage comments when people noticed another part of the team struggling with an issue but didn't have a chance or felt out of place making a suggestion at that time

The final guideline is that the Lessons Learned process is intended to capture positive lessons. Anything that was tried and found to be particularly effective should be included so that future efforts gain that benefit as well.

Since one of the overall goals is to prevent future problems, input on any contributing factors where also requested. To effectively learn a lesson there should be an understanding of why something happened as well as the specifics of what happened. There are several general categories used to look for the contributing factors to an event. They are:

- The 4 M's:
  Methods, Machines, Materials, Manpower

- The 4 P's:
  Place, Procedure, People, Policies

- The 4 S's:
  Surroundings, Suppliers, Systems, Skills

Findings:
Research and data gathering is on-going as this time. In fact this is expected to be a continuing process. The initial responses were generally quite positive, enthusiastic and thoughtful. In their responses several people made additional suggestions of events and over a dozen other people who will be included for follow-up.

The items below represent a top-level view of some of the comments received so far. Some of them represent recurring themes. Others are a summary of multiple pages of specific technical recommendations. Included are some examples of the types of events that prompted the Lesson. Since it is not the purpose of this paper to provide an exhaustive listing but instead an introduction to the process, there may be additional events which also support the Lesson which have not been included at this time.

The most common recurring Lesson revolves around the need for adequate testing. Early and adequate testing allows problems to be found while the resources are still available for corrective action to be taken. However, testing must be done in a planned and thoughtful manner if the benefits are to outweigh the risks. Every time that any piece of flight hardware is handled there is an element of risk that some damage may result. Also, testing can be very expensive because there is almost always some transportation involved. Either people must travel to the test site or in some cases the satellite must be moved to a specialized testing facility for things like vibration and thermal/vacuum testing. In order to manage those risks and costs, a three part process has been suggested for testing. The three parts are planning, procedures and reports.

Planning involves thinking through and documenting the test. At a minimum it should include what, how and why the test is being done. Planning has many benefits. By working through the three general questions the team will be better prepared and be able to make better use of the volunteer’s time. During the P3D project there were occasions when volunteers representing one module were at the lab for testing but were hampered in doing so because of other activities being done with the spacecraft. A plan is also needed to ensure that all the subsystems are checked together in all possible combinations. One result of not performing fully integrated testing on P3D was that the interaction between RUDAK and the S2 transmitter and L-band receivers was not found until the satellite was in orbit. The Echo commissioning effort was also hampered somewhat by the lack of fully integrated pre-launch testing. Once Echo was on-orbit the command teams found that there appeared to be some desense of the receivers when the transmitter power was increased above 2w. The problem was finally isolated to one of the ground stations. Considerable time and effort had to be used to rule out a spacecraft problem since no prelaunch testing had included RF checks with the actual flight antennas installed. Planning also provides the opportunity to identify all the equipment that is expected to be needed. This again helps the volunteer builder since they will have a higher confidence that their time will be productive. As the planning process matures an outline of the procedures will begin to take shape.

Procedures differ from plans in that they contain the details of what is to be done and how. One of the Lessons provided from several sources is that the procedures need to be detailed enough that any member of the integration team can follow them to perform the test. This provides several benefits and frequently ends up feeding back into the planning part of the process. For example, by having to define where to make connections and take measurements, shortages in test equipment, cabling and connectors can be identified in advance.

The procedure should also include steps and checks to ensure that all the systems are operated only within their specifications. During one of P3D’s tests the ground test batteries where substantially overcharged. The result was an energetic venting of the cells which disrupted the testing schedule. A thorough procedure will also have all the steps needed to initialize the system. During Echo’s launch campaign the procedure that had been used in the lab resulted in the SQRX receiver audio being unable to connect audio through to the transmitter. It was eventually found that some additional steps where needed but by the time an updated procedure got to Bakinour, the satellite had already been integrated onto the launcher. Once in orbit the revised procedure was used and the SQRX was found to be operating correctly. Another advantage of having a detailed procedure is that it avoids the problems of having anything critical be dependent on the presence of a single person or a limited group of people. During the P3D launch campaign it was that type of dependence that lead to a plug being left in the Helium vent line. Having well written procedures is also beneficial in that it helps to keep the overall project from falling behind due to schedule conflicts with the people doing the integration effort. This serves the other members of the team as well because the testing that they need to perform on one sub-system will not be held up do to the availability of an individual from another sub-system. Since part of the planning and procedure development process is figuring out what is desired to learn or document from the test, the format for a test report will also begin to present itself.

Writing a report is something frequently looked on with dread among volunteers. If planned for in advance the report can be filled in as the test progresses. This helps to reduce the additional workload on the people running the test and also has the benefit of helping them to ensure that they have gotten everything they had hoped for out of the effort. The reports also can serve as background information for use by the publicity team in writing and updating articles for the Journal about the satellite's capabilities as it progresses from design to actual flight hardware. The reports will also serve the Operations Team. If some behavior is noted once the satellite is in orbit, they will be better able to troubleshoot and resolve if there is a solid set of prelaunch measurements available for comparison.

While testing is important, the reality is that some things may not be testable on Earth or may require substantial resources beyond our means. In these cases some of the risk associated with not testing can be reduced through thorough simulation and analysis. Since the Eagle team has committed that Eagle will be an open project, there will be many more opportunities for reviews and independent analysis. One benefit from the P3D project is recognition of the benefits of peer reviews prior to actual construction. The P3D structure required substantial rework some of which was driven by changes in the launcher environmental data provided by Ariane but some deficiencies were noted even before those changes. One of the challenges will be finding the additional volunteers to perform the analysis and reviews. One of the hopes is that by making the Eagle team meetings open, those volunteers might be found. Reviewers with experience from all aspects will be needed, mechanical, power, software, RF and thermal.

One of the goals is to capture the positive things which came out of each project as well. Two examples of the positive lessons from P3D include wiring harness management and documentation needed at the launch site. P3D had a very extensive wiring harness to interconnect all the various modules. The P3D harness included approximately 4000 wires. To manage this effort Lou McFadin, W5DID developed a database which was used to track each wire and assure that all terminations were accounted for. Being a database it was also searchable which made it possible to generate wire lists for a module, connector or to track a signal through multiple wires. The database also included an installation and verification field. Each connection in the harness was verified by someone other than the installer. A very limited amount of rework was required in those few cases where a connectors pin out was found to be different than what was provided to the harness team. Another positive outgrowth from the P3D project was the validation of the CAN bus[1] as a way of reducing the complexity of wiring harnesses in the future. A final example of a positive lesson learned was that plans for the launch campaign should include taking copies of the paperwork previously submitted to the launch agency. While P3D was in Kourou, several times the local representatives asked for copies of information that had already been submitted. Even though that bulk of paperwork wasn't expected to be needed, a great deal was carried anyway and proved to be quite valuable in keeping the launch campaign on-track. Similar events have been noted by those in the launch industry at other launch sites so it is not a situation unique to Kourou. Being aware of it, AMSAT can now plan ahead and be better prepared.

Summary:
In order to introduce the Lessons Learned process this paper has mainly focused on some recent technical events. However it is not limited to only technical items and will also be addressing other areas of AMSAT as a whole. One example of an area under development is the methods used for providing coverage of the Board of Directors meetings. The current methods work but are extremely labor intensive and result in delays getting information out to the membership. The next step is looking at why things are done as they are and evaluating options for implementing change.

Lessons Learned is an on-going effort. The overall objective of which is to produce a more efficient organization, better satellites and most importantly a better structure, environment and experience for the volunteers who make things happen by donating their time and talents.

Reference:
1. Bdale Garbee, KB0G, Chuck Green, N0ADI, Lyle Johnson, KK7P, Stephen Moraco, KC0FTQ "Doing More with Fewer Wires in the Harness: A new Approach to Spacecraft On-Board Command and Telemetry Interfacing", *The AMSAT Journal*, November/December 2003, pp.11-15

AMATEUR RADIO ON THE INTERNATIONAL SPACE STATION 2004 STATUS REPORT

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INTRODUCTION

The international working group called ARISS—Amateur Radio on the International Space Station—was formed at a meeting in Houston, Texas in 1996. ARISS is an international consortium of delegates that represent the 5 international regions that are actively supporting the development and operations of the International Space Station (ISS)—Canada, Europe, Japan, Russia, and the United States. Delegates were chosen from these region's International Amateur Radio Union (IARU) organizations (ARRL in the US) and Radio Amateur Satellite Corporation (AMSAT) organizations to represent each region in the development and operation of the ISS ham radio system. Thanks to the support of the space agencies and the IARU and AMSAT organizations, ARISS is thriving and continually looking toward the future. To date, the ARISS team has enabled tens of thousands of students to experience a ham radio contact with the on-orbit astronauts and cosmonauts. In addition, thousands of ham radio operators communicate through the on-board equipment which consists of two major hardware development phases.

This paper provides a status of the ham radio equipment and operations currently on-board ISS. It also contains reports from the delegates from the 5 ARISS regions, our expectations for the near future and our plans for the distant future.

HAM RADIO EQUIPMENT STATUS

The Amateur Radio on the International Space Station (ARISS) international team devised a multi-phased hardware development approach for the ISS ham radio station. Three internal development Phases---Initial Phase 1, Mobile Radio Phase 2 and Permanently Mounted Phase 3 plus an externally mounted system, were proposed and agreed to by the ARISS international team.

The Phase 1 system hardware development, started in 1996, was delivered to ISS in several increments starting in September 2000, and is currently operational on 2 meters. The Phase 2 system is partially operational with the Kenwood D700 operational on 2 meters and 70 centimeters. Phase 3 is still in the future. Several externally mounted systems are in different stages of design and development.

The following provides a high-level status of the hardware development. For more details on the ISS ham radio hardware, see reference 6.

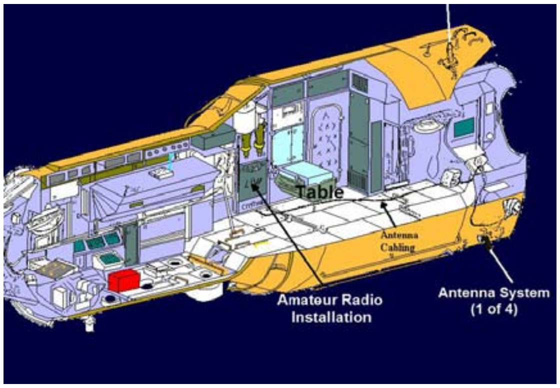
Ham Station Location

The ham radio equipment resides in two locations inside the ISS and several locations outside the ISS. 2-meter (144 MHz) operations are primarily conducted inside the Functional Cargo Block (FGB), named Zarya, using antennas that supported docking of the FGB with the Russian Service Module. See figure 1. This is the current location of the 2 meter portion of the Phase 1 ISS ham radio station.

To support multi-mode, multi-operation on ISS, four ham radio antenna feedthrough ports were installed on the Russian Service Module (SM), named Zvezda. This was accomplished through the leadership of Sergey Samburov, RV3DR, from the ARISS Russia team. The ham station is installed near the SM dining table. See figure

2. Simultaneous multi-band operations can be conducted with these two (SM and FGB) station locations.

The ARISS team is also working to install externally-mounted amateur radio equipment on the ISS. This hardware will enable the crew to communicate with Earth-bound radio amateurs and school students using handheld systems that can be moved throughout the ISS. It will also support communications experimentation that will enable students and radio amateurs to receive telemetry data from ISS.



ARISS Hardware in Service Module
Figure 2

Phase 1 Hardware

The Phase 1 system consists of two hand-held Ericsson MP-A transceivers for 2 meters and 70 cm, power adapters, signal adapter modules, packet modules, headsets, and the required cable assemblies. The Phase 1 system supports voice and packet (computer-to-computer radio link) capabilities. The packet radio system has several capabilities including an APRS Instant Messaging-type system and a Bulletin Board System that allows radio amateurs to store and forward messages and allows the orbiting crew to send e-mail to all hams or to individuals. This configuration can be operated in the attended mode for voice communications and either the attended or automatic mode for packet communications.

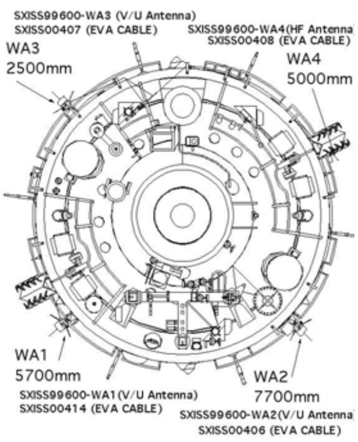
The Phase 1 radio system was launched on-board three space shuttle flights: STS-106 on

FGB 2 Meter Antenna Locations
Figure 1

September 8, 2000, STS-105 on August 10, 2001 and STS-108 on December 5, 2001.

Antenna Assemblies

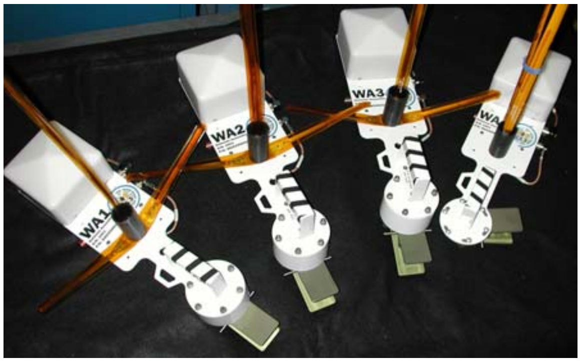
In 2002, a set of four antenna systems, developed by the ARISS team, were deployed on the aft-end of the service module during three Russian EVAs. These antenna assemblies permit operations on HF (20 meters, 15 meters & 10 meters), VHF (2-meters), UHF (70cm), and the microwave bands (L and S band), including GPS. They also permit the reception of the Russian Glisser EVA video signals (2.0 GHz). This dual-use (Ham/EVA video) capability is the primary reason the ARISS team received access to the four antenna feedthroughs located on the outside of the Service Module.



Antenna Location from End of Service Module
Figure 3

These four antenna systems were installed around the periphery of the far end of the Service Module. See figure 3. Three of the antennas (WA1-WA3) include a VHF/UHF flexible tape antennas. WA4 includes a 2.5 meter flexible tape HF antenna. The antenna systems were developed by the U.S., Italian, and Russian ARISS partners.

Each antenna assembly consists of a mounting plate, spacer, a black striped handle, a Russian handrail clamp, an orange-colored VHF/UHF (or HF) metal flexible tape antenna with black delrin mounting collar, an L/S band flat spiral antenna with a white delrin radome cover, a diplexer (mounted underneath the plate) and interconnecting RF cables. See figure 4.



Antenna Systems WA1-WA4
Figure 4

Phase 2 Hardware

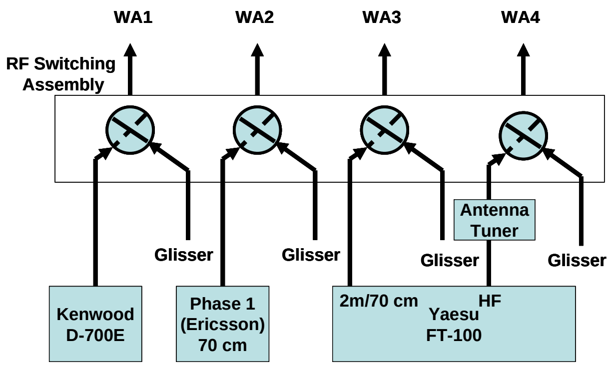
The Phase 2 hardware, consisting of two new radio systems, utilizes the ham radio antennas mounted on the Service Module. The phase 2 hardware augments the Ericsson Phase 1 hardware already on-board the ISS. Combined, the Phase 1 and Phase 2 system provide more capabilities for the crew and permit simultaneous, multi-mode operations by more than one crew member.

The Phase 2 hardware includes the Kenwood TM-D700 radio and the Yaesu FT-100D radio. The Kenwood radio supports 2 meter (144-146 MHz) and 70 cm (435-438 MHz) transmit/receive operation and L-band uplink operation. It provides a higher output power capability (10-25 Watts) than the Phase 1 radio system and can support FM and packet operations. The Yaesu FT-100 permits operation in the high frequency bands as well as on 2 meters and 70 centimeters. The Yaesu will also enable ionospheric propagation experimentation using the WA4 (high frequency) antenna.

The Service Module ham radio equipment includes the Phase 2 hardware: the Kenwood and Yaesu radios, an RF tuning unit for the Yaesu radio system, interconnecting signal and RF cables, two specially developed Energia power supplies, a power distribution assembly developed by the USA team, and a computer. It also includes the 70 cm Ericsson Phase 1 hardware system. These are all mounted on a Velcro-backed table as shown in the on-orbit photo depicted in figure 5.


Mike Foale, KC5UAC Next to the
Velcro Table Mounted in Service Module
Figure 5

In the future, these radio systems will be connected to the four Service Module antenna systems through a Russian developed antenna switching system. See figure 6.



Service Module Antenna/Radio System Utilization
Figure 6

Kenwood D-700 Specifics

A set of 5 default options, or Programmable Memories, were embedded in the D700 to support ISS operations. These five memories enable 2 meter and 70 cm operations to be conducted using these fundamental configuration baselines:

PM1: Voice Operations (mono band)
PM2: Voice Operations (cross band/repeater)
PM3: APRS/Packet and BBS operations
PM4: Attached PC and packet operations
PM5: Emergency Voice and alternate 9600 baud Packet Operations.
PM-off: No defaults. This mode is for knowledgeable licensed crew member's experimentation.

Yaesu FT-100 Specifics

The ARISS technical team has specified several modifications to the Yaesu radio system to prepare it for flight. These modifications include:

1. Replacing cable to enable flight certification of the hardware.
2. Reducing power output to 25 watts maximum.
3. Replacing the RF cables and connectors on the back of the radio with SMA connectors.
4. Tuner cable replacement with flight cables
5. Replacement of 6-pin data connector with an 8-pin connector. One of the additional pins on this connector supports a 12 V DC output capability.

Development of the Yaesu system is still on-going.

Phase 2 Delivery, Testing and Checkout

The initial set of Phase 2 hardware, including the Kenwood D-700 radio, were delivered to the Baikonur Cosmodrome and launched on the Progress 12P rocket on August 29, 2003. A series of tests were performed in November, 2003 at the KIS facility (Service Module engineering model equivalent) located at Energia in Korelev (Moscow area) Russia. These tests validated that the Kenwood Phase 2 system and the Ericsson Phase 1 system are compatible with the other electrical systems on the Service Module. See figure 7.

Sergey Samburov, RV3DR, Conducting
Phase 2 Hardware Testing in the KIS Facility
Figure 7

Once the KIS testing was completed, Expedition 8 crew members Mike Foale and Alexander Kaleri were given the go ahead to install and checkout the Kenwood Phase 2 hardware. This was completed on December 8, 2003. Equipment checkout was accomplished through an engineering checkout opportunity in Russia on February 2, 2004 and a USA-based opportunity on July 22, 2004. With the completion of these checkouts, the D700 has been cleared for use for school contacts. Tests of the PM 2 cross-band repeater are planned to be performed in the August-September timeframe.

The remaining Phase 2 hardware, including the Yaesu radio system is planned to be launched on a future Progress flight.

Hardware Systems Under Development

Two projects are currently in development for delivery in the near future. These are the SSTV system which can be operated with the Phase 1 and Phase 2 hardware and the MISSE-5/PCSat-2 externally mounted payload.

In the near future, a Slow Scan Television (SSTV) system will be deployed on ISS. This system will consist of a software interface, developed by the MAREX-MG team and a hardware interface, developed by the AMSAT-NA hardware team. Flight hardware and software systems have been developed and are completing the final validation and certification phases. The SSTV system will allow digital still pictures to be uplinked and downlinked in both crew-tended and autonomous modes. The ARISS team expects the SSTV system to be flown within the next year.

MISSE-5/PCSat-2 is an externally mounted ISS payload that will support 2 meter and 70 cm voice, APRS, PSK31 and telemetry downlink of the spacecraft solar cell experiment. Launch of MISSE-5/PCSat-2 is currently planned on a shuttle after return to flight.

ISS HAM RADIO OPERATIONS STATUS

All ISS operations have slowed as a result of the reduction of the ISS crew size from three to two. This temporary reduction will continue until Shuttle return to flight. ISS ham radio, too, has seen a bit of a slowdown in school group events. However, ISS Ham radio community experienced a substantial increase in general ham radio contacts. In a sense, the school slowdown, coupled with the enthusiasm by the Expedition 9 crews on general contacts have resulted in a more balanced program which includes school contacts, general ham contacts and experimentation.

Packet Operations

After being off the air for about a year, packet operation was brought back to life in early December 2003. The activation of the Kenwood D700 has enabled the ARISS team to restart packet despite not having access to a computer. The two packet modules that have been utilized as part of the Phase 1 system require a reset and parameter modification that can only be done by computer. The ARISS international team is working diligently to acquire a dedicated computer system. Once it is available, the ARISS team hopes to re-enable phase 1 packet system. The current plan would be to have the Phase 1 packet and the D700 voice repeater capabilities running on ISS simultaneously. This will provide multiple capabilities to ground-based hams.

School Group Contacts

The ARISS school contacts for expeditions 8 and 9 are about half of what it was for the previous expeditions. To date, 21 school contacts have been completed during the expedition 8 and 9 combined. This compares with an average of 15-18 school contacts on previous increments. These two increments have had to contend with several anomalies on their flights (e.g. crushing noise on expedition 8 and unplanned EVA on expedition 9). These anomalies, coupled with the small crew size resulted in frequent postponements and rescheduling of ARISS school contacts. Despite these challenges and delays, the schools have all enjoyed a one-in-a-lifetime opportunity to talk to a crew member in space. Survey information from the schools indicate that about 15,000 students participate in ARISS each year. Some of the comments from the educators include: "Students realized an opportunity of a lifetime by speaking to the astronauts on the ISS. This was a life changing events for all participants."
And: "This event brought an awareness of space exploration to not only the students, but teachers, parents and the extended community. It made space exploration meaningful to them."

Roy Neal Commemorative Event

ARISS team member and noted NBC news correspondent Roy Neal, K6DUE (SK), had a vision---to make amateur radio a permanent feature on human spaceflight missions. To commemorate Roy Neal's vision and dedication to the development of amateur space communications, the ARISS International team sponsored a special event activity with the ISS crew during the months of November and December 2003. These two months were significant because they represented the convergence of three major milestones for ham radio operations on human spaceflight vehicles.

November 28, 2003 represented the 20th anniversary of the launch of the first amateur radio station on the STS-9 Space Shuttle Columbia mission. During this flight Astronaut Owen Garriott, W5LFL, became the first on-orbit crew member to talk to hams from space.

In October 1988, the Russian Amateur Radio team, led by Sergey Samburov, RV3DR and Larry Agabekov, UA6HZ/N2WW, launched and deployed the first amateur radio station on Mir. On November 12, 1988 at the AMSAT-NA symposium in Washington DC, Leo Labutin, UA3CR (SK), started amateur radio operations by communicating with cosmonaut Musa Manorov, U2MIR on-board Mir. Soon thereafter, hams all over the globe were talking with the cosmonauts and astronauts through the Mir amateur radio station. 15 years later, hams still reminisce about their ham contacts with the Russian cosmonauts and US astronauts on Mir.

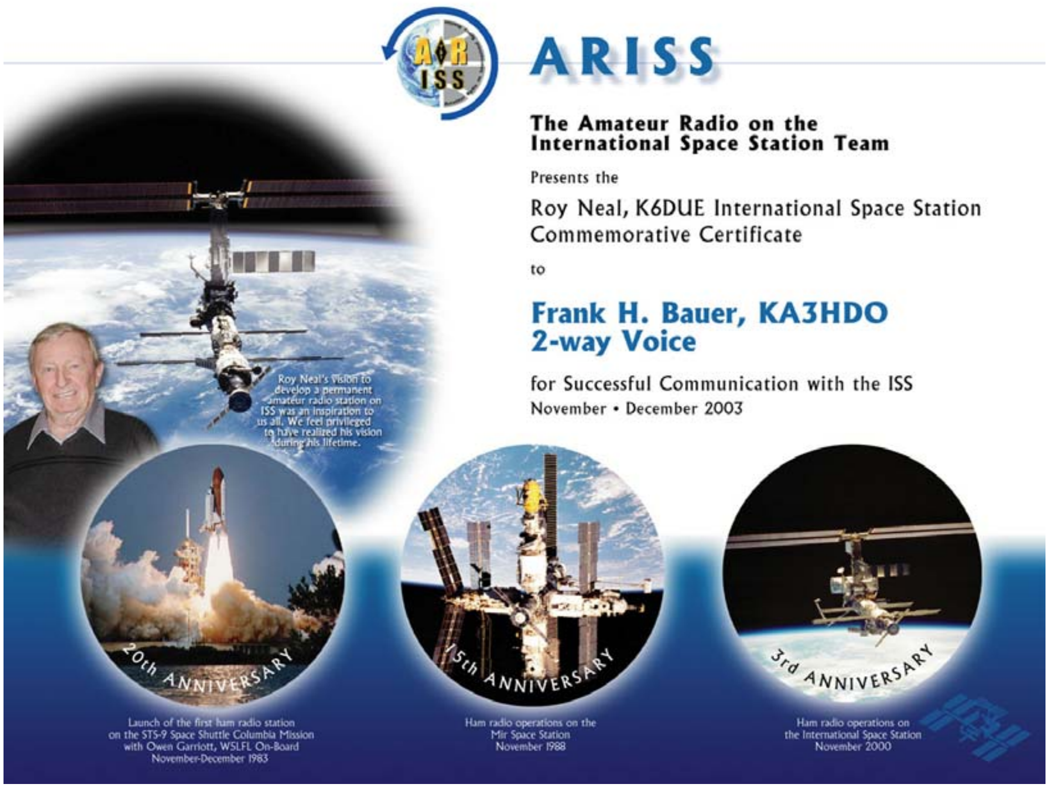
The third milestone was the 3rd anniversary of amateur radio communications from the ISS. On November 13, 2000, Sergei Krikalev, U5MIR and Bill Shepherd, KD5GSL, on ISS could be heard talking to the ham radio teams located at the Energia amateur radio station, R3K, in Russia and the Goddard ISS ground station, NN1SS in the USA. Roy's vision was suddenly realized with the deployment and first operation of a permanent amateur radio station on ISS.

A special commemorative certificate was developed for this special event. See figure 8. Shortly before the commemorative event, the Expedition 8 crew members, Mike Foale and Alexander Kaleri, installed the Kenwood D-700 radio. In late November the packet system was activated and during the weekend of December 6 Mike Foale got on the air in the voice mode. He made numerous contacts during several opportunities, worldwide over the next few weeks. When the commemorative event was complete, over 150 hams worldwide contacted the ISS. This very successful event was a fitting tribute to Roy Neal's vision as well as to the worldwide teamwork of the ham radio volunteers that transformed the dreams of ham radio permanence in space to reality.

Expedition 9 General QSO Operations

The expedition 9 crew, consisting of astronaut Mike Finke, KE5AIT, and cosmonaut Gennady Padalka, RN3DT, are the most active general QSO ham radio operators to date. After being licensed just a few months prior to his flight to ISS, Mike Fincke learned how to beacon a special packet radio message to hams on the ground. This knowledge was put to good use when his wife Renita gave birth to a daughter on Friday June 18, 2004 while Mike was on-orbit. On Saturday June 19, the proud father announced the birth of his new daughter via the packet beacon. "It's a girl! Tarali Fincke" was sent down on the packet beacon about once a minute over the next week.

During the annual ARRL Field Day, both Mike Fincke and Gennady Padalka were on the air. Mike supported 2 meter operations using the Phase 1, Ericsson radio system using the callsign NA1SS and Gennady surprised the ham community with a booming signal on 70 cm using the Kenwood D700, the new ARISS antenna systems and the callsign RS0ISS. For the first time in human spaceflight history two crew members in the same vehicle were on the air at the same time. Multi-band, multi-operation became a reality on June 27 during



Roy Neal, K6DUE Commemorative Certificate
Figure 8

ISS field day operations. All in all, Mike and Gennady made 56 contacts during Field Day. Field Day 2004 was a huge success on ISS!

After getting bitten by the ham radio "bug," Mike Finke continues to make random contacts with the ham community throughout his ISS expedition. Most of these are during the weekend, including the weekend of July 31-August 1 when he made 30 QSOS on 5 continents. However, he also picks up the microphone when he has an opportunity and he is over "dry land." This is much easier in the Service Module since the new Phase 2 hardware is located near the window, dining table and exercise equipment.

ARISS DELEGATE REPORTS

Canada Team

The Canadian team has been busy investigating and developing various ways of presenting the ARISS Program as well as amateur radio in general to the public with a specific focus on educators. The areas of concentration are:

- Evaluation of various Voice over Internet (VoIP) techniques that can used to distribute ARISS events (school contacts), with emphasis on the use of the IRLP
- Development of a dedicated IRLP "Reflector" (located in Halifax, Nova Scotia) capable of providing effective distribution of ARISS events
- Providing ARISS Educational Outreach Information to Educators
- Development of "updated" ARISS displays
- Publicizing visible passes of the ISS and
- Planning for future collaboration with the Discovery Center (located Downtown Halifax) for a permanent ARISS/amateur radio display.

More details of these initiatives follows.

Investigation into the various VoIP (Voice Over Internet Protocol) voice communications methods that are available to the radio amateur and how they might be interfaced with the IRLP system is ongoing. Our findings to date indicate that an interface is possible. In fact a few owners of IRLP Nodes have successfully "cross-linked" various VoIP based systems with the IRLP. Despite these successes some concerns remain as to whether these methods of "cross-linking" would be suitable for an ARISS application. It is expected that much of this will be sorted out in the near future through planned teleconferences.

In the event that the IRLP is selected as the method of distribution for ARISS events, the Canadian team is planning the establishment of a dedicated reflector based in Halifax.

Arrangements have been made to provide delegates to the 2004 Nova Scotia Association of Science Teachers (NSAST) Conference information on the ARISS Program. It's hoped that this will help to inform educators of how they and their students might benefit by integrating not only ARISS but amateur radio in general into their course studies. In addition, the ARISS Canada team has been approached by the Editors of both the NSAST and Nova Scotia Teachers Association to submit an article describing ARISS for publication in their Journals. This article would result in the maximum amount of exposure to educators in Atlantic Canada. Work has already begun with these articles with expected publication in the first quarter of 2005.

While not yet officially released, newly designed ARISS "display panels" continue to evolve. It's expected that design changes will be made in mid-fall with an official presentation of the completed design being made shortly thereafter. In addition, information is being collected in support of an ARISS information brochure.

In an effort to increase public awareness of the ISS, local Broadcasters (both television and radio) are provided information from the ARISS Canada team on high elevation passes over Canada. The criteria for broadcast are that the pass is over 45 degrees elevation and that sky conditions are clear. Canada is blessed with fairly "dark skies" which make the ISS very bright and easy to pick out amongst the background stars. Efforts are also being made to provide this service to Parks Canada within Nova Scotia (on a trial basis) for the enjoyment of visitors to the parks.

Also, the ARISS Canada team has been in discussions with the Discovery Center located in Downtown Halifax regarding the inclusion of a permanent amateur radio station in their future expansion plans. Current plans include providing radio equipment and antennas, operators as well as contributing to the schedule of on-going "special events" that the Center offers to visitors. This is an obvious opportunity for ARISS and amateur radio.

Europe Team

The ARISS-Europe team have developed a terms of reference to define the roles and responsibilities of the various team members. As such, ARISS-Europe is defined as the common working group of the European societies involved in Amateur Radio operations on board of the International Space Station (ISS). The ARISS-Europe working group is a subgroup of the Amateur Radio International Space Station (ARISS) working group.

The objective of ARISS-Europe is:

- to plan, implement and co-ordinate amateur radio projects and activities on board of the International Space Station, in agreement with the ARISS teams worldwide
- to build flight and monitoring equipment for ISS amateur radio
- to carry out the technical and operational service for ISS amateur radio equipment
- to develop operating procedures for ISS amateur radio
- to plan future development of ISS amateur radio

- to promote ISS amateur radio in the educational field and toward the general public.

Membership of ARISS-Europe consists of all European astronauts wishing to perform amateur radio operations during their flights and owning a corresponding Amateur Radio license, European national societies, members of the International Amateur Radio Union, Region 1 (IARU R1), involved in planning, organising and co-ordinating Amateur Radio projects on board of the ISS, European AMSAT societies and other European societies, wishing to contribute and introduced by their national IARU R1 society.

According to the Memorandum of Understanding established in Noordwijk, the Netherlands on March 27, 2000 the founding members of ARISS-Europe are AMSAT-Belgium, AMSAT-France, AMSAT-Italy, ARI, DARC, REF-Union, RSGB and UBA. Other societies are invited to join ARISS-Europe. To date, these additional societies include AMSAT CT (Portugal), AMSAT UK, PZK (Poland), and REP (Portugal).

ARISS-Europe is administered by a board consisting of a chairman, a technical director, and two technical counselors. The members of the board are elected for two years terms and they can be re-elected. Gaston Bertels, ON4WF serves as the ARISS-Europe chairman.

ARISS Europe has organised three ARISS International meetings: ESTEC, March 2000, ESTEC, May 2001 and ESTEC, March 2004. The ARISS Europe team has also prepared and performed 30 ARISS School Contacts in the 2002-2004 period.

ARISS Europe has developed close cooperation with ESA, the European Space Agency. ESA's Directorate of Human Spaceflight has hosted ARISS International meetings at ESTEC, (European Space Research and Technology Centre), Noordwijk, The Netherlands. ESA's ISS Utilisation Strategy and Education Office has submitted a Memorandum of Understanding to ARISS, intended to set up every semester an educational event in one of the European ESA countries. All the primary schools of the country are invited to participate to a Space and Science oriented competition, especially dedicated to an ESA astronaut performing a Soyuz Mission. Winning classes participate, courtesy of ESA, to an overnight educational encounter, the ARISS School Contact with the ESA astronaut being the climax of the event. To date, these events have been accomplished with the following ESA astronauts: Frank De Winne, ON1DWN in November 2002, Pedro Duque, ED4ISS in October 2003 and Andre Kuipers, PI9ISS in April 2004.

ESA's Directorate of Human Spaceflight has accepted the principle of incorporating an ARISS station on board Columbus, the future European Space Laboratory ISS module. To this end, patch antennas would be fixed on Meteorite Debris Panels on the nadir (Earth) side of the module. The antennas would be designed for UHF, L- and S-Band. Danny Orban, ON4AOD is in charge of developing and building these antennas. Currently, the stumbling-block in the design development is the +100,000 Euro price ticket of the engineering work to be done by the Columbus contractors for fixing coaxial feedthroughs, coax cables and the antennas. ESA's ISS Utilisation Strategy and Education Office offers 50,000 Euro for the project. No other funding has yet been found, despite our intensive efforts.

Japan Team

The Japan Team have been quite engaged in school contacts and working with the hardware team on the Phase 2 radio systems. To date, eight ARISS school contacts have been successfully accomplished in Japan. These include: 1) Iruma Children Center JK1ZAM on 23 November 2001, 2) Kansai Ham Fest 8N3ISS on 02 August 2002, 3) Hirano Elementary School 8N3HES on 08 February 2003, 4) Higashi Kaneko Junior High 8N1ISS on 26 Mar 2003, 5) Kuise Elementary school

8N3ISS on 18 June 2003, 6) Ube Collage Junior High 8N4ISS on 20 September 2003, 7) Meizen High school 8N6A on 13 July 2004 and 8) Habikino social and welfare committee on 29 July 2004. For the Meizen contact, the high school students prepared and carried out this ARISS contact by themselves. See figure 9. The audience included 50 elementary school children, 20 junior high students, 250 high school students, 80 parents, 6 TV stations and 5 Newspapers. The educational benefits of the ARISS program have resulted in follow-on, noteworthy accolades for the schools and educators. For example, the Iruma Children Center Ham club, JK1ZAM received the Yomiuri Education Award on 16 July 2004 under the category of Local Social work and Education activity. Also, an ISS educational application Workshop was held on 08 August 2004 at Chiba University. Mr. Miki, ex-director of Hirano Elementary School made a speech regarding their ARISS school contact.

Meizen High School, Japan School Group Contact, 8N6A
Figure 9

The Japan team was also instrumental in the acquisition and modification of the Phase 2 radio systems. Working with the leaders in Kenwood and Yaesu, the ARISS team was able to swiftly acquire the Kenwood and Yaesu radios for flight use as well as crew training. Also, the Kenwood team in Japan was instrumental in providing technical support to modify the D700 radio to best support on-orbit operations.

<u>Russia Team</u>

The ARISS Russia team have made some substantial contributions to the ISS Ham radio program, especially in the hardware development and installation area. The ARISS Russia team is led by Sergey Samburov, RV3DR. At the first ARISS meeting in 1996, Sergey Samburov proposed the potential use of 4 antenna feedthroughs on the Service Module. This proposal is now realized through the four ARISS antennas, WA1-WA4 on the aft end of the Service Module. Also at this meeting, Mr. Samburov proposed the use of the FGB antennas as an interim solution while the Service Module antennas were being developed, qualified and installed. All three Extra-Vehicular Activities (EVAs or spacewalks) performed to install the ARISS antenna systems were led by the Russian team. As such, it was the responsibility of the ARISS Russian team to develop and validate the EVA procedures and then participate in the EVAs as a member of the Russian Mission Control, TSUP, team. The successful deployment and utilization of these ARISS antenna systems is the result of significant coordination of the EVA planning by the Russian team. See figure 10.

The Russia team is also responsible for coordinating the Ham Radio activity and training of tourists and ESA astronauts on the Soyuz flights to ISS. In addition to training ESA astronauts, Frank De Winne, Pedro Duque, and

WA4 Antenna being Deployed During EVA
Figure 10

Andre Kuipers for ISS ham radio support, the Russian team also trained USA tourist Dennis Tito and South African Tourist Mark Shuttleworth for their use of the ISS Ham radio equipment.

A satellite proposal is currently being submitted to the Project Selection and Use Committee to honor the 175th anniversary of the Bauman Moscow State Technical University. Most of the engineers at Energia went to this University. It is expected that the satellite would be launched on a Progress in September/October 2005. Because it is still in the proposal stage, the satellite specifics are still open to suggestions. The current plan is for the satellite to be attached to the side of ISS by EVA. For several months it will be operated as an attached ISS payload. Ultimately, it would be deployed overboard on a subsequent EVA where it would operate for several more months, until it re-entered the Earth's atmosphere. The baseline design of the satellite is a 23 cm cube. Some of the ideas for this satellite include a digital camera with S-band capability. In addition to the satellite payload being undefined, the Russian team proposing this satellite is looking for solar arrays and batteries to power the satellite for its expected lifetime.

USA Team

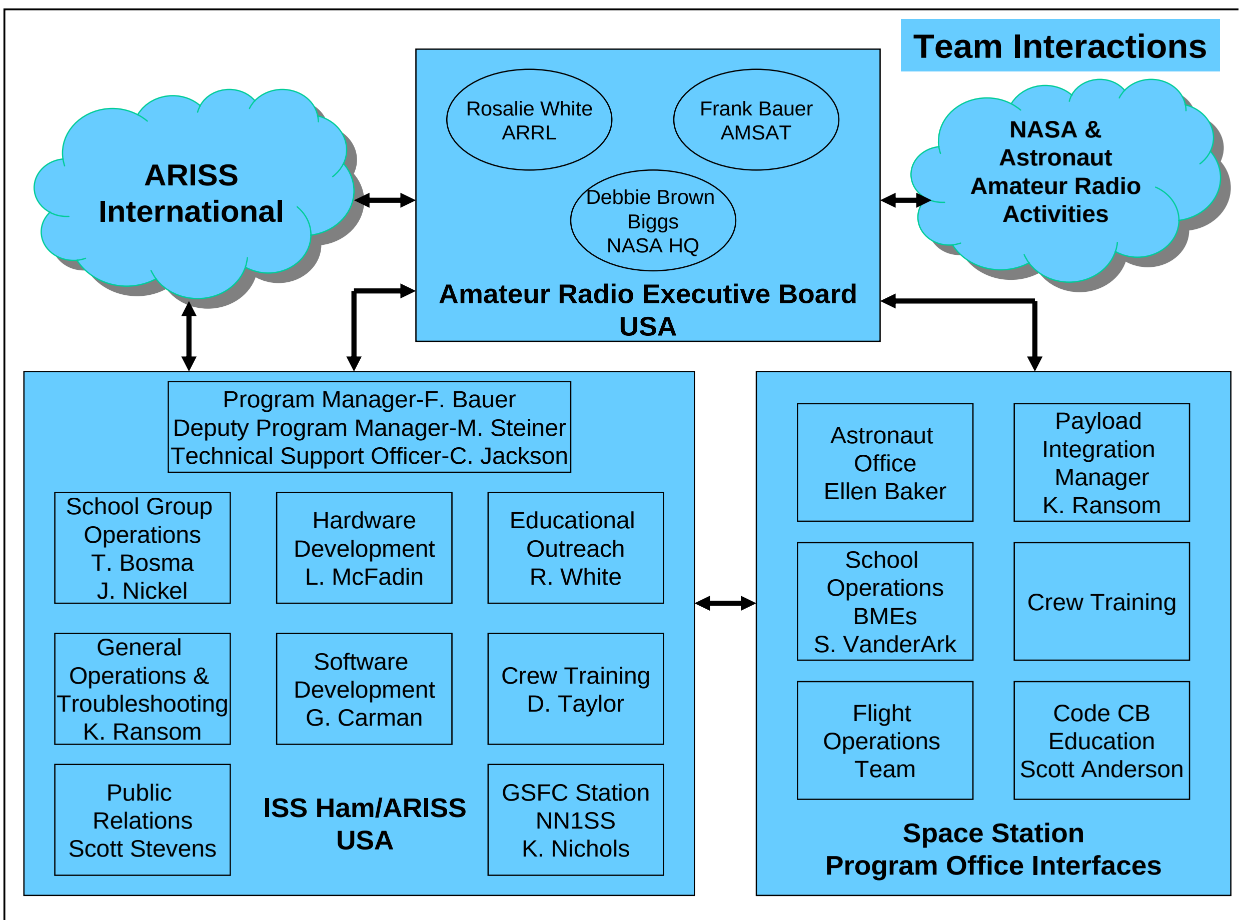
The ARISS USA team has undergone a substantial reorganization over the past year with new roles and responsibilities to better serve the ISS Ham program. Several new positions were modified to ensure that the USA has team backups. In addition, over the past year, several new leaders were added to the team and several others no longer support the team.

Some of the key personnel changes within NASA were that Debbie Brown-Biggs replaced Pam Mountjoy (SK) as the new NASA education outreach coordinator, Carlos Fontanot replaced Jeff Theall as the NASA ISS Program Office Liaison, and Kenneth Ransom, N5VHO, replaced Carolynn Conley, KD5JSO, as the ISS Ham technical manager at the NASA Johnson Space Center.

Key appointments within the ARISS USA team included the selection of Mark Steiner, K3MS as the ISS Ham USA Team Deputy Program Manager, Scott Stevens, N3ASA as the USA team's public relations lead, Mark Spencer, serves as an educational outreach specialist from the ARRL, Dave Taylor, W8AAS serves as the USA team's training coordinator, and Carol Jackson, from Orbital Sciences Corporation, serves as the technical support officer to the ISS Ham team. In addition, Rick Lindquist, N1RL, was named to the public relations committee. Rick regularly posts stories for all schools worldwide about their ARISS contacts after compiling this information from the school mentors.

The USA team responsibilities and interactions with the ISS program office and the ARISS international team is depicted in figure 11.

This new team structure has substantially improved the effectiveness of the team and the communications of key information to the general public and to NASA. For example, the team is now posting weekly reports on ARISS-related activities. These reports are disseminated to NASA, ARRL, AMSAT, the ARISS International team and are posted on the ARISS web site: www.rac.ca/ariss Also, by clearly defining the new roles and responsibilities, the USA team and the ARISS international partners



ARISS USA Team Interactions
Figure 11

now know who best to work with on the US side to accomplish a specific task. These organization changes have also lifted a significant burden off a few individuals so that more are sharing the load. For more details on this, refer to reference 7.

This past year, the US team worked with NASA to complete layout and printing of an ARISS lithograph. This photo montage, with a detailed description of the ARISS goals and mission printed on the back, will be given to students, educators and the general public during ARISS events and NASA outreach activities. See figure 12.

ARISS Lithograph
Figure 12

THE FUTURE

NASA is now embarked on a new exploration initiative---a focus on going to the Moon, Mars and beyond. There are strong expectations that, like ISS, the exploration initiative will be an international endeavor. The ARISS program has shown that volunteers, internationally, can come together and do great things. Together we inspire the next generation of explorers. Together we improve the well being of the ISS on-board crew. So it makes logical sense that ham radio, using the ARISS team as a model, should be an important part of this new exploration initiative. As such, the NASA Education Office has asked the ARISS team to to look at the role ARISS might play in the exploration initiative. We need to focus on specific strategies to bring ham radio into this initiative. This could include things such as a Mars payload, a repeater on the moon, a Mars telecom satellite, and hamsats at the Moon-Earth libration point. There will be many challenges, such as the long path length. But it will be the ingenuity of the ARISS team that will bring cost effective, volunteer solutions to the space agencies.

Our space agencies are starting their trek to the moon and Mars. It is our challenge and destiny to be an integral part of this challenge. The ARISS international delegates will discuss this at length at the October 2004 meeting in Arlington, Virginia. You are welcome to attend and participate.

CONCLUSIONS

2004 will be known as a year that the ARISS international team has made great strides in on-orbit hardware installation, new antennas, simultaneous operation on 2 bands, outstanding school group contacts, numerous voice contacts with hams and a robust on-board packet system. The ARISS international working group has proven itself as a highly motivated, results-oriented team that can provide significant positive benefits to the space agencies. As such, their current and past efforts have resulted in dialogue with NASA on the new exploration initiative to the moon and Mars. As the ham radio community has achieved permanence on the International Space Station through ARISS, it is our expectation that this ARISS team will evolve in the future to support the next ham radio challenges to places and planets unimagined.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the tremendous support, teamwork and volunteer spirit of the ARISS-International team as well as the technical, financial and administrative support of the ARISS member organizations--the AMSAT organizations and IARU organizations (ARRL in the USA). As a working group, ARISS acknowledges the pivotal importance of

these organizations if this program is to remain successful. Also special recognition is in order to the space agencies: NASA, Energia, ESA, JAXA & CSA. Together we are pioneering the new frontiers of amateur radio and educational outreach.

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For more information on the ARISS program, you are welcome to visit the ARISS web page at: http://www.rac.ca/ariss

REMEMBER, WE'RE PIONEERS!
The First School Contact with the International Space Station

Rita L. Wright, KC9CDL

Introduction

Those words came floating back to me as I watched the rocket being launched to Mercury. "Remember, Mrs. Wright, we're pioneers" said one of my eighth grade students as we stood on the stage at Burbank School, Burbank, Illinois shortly after our failed attempt to contact Comdr. Shepherd on the International Space Station. The date was December 19, 2000. Our gym was filled with students, parents, teachers, and dignitaries, along with various news media. It had been a long and sometimes wild ride up to that point. But I was soon to learn, it wasn't over yet!

How do you fill your time from application to contact?

Memories…I would have to go back to 1988 when I first attempted to involve my students in a NASA project. At that time we were trying to come up with a name for the new shuttle. Too bad the student who said "Endeavor" was out voted by his classmates. But we had fun investigating the history of various sailing ships and developing a board game about a lost treasure in Burbank.

It was shortly after that I heard about SAREX and the opportunities being offered for school children to communicate with astronauts on the Shuttle. I was so impressed with the program that I finally sent in my application in 1996. And so the wait began.

A waiting period can be boring as when you are sitting in a doctor's office watching mold grow on the fish in the fish tank. Then again, it can be an exciting learning and sharing time. I was once asked, what did I do during those years between application and contact? My answer was, I kept the dream alive. We did projects on space that involved designing and building spaceships of the future, art work showing the students ideas as to what they would see if they were in deep space, and research work involving discovering earth's problems and designing a solution.

We became involved with Argonne National Laboratory's Junior Solar Sprint. Students designed built and raced solar powered cars. We were lucky to race in the National Solar Sprint held in Washington D.C. where we placed 5th in the nation. We went on to win several 1st and 2nd places in Argonne's races over the years.

Eighth graders try to pick a name for the new shuttle. (1988)

Receiving a trophy at the Junior Solar Sprint National Championship race in D. C.

Speaking of racing, every year students had to design a car with as little friction as possible and one that was aerodynamically sound. Students raced these down a 5cm high ramp in the classroom. No motors, batteries, or flywheels were allowed. The students ran the entire race themselves. That included weighing and measuring the vehicles, measuring the distance traveled by the vehicle, and deciding upon a fair grading system.

Students participate in the Wheeled Vehicle race

Then my students became part of a project designed by Adler Planetarium. This project involved research, writing, designing, building, and artwork, but also involved children from different schools in the Chicagoland area sharing and critiquing each others projects using computer technology. One of the nicest things that came out of this project was the 30 robotic kits we received from Adler. That, of course, led to another fascinating project on robotics and the exploration of Mars.

From Newton's laws to the theory of flight to the building of rockets and looking into the Universe with help from Hubble photos. We researched, studied, wrote, designed, built and thoroughly enjoyed our adventure. We especially liked the trip to the space center in Woodstock, IL where students flew in a 737 simulator! Among all of that were trips to Argonne National Lab, Fermi Lab, and even appearing with Bill Kurtis on the show "Different Drummers".

Burbank's Robotics ready for Mars

And we waited. Time passed, students moved on to high school and then college. Teachers retired and a new group moved into their places. We waited for a Shuttle contact. Next it was Mir. I remember visiting Jerling Jr. High when they had their contact with Capt. Jerry Linenger (KC5HBR) on board the Mir space station. I kept pushing the dream, while we waited longer. My room was always filled with Hubble photos, NASA posters, and standing in the corner, was the life size trio from the movie Apollo 13.

The Apollo 13 movie crew

We get the call!

Finally in August of 2000 we received the call! Once school started, we hit the deck running. Our contact would be handled by Charles Sufana, AJ9N, with assistance from the Commonwealth Edison Employee Amateur Radio Society and the Lake County Amateur Radio Club. We were in good hands!

At our first teachers' meeting of the new school year, we set about explaining the opportunity and educational value afforded us and defining and describing the tasks we had to accomplish by December. We were met with school wide enthusiasm and cooperation. We were a team! We designated our school as Earth Station Burbank School, and the entire staff and students became our crew. Our very capable secretary, Colleen Sopkin, headed Mission Control.

We began by putting together a judging team composed of parents and teachers. Next, we sent out a call for students to audition for a position on our ISS team. Eighty students auditioned and from that group we selected 14. The students were from grades one through eight.

Our next task was to design a mission patch. Our entire school population participated in an art contest involving the creation of our Burbank School/ISS mission patch. This patch was to represent our school's contact with Commander William Shepherd, KD5GSL, on the International Space Station Alpha. After narrowing down the contestants to a manageable few, we held a general election. Burbank students selected our mission patch.

Burbank/ISS mission patch

Of course we had to have questions. Once again we sent out a call to all students asking them to write questions for our contact. Each teacher helped by evaluating all of the questions from her/his own class and then submitting the best. From that group, our Language Arts teachers helped select the questions our team would ask.

In the weeks and months that followed our initial notification, teachers and students in every classroom began working on a wide variety of "space topics". Our first graders

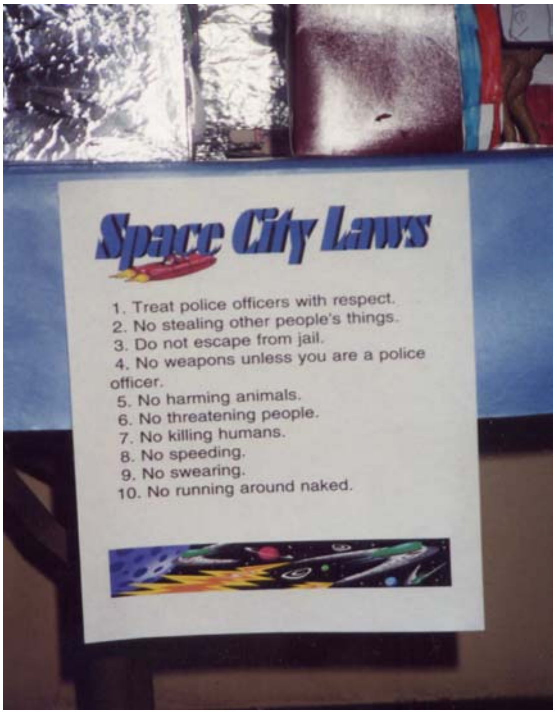

The Burbank/ISS team

created space people and space capsules. Their themes were "Flying High in Grade One" and "Adventures in Space". Their bulletin boards reflected the imagination and creativity only a first grader can have. They even had Winnie the Pooh in a space suit.

Second graders wrote stories about why they would like to be an astronaut and then made shuttles out of Pringles chip cans. They colored pictures of astronauts and put their own photos in the helmets. Their work decorated the hall outside their classroom.

Second graders shuttle to the Space Station

Fifth graders did one of the more spectacular displays. They created an entire Space City. It included cafes, laundromats, theaters, a water tower, shuttle station, and more. They even wrote laws for their Space City!



Fifth graders write laws for their Space City

Other students in middle grades created a Cosmic Café. Some of the items offered were Moon Popsicle's, Lift-off Lemonade, Space Station Steak, and Pluto Pudding. Their work also decorated the hall outside of their classroom.

Students in other classes were busy imagining they were astronauts working on the space station. They wrote their own biographies and included future missions they would like to be involved with. They tracked the ISS on the web and plotted on a map where the space station was every 45 minutes. They wrote time lines comparing our school day to the ISS. Some children wrote poems and made chalk drawings to accompany their poems.

To prepare for our ISS contact, the junior high students searched the web for information on the space station. After much discussion, the students created power point presentations. They made a ten-slide show, which consisted of one slide telling what the ISS is, one slide for the astronaut, and one for each cosmonaut on the ISS. The remaining slides contained information about space and the space station. Students presented this to our audience on the day of the contact. Our Special Education students in junior high did the power point work.

Students in a junior high Math class used the distance formula to calculate the distance to the ISS from Burbank School. This was done over a period of several days so those students would understand the idea that the station was moving constantly. In addition to distance, they considered time. They thought about their own future and where they would be in the year 2030. By then we will need a new ISS, so some of our future engineers designed and built the station of 2030. They also wrote a paper describing how and where it would be built. Our more artistic students decided to be scientists on the space station. They used their creativity and imagination to draw what they saw when they looked through a telescope while out in deep space. Our computer oriented students researched various Earth problems and developed plans for solving the problem using the technology on the space station.

All classes at all levels spent time using many of the websites that Charlie Sufana shared with us. As our students continued their search, one site led to another and their enthusiasm grew proportionately. If you were lucky enough to walk down the halls of Burbank School during those months you would hear students and teachers alike talking about space, shuttles, space stations, and what the latest information was about the ISS. You would be surprised at the variety of the topics, activities, and displays of work all centered around the ISS mission. Our school was vibrating with excitement and activity!

It's lovely weather in December. Time to put up the antennas!

December was soon upon us. The weather hit with a vengeance. Charlie Sufana and his team began setting up for the contact on December 10th. One of the biggest challenges had to do with setting up the antennas. The system had to be placed on top of a 2-story building. According to Charlie, they had to carry up 12 concrete blocks, five 35-pound sandbags, 4 sheets of plywood, 2 tripods, and 2 antennas with their associated azimuth and elevation rotors, control cable, and coaxial cable. All of this was done with about 10 inches of snow on the roof and temperatures at the start of the day at about 34 degrees and falling, wind-chills were about zero. Charlie said it took about 8 hours to do the job. During the following week and a half Burbank was hit with 2 full-blown blizzards and 4 additional snows. Temperatures were mostly in the 20's and usually had below zero wind-chill factors. Charlie would stop by the school occasionally to see if everything was still in one piece.

On December 11th, Charlie Sufana met with the ISS student team and their parents at Burbank School. It proved to be a very informative meeting. Mr. Sufana shared with us his experiences with other school contacts. He went on to describe how we would make the contact and what was expected of the students. There were many questions from students, parents, and teachers. He did a tremendous job in responding to them and explaining in detail that what we were about to do was an experiment. There were no guarantees as to the outcome.

Contact! Or, Houston, we have a problem!

Which brings me back to the beginning of this paper. Contact day was December 19th. Yes it snowed the previous night. After re-hooking all of the cables and getting everything in place on stage, his team was ready. Our students were nervous and excited as they stood on the stage looking out at our capacity filled auditorium. A state senator and our mayor were sitting in the front row. A TV station was filming and reporters were making the rounds. Along one wall the audience could watch a map showing the exact position of the space station as it neared our contact window. Suddenly, the exuberant audience hushed. At about 2:59pm CST Charlie Sufana gave our first call to NA1SS. Nothing, we called and called but we were never able to establish contact. After a second attempt an orbit later, it became obvious that today was a "no go". I'm not certain what went wrong. Mr. Sufana said it was a technical problem. I think I crashed further down than my student team members. I was so disappointed for all of them. But then, they spoke to me.

A disappointment, certainly. A defeat, never! After all, we are pioneers!

Alpha Juliet 9 November NA1SS we have you readable. Go ahead.

To our great surprise and delight, we were given another chance. December 21st was our new contact date. And yes, it snowed again! The temperature was about 13 degrees - what else? Once again our audience was filled to capacity. They did not give up on us… but the media? Where were they? We had reporters from a few local papers, but nothing more. Once again we used the computer program to show the audience where the space station was and once again the audience hushed when the station came within our contact area. Then at 20:28 UTC, Bill Shepherd and the ISS came up over the horizon for what turned out to be a near direct overhead pass! Charlie and his team made a connection within seconds and continued up to 20:39 UTC. Upon hearing Bill Shepherd's voice the audience let out a loud cheer! At that moment I was saying a

Charlie Sufana, AJ9N, makes the call

prayer of thanks! Soon Jessica Lehocky was at the mike asking the first question. We had 14 students and everyone had their turn at the mike. Jessica, in fact, was able to ask an additional question. Charlie had a chance to ask a question and then at the end of the contact, I was handed the mike. I simply thanked Commander Shepherd for taking his time to talk to the students of Burbank School. The entire team said "73" and it was over. What a ride! The audience cheered.

Alex Bandyk asks a question

Some time later our principal wrote the following insightful statement. "Rita Wright's letter (to Commander Shepherd) pretty much summed up what the school did to make the contact an interdisciplinary learning experience for all grades across a variety of academic concentrations that included math, science, reading, writing and art…Howard Gardner would be proud of us for engaging multiple intelligences. Making the contact such an experience is a must for others who follow because the transformation that took place was quite revolutionary. We came closer together as a school. Teachers who might otherwise have stayed in their own worlds didn't. They wanted to be part of the experience. Junior high students who ordinarily trudge their way to school day in and day out hardly taking time to say hello were walking into school talking about why they thought the experiment failed the first time. Parents pitched in and helped because they sensed how special the event was and because they genuinely wanted to be a part of it. The community at large read about us in the papers…The excitement of the event will fade in time but some of the changes will endure to our benefit."

A lot to show, a lot to share

Christmas 2000 is over and we're back at school. Time to kick back and relax? Hardly! The school was still vibrating with excitement. We had another power point put together depicting our contact with Commander Shepherd and the ISS. A video was edited and offered to students and their parents. We had a big demand for more t-shirts and buttons displaying our mission patch. All of us were collecting photos for a memory album. One of our parents began sewing a huge banner commemorating the contact. And we had many people to thank. We were getting ready for parent conferences and we certainly had a lot to show them and a lot to share.

It was an exciting time for all of us. Our ARISS contact awakened our community to the adventures and thrills found in space exploration. The contact sparked an interest in careers in space-related subjects and a sharper interest in the study of astronomy and the design and building of the tools of exploration. The event did bring this K-8 school together as no other event ever did. We participated in an interdisciplinary learning experience for all grades across a variety of academic concentrations. All of us here at Burbank School believe that this type of experience is a must for all other schools who participate in a contact. As our principal pointed out, the transformation that took place in our school was revolutionary. Students, teachers, parents and community worked together to make our contact a success.

We send an invitation to a friend

In February our school extended an invitation to Commander Shepherd to visit our school and community. He is a positive role model for all young people. It seems a lifetime ago when young people had many positive role models to look up to, to help guide them through some of life's trials and to teach them some basic life lessons. Like the lesson of perseverance. There were fliers like Lindbergh, Earhart, Glenn, and Yeager, ball players like DiMaggio and Ruth. Today young people have to search to find positive role models. Here at Burbank our students found a treasure in Commander William Shepherd, who took the time to talk to a group of junior high and elementary students in a small school in a small community. He touched their lives and opened their eyes to a whole New World a world of new opportunities and new career possibilities.

Commander Shepherd comes to Burbank School!

If we thought for a moment that the contact of December 21st was the only time that our students, teachers, parents and community would come together to accomplish a single goal, we were wrong. May rolled around and along with sunny skies and warm temperatures came another momentous phone call! Commander William Shepherd was coming to our school! The date of his arrival was to be May 10th!

Suddenly we were back in action! News items and invitations were immediately sent out. By now we had a teacher who handled all public relations. Meetings were held and tasks were divided among our team members. In no time we had our school organized and ready! Burbank's Mission control team was operating on all cylinders.

May 10th, Commander Shepherd walked into our building greeted by a line of teachers, staff, and parents. The halls were decorated with signs of welcome and a power point display was being shown on a screen in the foyer. A team of 8th grade students proudly exhibited their robotics and delivered an invitation to the Commander via one of their robotics. It was lunchtime and our parents had a surprise for Commander Shepherd. He was taken to the lunchroom where Burbank parents had worked tirelessly to decorate the room and then prepare a wonderful lunch for

Commander Shepherd greets the students at Burbank School

all. Shepherd was introduced to parents, staff, teachers, our ham radio team, and to three young ladies from the education department of Adler Planetarium.

After lunch it was on to the gym where about 500 students waited. After introductory ceremonies, everyone sat spellbound as Commander Shepherd described his days on the ISS. He even had a "home video" that showed Shepherd and the two cosmonauts at work on the ISS. This was the first showing of the video. Throughout his talk he

Commander Shepherd and Mrs. Wright

Cmdr. Shepherd signs autographs for the Burbank/ISS team

answered questions from students. What he really wanted to talk about was the kids and what was available to them if they just worked hard. "The first crew for the Mars mission already exists, "Shepherd told a rapt audience as he explained what big step was next for NASA. "We just don't know who they are yet. That's the problem. I'll leave it up to you to do what needs to be done to get there." Shepherd told them that the choices they make, even at an early age, could have consequences that ripple throughout their lives. Upon leaving the gym we headed out to the front of the school where a group of kindergarten through second grade students sat in the grass anxiously awaiting the astronaut from the space station. After sharing some thoughts with them, he answered some of their questions. He was surprised when our music teacher led them all in a song entitled "Mission Control". Then it was back to the gym where he graciously gave numerous autographs and

Cmdr. Shepherd meets the Ham Radio team

K-2 students sing "Mission Control" to Cmdr. Shepherd

posed for many pictures.

Our principal, Bob Mocek, later remarked that there probably is no such thing as a perfect day in a school, or anywhere else in this world, but that day (May 10th) was about as close as he could remember ever coming to that point. The harmonious spirit of cooperation throughout the building, the special efforts to show support for space exploration, more special efforts to decorate hallways and the gym, getting the best behavior out of our students all set the scene for an exceptional experience, one that held the power to inspire greatness.

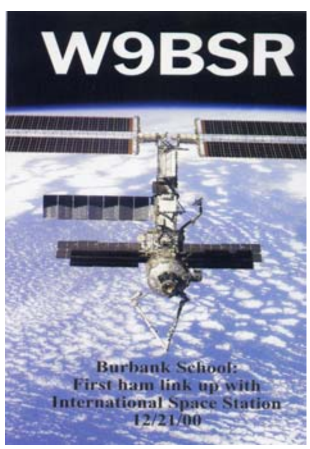
A perfect day!
Bob Mocek Principal

The antenna challenge and the birth of W9BSR

We were inspired enough to decide we wanted a Ham Radio Club in our school. Mr. Mocek and I enlisted the help of three other teachers and set out to put together a club.

Personally I felt confident that this would be an easy task to accomplish since our ARISS contact and the visit by Commander William Shepherd. I worked on getting my Technician's license and in the process was able to get help from Hamfesters Radio Club in guiding us in setting up a station. We needed, of course to get an antenna on our school. And that is when we hit a brick wall in the form of the building commissioner of the city of Burbank. Months went by. Mr. Mocek sent many requests to the building commissioner asking for an appointment. He ignored all of those requests. Not depending on any one avenue of attack, I wrote letters and/or spoke to our assistant superintendent, the superintendent, to the director of curriculum, and to the mayor of Burbank. I was about to give up when one day the Superintendent of our schools walked into my classroom while I was teaching, asked me a few questions about our proposed radio club and then promptly said OK! Great, but it still didn't happen until one summer's day I was called back to Illinois to speak to the school board during a general meeting. After explaining to them what we intended to do and how it would benefit the children of Burbank, the board gave their OK. Finally, our principal went to the mayor of Burbank and enlisted his help. The antennas went up! W9BSR was born!

We just ended the second year of our club. It has not been easy. I personally have a lot to learn about operating a station and getting students interested in getting licensed. I find that they enjoy learning Morse code and so we had them build their own keys and learn how to spell out their names. We started out our first year with about 8 members. The second year of operation we had 25. We have made some good contacts but it is becoming more and more apparent that we need more antenna power. I finally passed my code test and am now a General. So we are making progress.



W9BSR QSL card

Final thoughts

Our ARISS contact and subsequent visit by Commander Shepherd was like tossing a pebble into a stream. The ripple effects are still occurring and I suspect will continue to occur for a long time. We have a young staff and witnessing these events has inspired some to look for other interdisciplinary projects. They are beginning their dream. Many of our students are looking forward to careers associated with the space industry. As for myself, I keep looking up. I know we can put a bigger antenna on that school!

The antennas on Burbank School

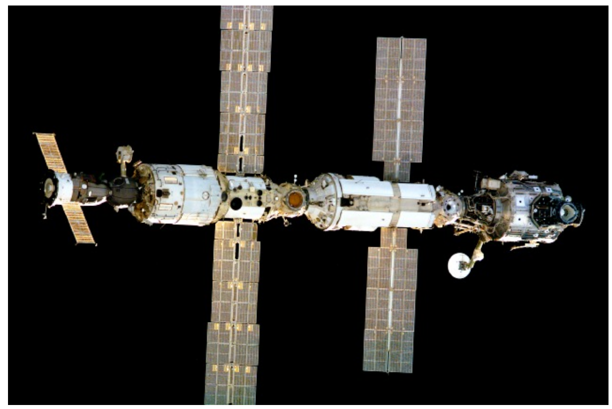
NA1SS, NA1SS, THIS IS KA7SKY CALLING…..

Carrie Cunningham, N7NFX
Sonoran Sky Elementary School, KA7SKY
Scottsdale, AZ 85260
Telephone: (480) 367-5820
http://epage.pvusd.k12.az.us/sonoransky/
Email: ccunningham@pvusd.k12.az.us

ABSTRACT

On Monday, April 5th, 2004, fourteen exuberant students at Sonoran Sky Elementary School in Scottsdale, Arizona had the unique privilege of a personal chat with an astronaut aboard the International Space Station (ISS).

This ARISS contact was the project of third grade teacher, Carrie Cunningham, N7NFX, an AMSAT member. Classroom representatives from grades 3rd-6th posed twenty-one questions via amateur radio to Expedition 8 astronaut Mike Foale, KB5UAC, as the ISS orbited over the school. ARISS (Amateur Radio on the International Space Station) is a program created through a partnership between NASA, ARRL and AMSAT.



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1. BACKGROUND

Sonoran Sky Elementary was built 10 years ago based on the theme of flight, with each grade level focusing on a particular aspect from bubbles and insects to aircraft and spacecraft. It is a K-6 school with approximately 500 students. The school has a classroom dedicated to the students' special projects relating to flight called the Flight Room.

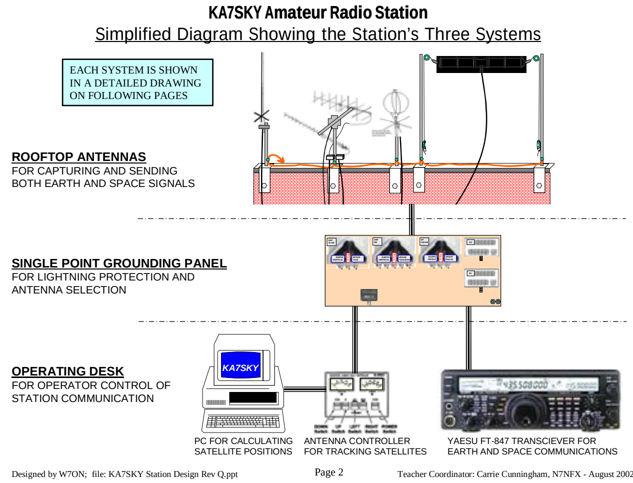
At Sonoran Sky there is an amateur radio station installed in the Flight Room having the appropriate call sign, KA7SKY. In addition to normal HF and VHF contacts with other hams, students have participated yearly in special events such as Kid's Day & JOTA.

It was the opportunity to talk with astronauts in flight that really sparked the students' imagination and was the motivation for installing the station in the Flight Room. But getting ready and being selected for a scheduled ARISS contact was not a quick or easy process. ARISS Schools are selected through a thorough and rigorous application process and generally must wait two to three years for their opportunity.

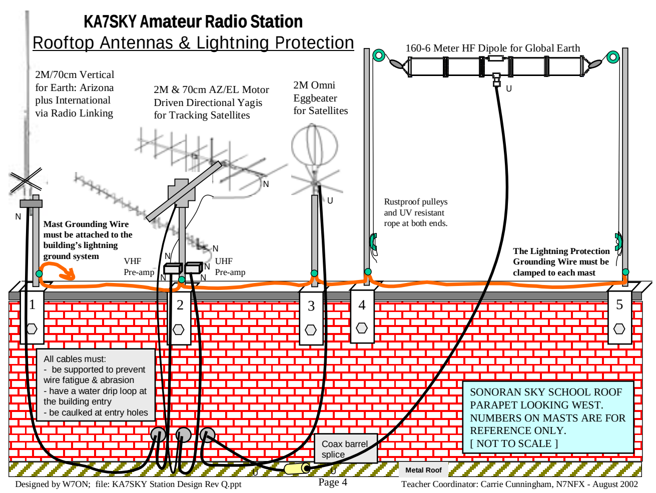
2. FUNDING

Teacher, Carrie Cunningham, N7NFX, submitted grant request applications to local community groups, organizations and businesses. One local community group, Scottsdale Charros, provided the initial funding of $5,000 by donation to Ms Cunningham. The Paradise Valley Unified School District provided much of the coax along with installation materials and labor. Yaesu and Ham Radio Outlet offered generous educational discounts on equipment and antennas. The Sonoran Sky PTO and others in the community donated the remaining needed funds.

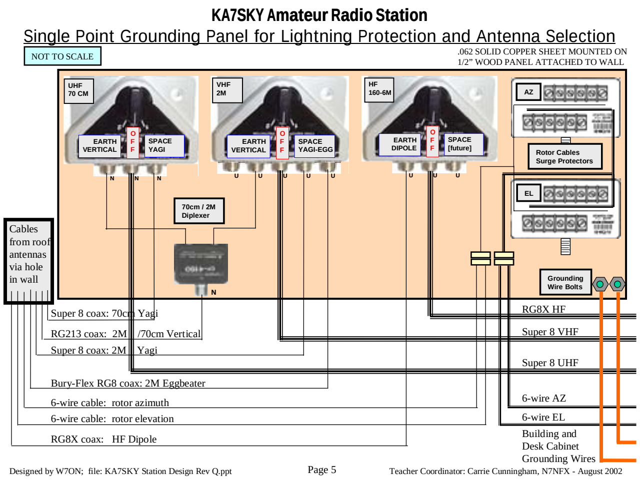
3. STATION DESIGN & EQUIPMENT



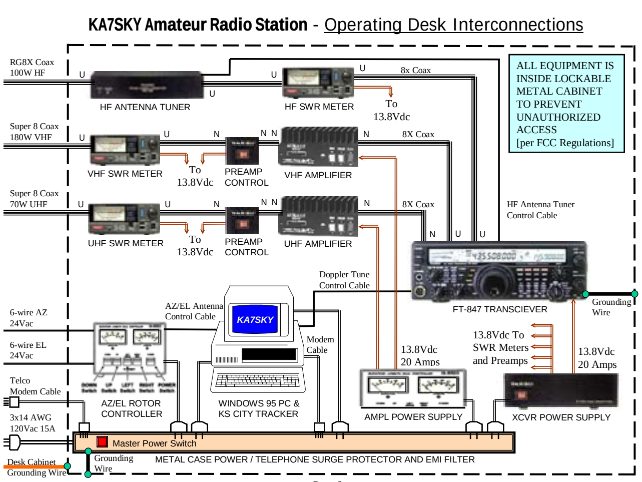
The station for KA7SKY was designed and installed by George Anderson, W7ON. The design consists of three basic systems: Rooftop Antennas, Single Point Grounding Panel, and the Operating Desk. A primary design objective was absolute safety for the children and others at the school while maximizing fun and easy operation.



The Rooftop Antennas are mounted on a brick parapet about 50 feet high on top of the school, two for space communication and two for terrestrial communications. The main antenna for the ARISS contact was the 2m & 70cm AZ/EL motor driven Yagis. The ARISS back-up antenna was the 2m Omni Eggbeater. For ongoing terrestrial use of the station by students, there is a 2m/70cm vertical as well as a 160-6m HF folded dipole. PVUSD employee, Paul Lintz, AA7AQ, spearheaded the design of the sturdy tilt-over mast and construction plus antenna installations.



The Single Point Grounding Panel is used as secondary lightning protection, station safety grounding and antenna selection. The copper panel connects via a large copper strap to a Ufer ground consisting of a steel building column embedded in the concrete slab foundation. Another large strap connects to the steel desktop station cabinet and equipment. Three gas discharge antenna switches select either an earth or space antenna for UHF, VHF or HF and routes the signal to the appropriate transceiver antenna connector. Surge protection is also provided on every line of the AZ/EL rotors.



The Operating Desk equipment consists of three parts: a transceiver with amplifiers and SWR bridges, a personal computer, and an AZ/EL antenna controller. For safety and in compliance with FCC Part 97, all Operating Desk equipment is housed inside a large grounded metal, lockable desktop cabinet.

Although the station normally has one Yaesu FT-847 transceiver, a second one was borrowed as a backup for the ARISS contact. It was identically programmed as a "hot" back-up including a separate power supply and antenna. A large speaker let everyone in the Flight Room clearly hear the receiver. A personal computer was used to track the ISS using NOVA software. Another software program and interface card, Kansas City Tracker, ran the antenna controller, which in turn guided the directional Yagis high on the roof as the ISS orbited above the school.

4. CLASSROOM INTEGRATION

Every student in the school wrote a question to be asked of astronaut, Mike Foale, KB5UAC. Each classroom in grades 3-6 had one representative chosen to read their question. In addition, each representative read a second question, one that was posed by a student in grades K-2.

Teachers were provided with books, posters, photographs and daily information about space exploration, the ISS and amateur radio. Students were provided with information about visible passes of the ISS to share with parents.

Many students had prior experience with amateur radio from previous visits to the KA7SKY station in the Flight Room.

5. ARISS CONTACT PREPARATIONS

Student representatives met with teacher Carrie Cunningham several times prior to the ARISS contact to practice reading their questions. Two days prior to the contact the students conducted a live run-through by cell phone with Frank Bauer, KA3HDO, International Chairman for ARISS. He provided valuable feedback to the students.

Invitations, handwritten by students, were sent to a variety of VIPs including the Governor of Arizona, the Mayor of Scottsdale, the Superintendent of Education, Paradise Valley School Board Members, and PTO Members.

A press release was sent out to TV and radio stations, newspapers, ARRL, and local media.

Arrangements were made to have the event documented by a videographer.

The PVUSD technology department arranged for a live video broadcast of the event throughout the school district.

Sonoran Sky's PTO designed and purchased a large KA7SKY banner for the Flight Room wall.

Bright aqua green KA7SKY shirts, in the school's colors, were given to each classroom representative to wear on the Big Day.

All station equipment and computer antenna tracking were tested, then retested, with the latest Keps and simulated passes. It was a good thing, because about a week before the contact the 2 meter amplifier literally smoked! A new one was rapidly shipped overnight and worked great.

6. THE BIG DAY!

Finally the big day came. On the morning of 05 April 2004 students, parents, press, and dignitaries in the Flight Room and listeners across the school district were filled with excited anticipation. Our antenna was pointing at the horizon, our clock was precisely synchronized with NASA's clock, NOVA was showing the approaching ISS footprint, and the media cameras were rolling. We were ready!

At 1837 UTC, it was our appointed time to attempt contact with Astronaut Mike Foale as the ISS began its pass over Scottsdale, Arizona. After two unanswered calls as the ISS began to peek above the horizon, the third call was greeted by the crackling voice of Mike Foale. In an instant he was loud and clear, and ready for our students' questions.

Photo 1 - Adam asking Mike about his daily chores

During the full 10 minute pass, twenty-one of the twenty-two prepared questions were successfully asked by students and answered by Mike Foale.

Here are the students' insightful questions:

1. Why were you chosen for Expedition 8?
2. What did it feel like when you launched?
3. What did you do to prepare for working with people from other countries?
4. Do you have to wear a space suit all the time?
5. If you were not an astronaut, what job would you have?
6. If you could keep one thing from your mission, what would it be?
7. What is your favorite part of being an astronaut?
8. Do stars and planets look different from the ISS than from Earth?
9. What experiments are you doing?
10. How does the G-force affect your weight during launch?
11. How did you become interested in being an astronaut?
12. What is the most interesting thing you have learned in space?
13. How long does it take the ISS to orbit the Earth and at what speed does it travel?
14. What medical equipment and training do you have if someone is sick or injured?
15. What did you eat for Thanksgiving?
16. What are the pros and cons of living in space for so long?
17. What are some of your daily chores?
18. Do you have to steer the ISS?
19. How do you know what to do while you are up there?
20. What is the temperature inside and outside the ISS
21. How do you wash your clothes?
22. What is the most amazing thing you have seen while in space?

Mike Foale surprised the students with many of his answers. He shared his personal experiences while inspiring them to pursue their studies and dreams.

Photo 2 - Mia asking Mike what job he would have if he were not an astronaut

Photo 3 - Taylor asking Mike about the pros and cons of living in space for so long

Photo 4 - Rylee asking Mike about experiments being conducted on the ISS

7. MEDIA RELATIONS

Photo 5 - Bailey being interviewed by media as Nicholas looks on

The ARISS contact was well attended by a multitude of VIP's including the Mayor of Scottsdale and media personnel. Local representatives from FOX, CNN, NBC, the Arizona Republic, and the Scottsdale Tribune were in attendance. The TV and press coverage given by each of these media was phenomenal. In one case the event was used to promo the TV newscast. Newspapers ran various stories for several days. And, the full story was recently featured in World Radio.

Since the ARISS contact, Ms. Cunningham has given invited presentations to three local Amateur Radio Clubs and at the ARRL Southwest Division Convention.

8. THE FUTURE

Sonoran Sky Elementary School is beginning their very own after school Amateur Radio Club. Sparked by the excitement of the ARISS contact, many students have shown an interested in pursuing their own Amateur Radio experience.

There will be continued linking of the student experience to their classroom instruction for cultural sharing, geography, math, science and the general excitement space communication brings to their imagination. The students getting to know and use AMSAT's new Echo AO-51 satellite will be one of the first activities of our school's new Amateur Radio Club.

9. ACKNOWLEDGEMENTS

Our school's ARISS contact was the culmination of many people and organizations working toward the common goal of enriching our children's education. I would like to acknowledge the tremendous support of the Paradise Valley Unified School District, Sonoran Sky PTO, Scottsdale Charros, Yaesu, and Ham Radio Outlet.

10. DEDICATION

Photo 6 - George Anderson, W7ON, being interviewed about the successful ARISS contact

This paper is dedicated to my father George Anderson, W7ON, AMSAT Life Member, for the countless hours he spent making this ARISS contact possible for my students and myself. His expertise in the field of Amateur Radio and his ongoing dedication to the education of our youth is truly priceless and inspirational.

Voice/IP Communications for the ARISS Program

James Stefano, W2COP

Systems Administrator, Electrical Engineering
Rochester Institute of Technology
79 Lomb Memorial Dr., Rochester, NY 14623
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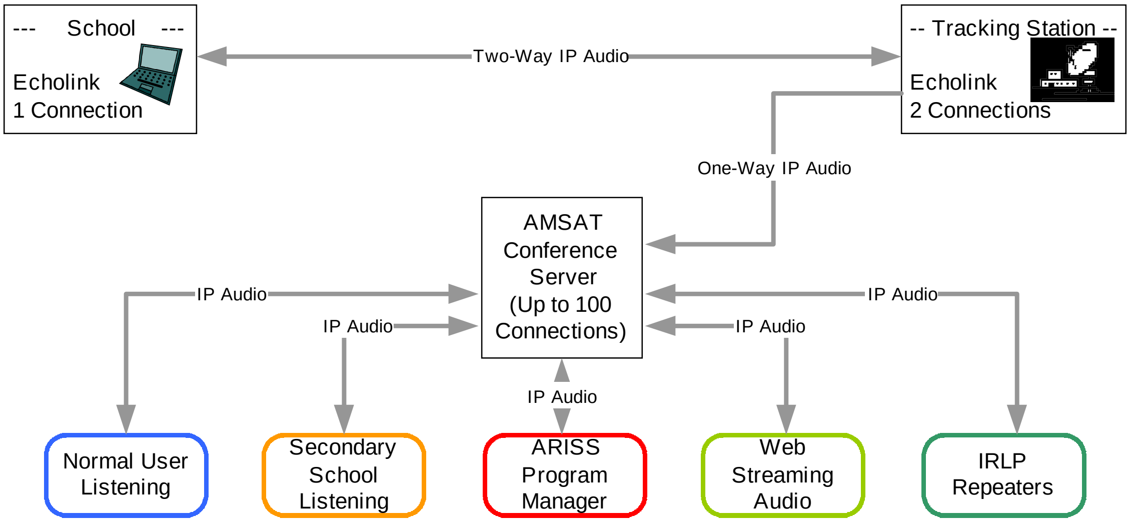
Voice over IP radio gateways have brought many new capabilities to Amateur Radio operation in the past 5 years. One application that would be extremely beneficial to the ARISS program is the direct connection between a school and a remote AMSAT ground station tracking the ISS, using nothing more than a notebook computer from the classroom.

Currently, half the schools wishing to participate in ARISS contacts do not have a local satellite ground tracking station available to enable a direct ARISS contact. Even when available, some schools may not have an appropriate location for the satellite tracking antennas in proximity to the staging area. An alternative to a direct ARISS contact for only 27% of the schools has been a telebridge phone patch. In a telebridge conference the visibility and excitement of amateur radio is lost and amateur radio equipment and operators are not visible. It is desirable to have a stronger amateur radio presence for those situations where a direct contact is not possible. It is also desirable to expose students to more current and interesting technologies that are relevant to their future.

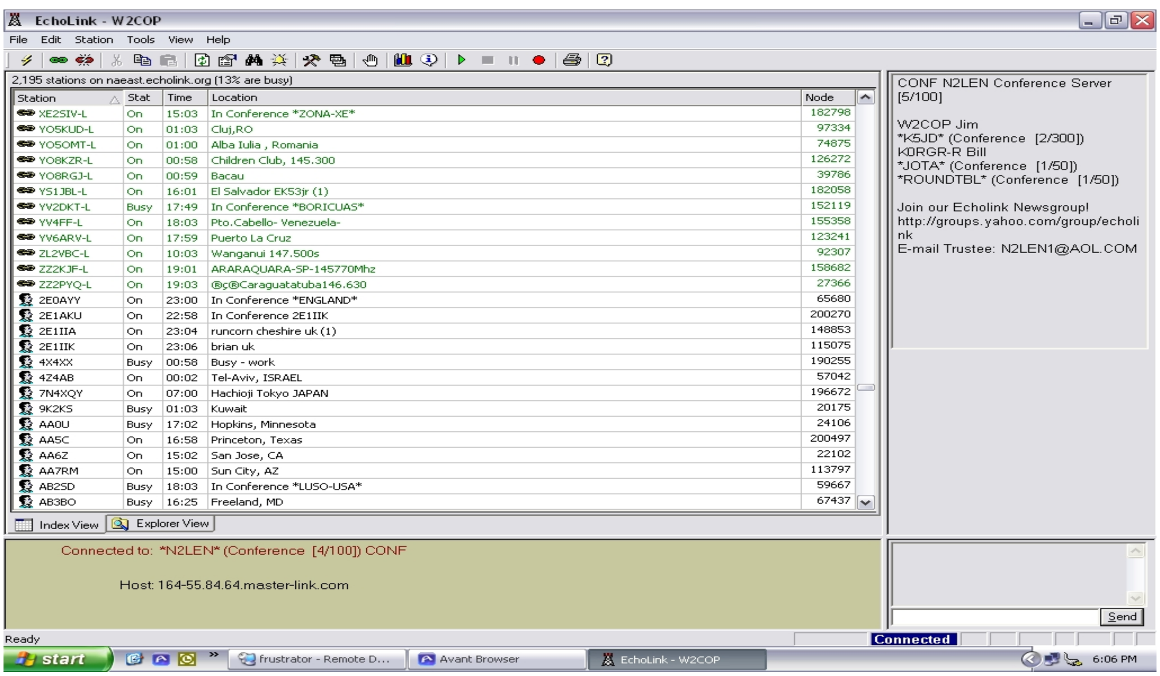
These scenarios can be easily overcome by a simple Voice/IP connection made from the school to any one of a number of existing Amateur Radio satellite-tracking ground stations throughout the world. A notebook PC at the school is all that is required by a ham operator at that location. Similarly at the other end all that is required is a PC connected to a radio tracking the ISS. The advantage of using a notebook PC at the school is portability, they are readily configurable, and can be easily connected to a video projector to present visuals such as tracking software and flight information allowing all students to see what is taking place. The PC also maintains positive PTT control for the duration of the event. Taking advantage of existing satellite tracking stations throughout the world would also allow for greater flexibility for the ARISS program administrator who schedules these contacts. Most importantly the quality of the communications is conveyed in a digital format over the Internet, ensuring the reliability and improving the voice quality of that long awaited contact between the students and the astronauts.

There are several free Amateur Radio Voice/IP software applications available today that are extremely reliable. The most popular application is Echolink, which can be downloaded from http://www.echolink.org. Echolink would be run in the single user mode on the notebook PC. At a remote ground station it would run in the sysop mode on a PC connected to a VHF radio tracking the ISS. Echolink does not require a lot of bandwidth and can be used over a local dial-up or direct Ethernet connection. Another advantage of this software is that the connection can also be tied to an Echolink Conference Server allowing any number of non-participating users or ARISS program administrators to monitor the event right from their PCs. Other Voice/IP gateways such as web streaming audio and IRLP can also be brought in as needed. This scenario can be viewed in the following diagram, outlining a conventional single school contact.



The capability also exists to allow multiple schools to participate in a single event and to extend the contact window to the ISS by using multiple ground stations conferenced together. Two-way audio paths would only be allowed for direct participants. Indirect participant's upstream audio would be muted. This is commonly done on large Echolink directed nets.

In the following Echolink screen shot you will see stations linked to remote base radios listed as –L in green lettering. The stations listed in black are single users. You will also see several Conference Servers chained together in the right hand pane, allowing more users.



THIS VOICE/IP CONCEPT USING ECHOLINK WAS TRIED DURING A SEPTEMBER 2003 ARISS CONTACT FROM A SCHOOL IN WEBSTER, NY, WITH MODERATOR PETER FOURNIA – W2SKY. THE TRACKING WAS DONE IN THE BACKGROUND IN THE RECEIVE-ONLY MODE DURING THE EVENT BY FIVE GROUND STATIONS FROM COAST-TO-COAST TO TEST RELIABILITY. COMMUNICATION FROM THE ISS WAS ACTUALLY EXTENDED TO A 27 MINUTE WINDOW. THIS EXPERIMENT has debugged many considerations for applying the technology to future ARISS contacts. The desired goal is to enhance the Amateur Radio experience in the school and to enable every school to have an equal chance to participate in the ARISS program using this technology and applied concept.

Software Defined Radios – The Future is Now

By:
Bob McGwier, N4HY
Gerald Youngblood, AC5OG
Eric Wachsmann, FlexRadio Systems Software Engineer

Background

A Software Defined Radio (SDR) is a radio in which all modulation and demodulation functions are defined, and therefore configurable, through software. This creates tremendous flexibility to improve and adapt the capabilities of the radio over time without changing the hardware. The potential for amateur radio experimentation is virtually limitless in terms of performance improvement and the introduction of new operating modes.

The idea for the SDR-1000 Software Defined Radio was formed about six years ago while observing PSK31 running on a PC and sound card. Effectively, PSK31 uses the sound card and PC as a Digital Signal Processor (DSP) to perform modulation and demodulation of a digital signal. It became clear that a phasing-type transceiver could be built using the stereo inputs of the sound card for the in-phase (I) and quadrature (Q) signals. Four years and many hundreds of hours of study resulted a working transceiver that was described in the four part *QEX* series, "A Software Defined Radio for the Masses[1]." Interest generated by the articles was so strong that a decision was made to begin shipping the radio as a product in April of 2003. The articles, as well as complete information on the SDR-1000, are available on the FlexRadio Systems website at www.flex-radio.com.

The SDR-1000 ships with open source software written in Visual Basic 6, allowing users to modify and improve the code. Hams from all over the world have contributed to the enhancement of the SDRConsole code including both user interface improvements and advanced DSP code. Furthermore, a number of colleges and universities are using the SDR-1000 as part of their engineering curriculum.

The SDR-1000 continues to evolve based on input from the amateur radio community. This paper will focus on hardware and software enhancements that are in process and will be made available in the first half of 2004. The writing is a combined effort by Bob McGwier, N4HY, Gerald Youngblood, AC5OG, and Eric Wachsmann, FlexRadio software engineer.

SDR-1000 and SDRConsole Architecture – Gerald

As stated earlier, the SDR-1000 was described in some detail in the *QEX* series (endnote 1). The initial product consisted of a three-board set as seen in Figure 1. Recently, the enclosure shown in Figure 2 was added to allow a number of enhancement products to be added to the radio.

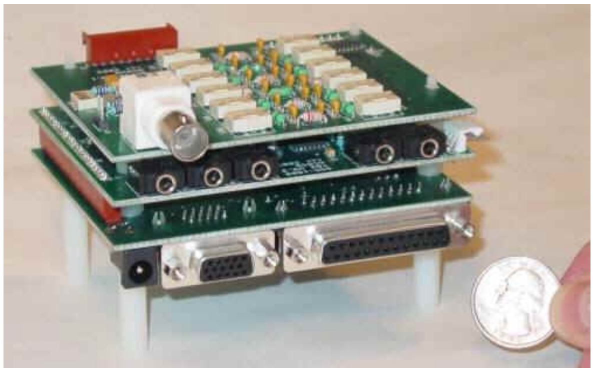


Figure 1 – SDR-1000 Board Set

Figure 2 – SDR-1000 Enclosure

The SDR-1000 incorporates a novel Quadrature Sampling Detector (QSD), which offers exceptional dynamic range as well as performing the function of a high Q tracking filter. Figure 3 illustrates a simplified version of the detector. It may be thought of as a rotary switch that rotates at the carrier frequency rate. Each of the four capacitors sample (or integrate) the RF signal for 25% of the carrier period at intervals of 0°, 90°, 180°, and 270°. By differentially summing the 0° and 180° signals and the 90° and 270° signals, we can generate the in-phase (I) and quadrature (Q) signals respectively. With I and Q, we can demodulate or modulate any type of signal. Not only is the carrier mixed to DC by the sampling process, the RC network formed by the antenna impedance and the sampling capacitors forms a commutating filter with a bandwidth of 1/(pi*n*R*C) (where n is equal to the number of sampling capacitors).

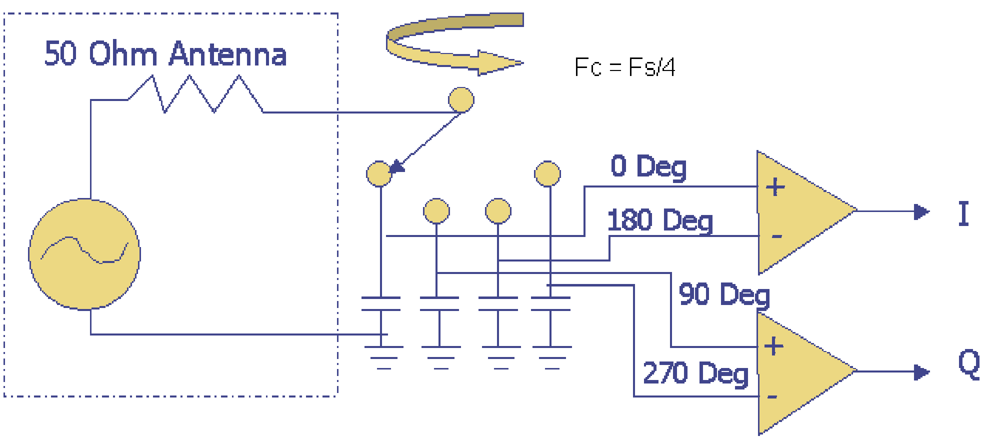


Figure 3 – Single Balanced Quadrature Sampling Detector (QSD)

The SDR-1000 uses a dual 4:1 MUX/DEMUX in a double-balanced QSD circuit that offers a 6dB improvement in large signal handling over the single balanced circuit shown in Figure 3. Using 5V parts, the QSD is capable of handling 10Vpp differential signals before going into compression. The double-balanced circuit also helps to suppress even-order harmonics. This large-signal handling capability allows more flexibility in gain distribution that is traditionally found in direct conversion systems. Gain can be placed in front of the QSD to improve the noise figure and reduce local oscillator radiation without significantly compromising large-signal handling capability.

While analog radios are properly characterized for distortion using third order (IP3) dynamic range, SDRs may not be adequately characterized in the same way. With a properly designed SDR, the radio will be highly linear up to the point of Analog to Digital Converter (ADC) full-scale saturation. When saturation is reached, the signal will be completely distorted and unusable. This means that third order products may not be detectable right up to about 1-2dB under ADC saturation. The full-scale voltage limit of the ADC will therefore set the maximum signal without distortion in a SDR. This may be as high as 4-5Vpp on some converters.

Because the SDR-1000 uses an offset baseband IF of 11KHz, it is possible to avoid many of the issues that have traditionally plagued direct conversion receivers. Above 1KHz, most of the 1/f noise, AC hum, and microphonic noise goes away and the dynamic range of the sound card greatly increases. Once the quantizing level of the ADC has been reached due to the total noise voltage in the filter bandwidth, it can actually resolve signals over a wider dynamic range than the 6dB per bit indicated by the converters resolution. For example, a high quality 16-bit converter has been measured to have a two tone, third order dynamic range of 90dB (RFE installed). Therefore, the dynamic range of the ADC will have the greatest effect on the dynamic range of the receiver in most configurations. Figure 4 illustrates two tone dynamic range using –20dBm tones at 1KHz spacing. Spurs may be seen approximately 95dB down from the fundamental tones.

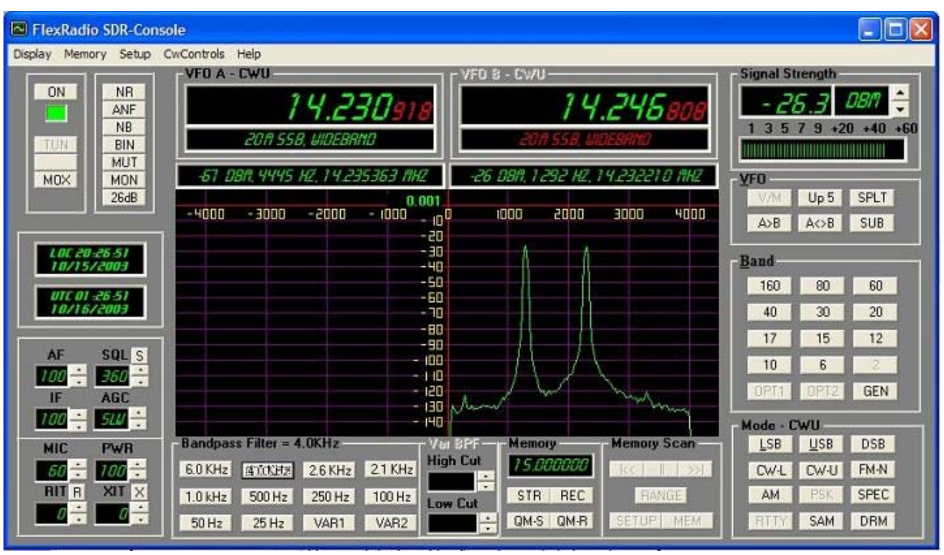


Figure 4 – Two Tone IMD Dynamic Range

The wide linear range of audio ADCs found in the better sound cards allows for some very interesting capabilities. First, it eliminates the need for analog AGC. This means that AGC can be performed digitally after the final filter, thereby greatly reducing the effects of strong adjacent signals. The effect is to remove the “pumping” of the AGC that is characteristic of analog AGC systems.

Further, by using double precision floating point values and fast convolution filtering in the frequency domain, we can achieve bandpass filter shape factors that exceed 1.05:1 (500Hz BW). A 2048-tap filter with 4096-bin FFT achieves stop band attenuation in excess of 120dB within 300 Hz of the 3dB cutoff frequency. Figures 5 and 6 demonstrate the frequency response characteristics of the 500Hz and 2.7KHz filters respectively. A description of the digital AGC system and fast convolution filters is provided in Part 3 of the *QEX* article series.

Figure 5 – 500Hz Filter

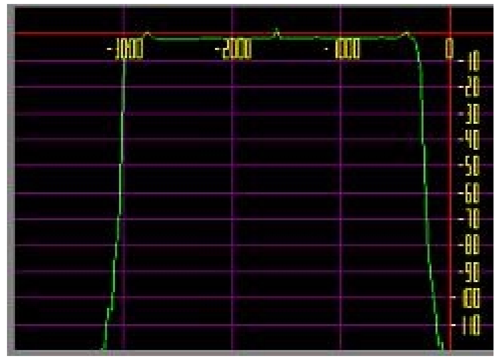


Figure 6 – 2.7KHz Filter

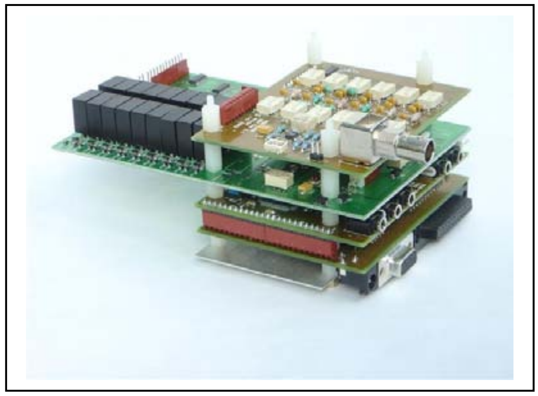
On the modulation side, we can also use the magic of DSP to do feed-forward compression of the audio signal to greatly improve average transmitted power without excessive distortion. The SDR-1000 uses a method of feed-forward speech compression wherein the gain is turned down quickly when the input signal is too large, but increases slowly if the signal drops off or ceases. This prevents the gain from increasing quickly between words. The net effect is similar to that of a good RF clipper without injecting distortion. VK6APH contributed the SDRConsole code for the speech compressor based on the algorithm in Marvin E. Frerking's book, "Digital Signal Processing in Communications Systems[2]."

Another capability of the SDR-1000 is that it also functions as a high dynamic range spectrum analyzer. The SDRConsole, as seen in Figure 4 above, may be calibrated with a signal generator so that its spectrum display and digital readouts display the actual signal levels over a frequency range equal to just under the sampling rate of the sound card (typically 40KHz). Use of quadrature signals doubles the effective sampling rate over that of a single channel. As stated earlier, signals may be measured over a range of 120dB using a high quality sound card.

SDR-1000 Hardware Enhancements

A number of new hardware add-on products extend the radio's capabilities and performance. Now shipping are a new RF Expansion board (RFE) and the Down East Microwave 2M transverter IF for the SDR-1000. A 100W PEP integrated linear amplifier and an automatic antenna-tuning unit will be added in the fall.

The SDR-1000 was designed for general coverage reception up to 65MHz. This requires compromise on the input band pass filters to minimize system cost. The RFE board adds 5th order low pass filters for each amateur band to enhance third harmonic rejection. Further, it adds a noise figure preamplifier ahead of the QSD that allows a 3dB receiver noise figure. With the preamplifier added, the gain behind the QSD may be decreased by the same amount as that added on the front end. This will not only improve the NF of the radio, but will also reduce local oscillator spur amplification.



The RFE also includes an experimental impulse generator that will allow for computation of the QSD and sound card impulse response. The impulse response will then be used to dynamically equalize the I and Q signals in order to maximize image rejection.

Table 1 provides dynamic range measurements that were performed on the SDR-1000 with RFE and using an M-Audio Audiophile USB in 16-bit mode. Two HP 8640B signal generators were combined through 16dB pads with a Mini-Circuits ZFSC-2-1-12 combiner. Port to port isolation was measured to be 80dB with a HP 8568A spectrum analyzer. Four different dynamic range options are possible using the 10dB attenuator and instrumentation amplifier (INA) gain settings. Third order dynamic range (or SFDR) is in the 88-90 dB range for all combinations. The noise figure is only 3dB for the entire receiver in the highest gain setting. Typically, the lower gain settings are preferable for all bands below 12M. All measurements are performed in a 500Hz bandwidth.

Gain Setting	NF	MDS	SFDR	Full Scale - MDS
0dB ATT, 26dB INA	3	-141	90	95
10dB ATT, 26dB INA	14	-130	89	94
0dB ATT, 0dB INA	17	-127	88	107
10dB ATT, 0dB INA	26	-118	89	108

Table 1 – Dynamic Range Experiments

The RFE sandwiches between the existing BPF and TRX boards so that the BPF provides front end filtering for the low noise preamp. The 1W PEP driver amplifier (OPA2674) will move to the RFE board as well so that the existing BPF board will filter its output. The RFE will also provide control signals for the 2M microwave transverter IF, 100W linear amplifier and automatic antenna tuning unit described below.

Provision has been made in the enclosure design to incorporate a Down East Microwave DEMI144-28ECK low-power transverter kit as seen in Figure 7. It is designed to function as an IF for microwave transverters. In receive; it uses a high-level double-balanced mixer (+17dBm) and a three chamber helical filter. It provides 50-100mW of linear output in transmit mode. TR control and RF interface is provided through a single coax connection to the RFE board.

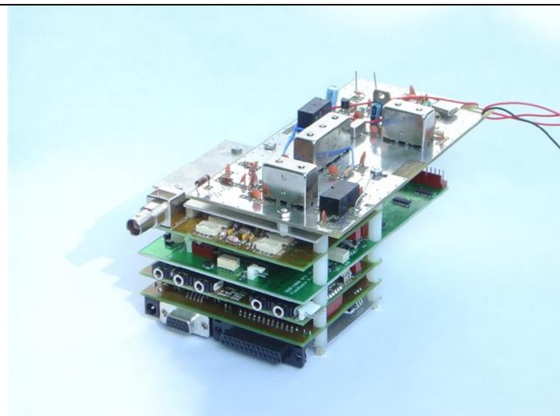


Figure 7 – DEMI144-28ECK 2M Transverter IF

The SDR-1000 has the provision to add an external oscillator for the AD9854 DDS. The unit ships with a 200MHz, low-jitter oscillator. Weak signal and microwave operation often dictates precise frequency control, including GPS locked references. The SDR-1000 can easily be converted to a 10MHz reference by cabling a 10MHz source to the oscillator connector, moving two pin jumpers, and setting the DDS PLL multiplier.

A 100W PEP linear amplifier with low pass filters is being designed to fit in the SDR-1000 enclosure. The TR relay and filter relays will be controlled from the RFE board. Further details are not available at the time of this writing.

To round out the SDR-1000 accessories, a third party automatic antenna tuner will be integrated into the packaging. Once again, control will be provided from the RFE board.

SDR Console Software – Continued Growth

One of the nicest parts of this entire project has been the tremendous outpouring of software, ideas, new concepts, and contributed software by many different individuals. Each software author's contribution is prominently listed in the source of the software which is released GPL. There are now at least three functioning console packages in addition to that offered by Flex-Radio and more are on the way. Home brewing of add-ons to radios is alive and well in this project and embodied primarily in the software.

Noise Blanking and Pulse Removal

One of the banes of narrow band receivers are the effects of pulse noise. The worst offenders are typically semi-periodic pulse trains such as line or alternator noise; but we would also like to reduce the impact of single large pulses like switch openings and closings. One day, while listening to the broadcast band and a horrible set of pulses arriving in a pulse train, we attempted a truly simple noise blanker. If a signal value rose too far above the Root Means Squared (RMS) value, it was blanked, or set to zero. The effects were immediate and surprising. We then analyzed many noise blanking circuits and found they did little more than this, but in many cases, required a pulse train to work properly. This pulse removal usually operates on the wider signal inside the “roofing filter” while the pulse is still narrow. Then when the blanked pulse sample is passed through the filters that follow, the filter acts like an interpolator to smooth over the hole you have made in the signal.

In the lab, a weak signal was dialed up on 40 meters. It was a South American station that was just above the noise floor. At the antenna, 4V pulses were added! The noise blanker was engaged and the weak signal rose out of the hash and was completely readable. It is clear we are able to not only duplicate the typical noise blanker, but also in some ways exceed its performance. But there is no reason to stop there. We can afford to do a more complex algorithm than this since we do not have to pay for the associated hardware. Our only cost is the time to code the algorithm.

There are two promising algorithms we are exploring. We have developed one such algorithm and it is now included in the SDRConsole. Image processing algorithms have often developed rank order statistics in an attempt to look in the neighborhood of a pixel to see if "it fit" into the overall picture. If it does not “fit in”, then it is declared to be speckle noise. Its value in the image is replaced by a combination of the surrounding pixels that more fairly represents the area of the offending pixel. The technique works wonders in the removal of speckle noise from the image.

We wondered how well this might apply to the removal of pulse noise in one-dimensional signals such as ours. In fact, we found it had already been investigated. Sanjit Mitra of the University of California Santa Barbara wrote a paper in which he described this exact algorithm. In his paper, he explains how to calculate the statistics and performs several tests. He called it the Signal Dependent Rank Order Mean Noise Reduction algorithm. How it works is really straightforward. We will consider our digitally sampled signal in groups of five adjacent samples

$$X(t)=[x(t-2),x(t-2),x(t),x(t+1),x(t+2)]$$

We will take every sample but the middle one and sort them into an increasing value array.

$$W(t)=[w(0),w(1),w(2),w(3)]$$

We will compute from this ranked ordering, the rank order mean. This simply means we will take the middle two values and average them.

$$\mu(t) =[w(1)+w(2)]*0.5$$

We will compare the signal at time t, x(t), with this rank order mean and then to its rank ordered neighbors. We will set two thresholds. We will test to see if it departs from the behavior of its nearest neighbors at one threshold. We compare it again to its farthest neighbors in our four long rank order vector against a larger threshold. If it does depart from the behavior of its neighbors more than these threshold values, we will replace the signal with the rank order mean $\mu(t)$. This has an immediate impact on the processed signal versus the blanked signal. We do not just zero out the signal and pray the filtering which follows will fill in the hole adequately. Anyone who has listened to a receiver with an activated noise blanker adjacent to loud signals knows how the AGC and cut-off action of the noise blanker can be modulated by these strong signals. In the SDROM case, we replace the offending value with a value that is determined from a smoothing of the surrounding values.

Initial Test Results of SDROM

In support of the picture-is-worth-a-thousand-words argument, we include the following in Figure 8 from our Matlab experiments when developing the algorithm. We have four signals in this graph. The blue trace (top) is the incoming simulated signal. It was the test signal during our development. It is a two-tone signal plus noise. We have added pulses to the signal. We have zoomed into a region of 160 samples around a pulse. The red trace (second from top) is the raw signal without pulses. The green trace (third from top) is what a traditional noise blanker would do and the black trace (bottom) is the SDROM output.

The differences are subtle to the eye, but profound to the ear. The large spike is clearly evident. We chose this spike in order to more clearly demonstrate the differences in the algorithms because it occurred near a peak voltage in the signal. At sample 62, you will notice that the blanker has just zeroed the signal, which causes a sharp edge, ***and the attendant clicks*** (just like key clicks) that accompany such an occurrence. The final black trace, the SDROM pulse noise canceller, has replaced the pulse with a smoothed version of the signal without the pulse. There will be no key click-like phenomenon with this approach. A traditional noise blanker incorporates these sharp edges that spray energy all over the spectrum, just like a key click.

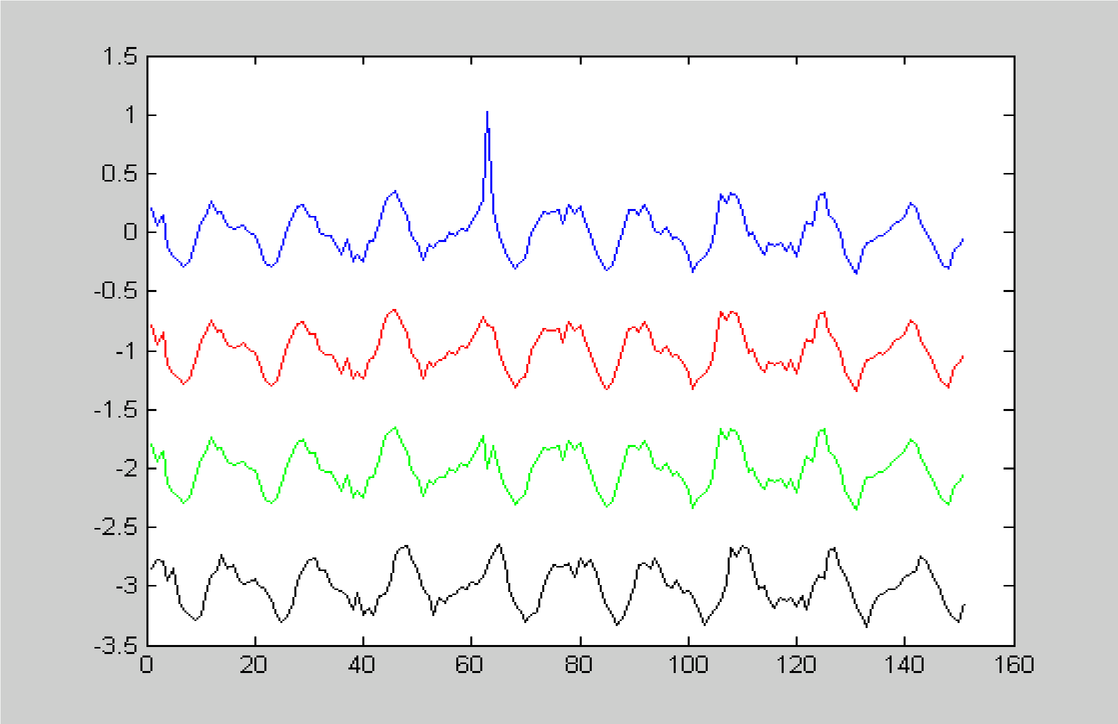


Figure 8 – SDROM compared to Noise Blanker

Nothing can more dramatically demonstrate this than the power spectrum.

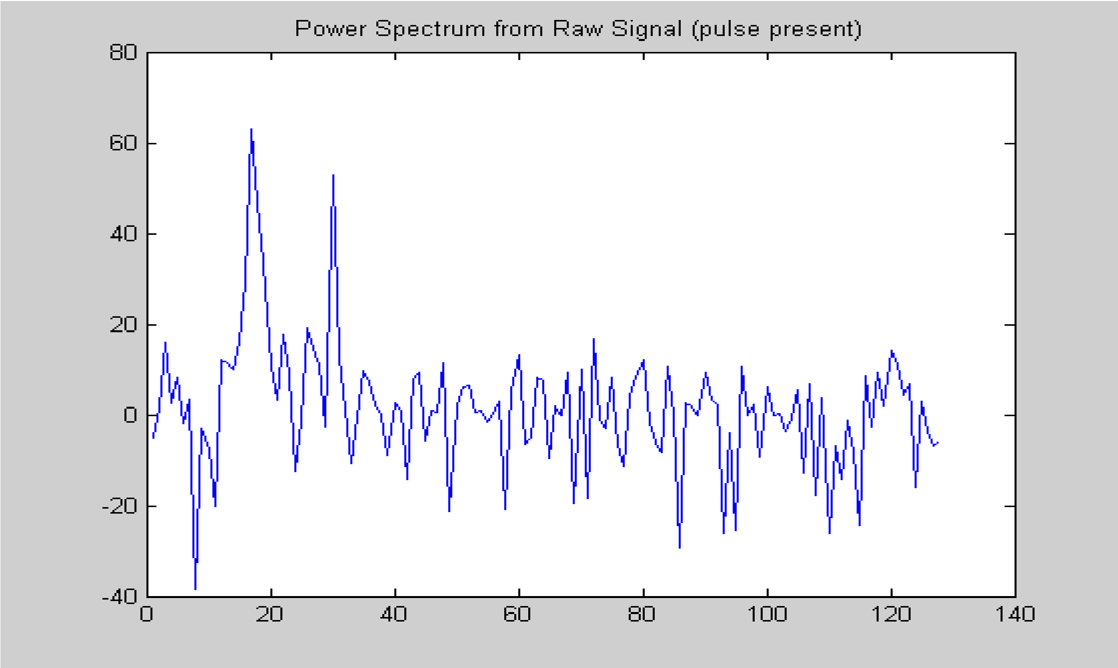


Figure 9 – Raw Signal

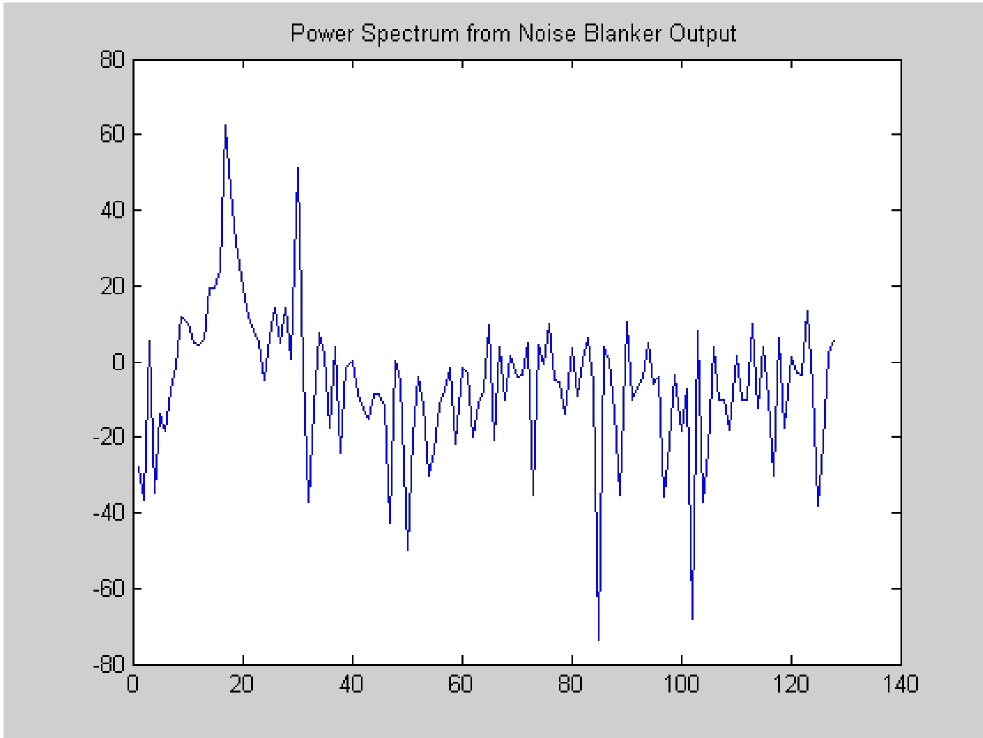


Figure 10 – Noise Blanker

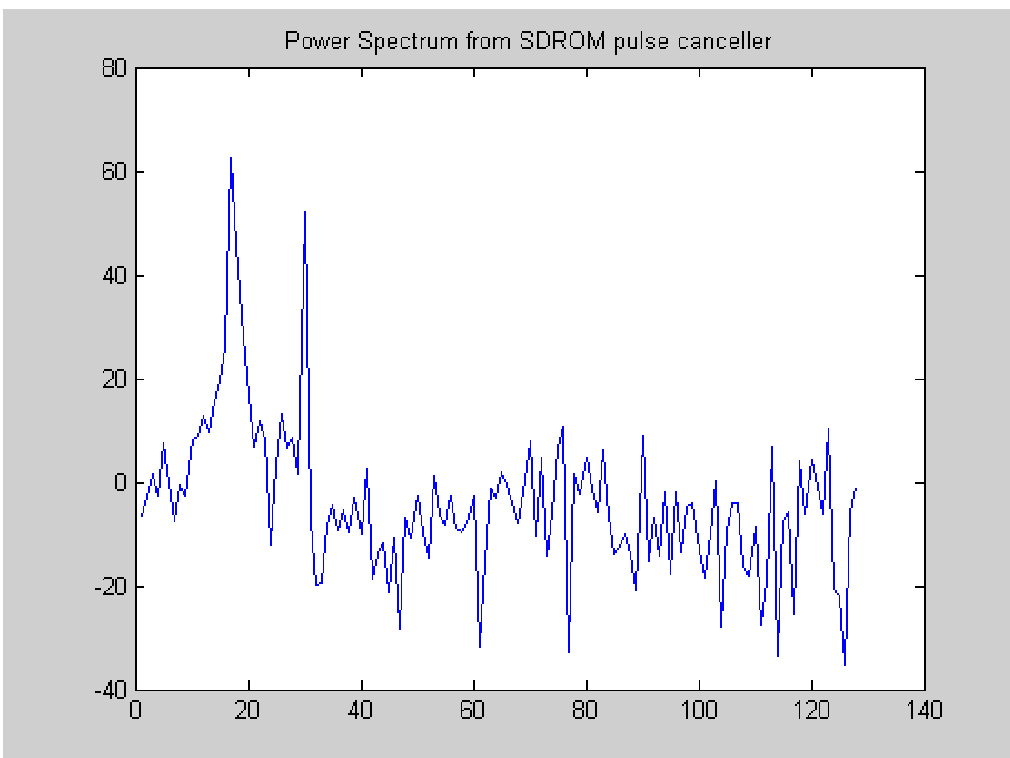


Figure 11 – SDROM

The differences are observed immediately if pointed out. The noise floor outside the area of the two tones is ***raised*** in the blanked signal over the signal with the pulse present. The SDROM output has the noise floor depressed by 10 dB from the signal plus pulse and more from the blanker. This extra energy will not be mixing in a nonlinear fashion with signals of interest in the SDROM output. It is a marked improvement over the noise blanker. But it is not perfect.

The primary drawback to the SDROM as implemented by Mitra, et. al. is that it treats the pulse in the same manner as the blanker insofar as it makes the assumption that a pulse is a single isolated event and limited to one sample. This is easily improved on by doing SDROM recursively. That is, we consider the filtered signal when deciding whether to replace a value. This will allow for wider pulses than spikes. We have not implemented this but we expect small dB improvement in the noise floor from this added wrinkle.

Improving Image Rejection

The ultimate in noise pulse removal would be to know what the pulse looks like and to subtract it from the signal. This might seem miraculous until you know that Leif Asbrink has approached this in Linrad as describe in several recent *QEX* articles. Leif attempts to find the pulses and subtract their pulse shape, using two parameters from the incoming narrowband signal: the phase angle and the amplitude. In our attempts to make a real radio out of the SDRConsole, it was thought to be a deficiency of this approach that it required the user to determine a single pulse shape through a measurement procedure done once and assumed correct. It is clear that this is not perfect, though it produces good results in VHF+ noise and has been utilized by many VHF/EME/Microwave users. The imperfection shows up in the need for Linrad to continue to blank with the zeroing algorithm those small pulses that make it past this. To the extent that you do not have the pulses correct, or the amplitude or phase correct, you are ADDING PULSE BACK into the signal. It seemed that we could, in fact, do a complete automatic job of determining more parameters and improving the performance.

It has been decided to add a single pulse-generating engine just before the mixer in the new add-on RFE board. Rather than reiterate all of the advantages of this new board, we will detail our approach to the pulse shape here. (See Hardware Enhancements section for more on the RFE board)

A terrific job of image rejection can be done if you know the phase and amplitude imbalance between the I and Q channel in the incoming signal. It would be ideal if this could be measured directly. We believe we can do this with a pulse generating mechanism. In our case, we need not know the exact relationship of our impulse response through our system, but rather its relative deviation from ideal. This is then easily added (convolved with) the filtering done for SSB, CW, etc. to remove the image in order to make both the I and Q response flat and equal with linear group delay across the spectrum of interest. In addition to accomplishing image rejection, this will give us the pulse shape of the ideal pulse entering the system and allow us to do a more complete job than Linrad can do with the one-size-fits-all impulse response. When we change bands (at a minimum), we will re-estimate the impulse response correction.

Experimentation will allow us to determine if it needs to be done more often than once per Mhz change in frequency.

To that end, we derived a slow repeated pulse from a signal generator so that we could isolate one pulse at a time. The following graphs show a pulse as it has passed through the SDR-1000 hardware and has been captured upon passing through the most important element in any system, the sound card. The graph in Figure 12 shows the imaginary channel of the filtered signal in the area of one of these captured pulses. In a perfect world, this and its accompanying real part would be exactly the impulse response of the filter we have applied in the SDR-1000 console software that is applied for SSB detection. It would have nearly flat response in the passband and no phase or amplitude distortions. However, we live in the real world of real components of our mixer, instrumentation amplifiers in the SDR-1000 and op-amps in the A/D's in our sound cards. All contribute to distortion that hurts image rejection and keeps us from doing fancy noise reduction. Since we designed the bandpass filter in the IF, we know its impulse response perfectly. We register the location of the pulse and place it where we believe we have captured most of the response that can be seen above the noise floor. We compare that to the complex impulse response of the filter and correct for distortions. This will yield "perfect" image rejection. It will also allow us to apply the subtractive pulse canceller in a completely automated way since we will have to account only for perturbations from the ideal of the now determined impulse response.

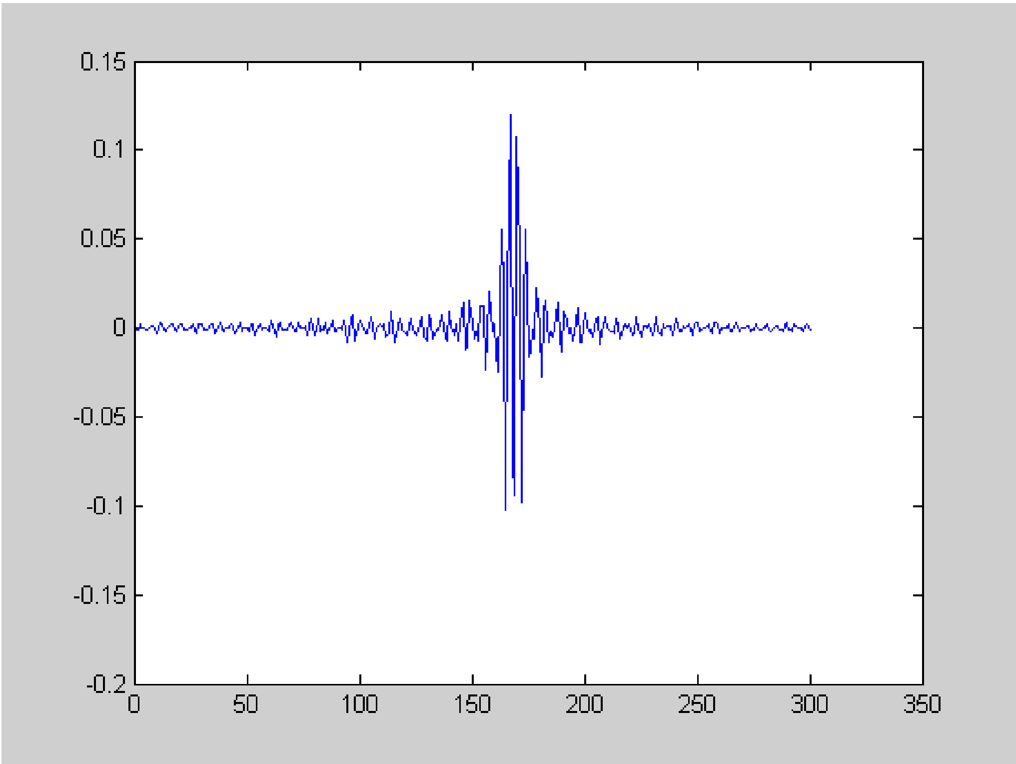


Figure 12 - A pulse time waveform in the imaginary channel

In most of the modern transceivers available to us, we have DSP processors which do automatic noise reduction and automatic notch filtering. Most of them (if not all) use a Least Mean Square (LMS) adaptive filter first described by Widrow, et. al. and commonly referred to as the “Widrow” filter. This filter has a serious drawback. It uses the longer term correlations present in tones, speech, or Morse to produce a filter which either enhances them and reduces noise or notches them if they are undesired. This correlation is done very weakly and at one lag or “look into the past”. A steepest descent based on this stochastic gradient is done. It is clear that this is a lossy and noisy look at the correlations needed to make this filter; yet it does work.

We would like to improve on this algorithm. One could use many different lags. As many lags as you will allow filter taps. This leads to a very expensive algorithm called Recursive Least Squares (RLS) and the unstable but fast versions of it known as Fast RLS or FRLS. Fortunately, there is another way that has recently been discovered outside of the area of noise canceling and notch filtering. We have adapted it for our use. It was developed in the echo-canceling world for multiple sensor microphone systems. Once you look past this function, you quickly see it is immediately applicable to other issues. It is known in that world as the Affine Projection Algorithm (APA) when you allow several more than one lag, but all the lags are adjacent to each other. There is an obvious extension of this to multiple lags that are not necessarily adjacent to each other, but cover a longer span. This can be extremely helpful in capturing more information about the signal. This version is known as Normalized Least Mean Square with Orthogonal Correction Factors (NLMS-OCF). A Google search will reveal numerous online documents if you need more detailed information.

Here, we will describe our first experiments and implementation. We have limited ourselves to APA in the Visual Basic console. This limitation will be removed in the upcoming versions of the console that will use other signal processing libraries and languages. For now, let’s describe the results. We chose to use 3 lags to compare to our current signal sample in order to determine a good filter for our single experiment in notching a two-tone signal. We used the APA algorithm with a delay of 65 samples at 44100 samples per second. At that delay, we look at a filter with only 32 taps. We attempted to strain the algorithm with a short filter. In the end, we were amazed. Even in a noisy signal, given a short filter, we converged with the APA at a rate that was heretofore only achievable with RLS. In addition, it is automatically normalized for changing signal strengths due to AGC. It exhibits the better tracking behavior that is more akin to LMS, rather than RLS, which shuts down and stops listening unless you force it to listen by adding a memory leak constant to the RLS algorithm.

In 48 samples, we converged to a notch. In the power spectrum shown in Figure 13, we have two traces. One is before the automatic notch while the other is after. We have artificially shifted the notched spectrum down so they do not lie on top of each other. This extremely impressive result can only get better and more stable as we allow non-adjacent correlations of NLMS-OCF and improved performance across the spectrum if we choose distances that represent non-periodic signals more accurately.

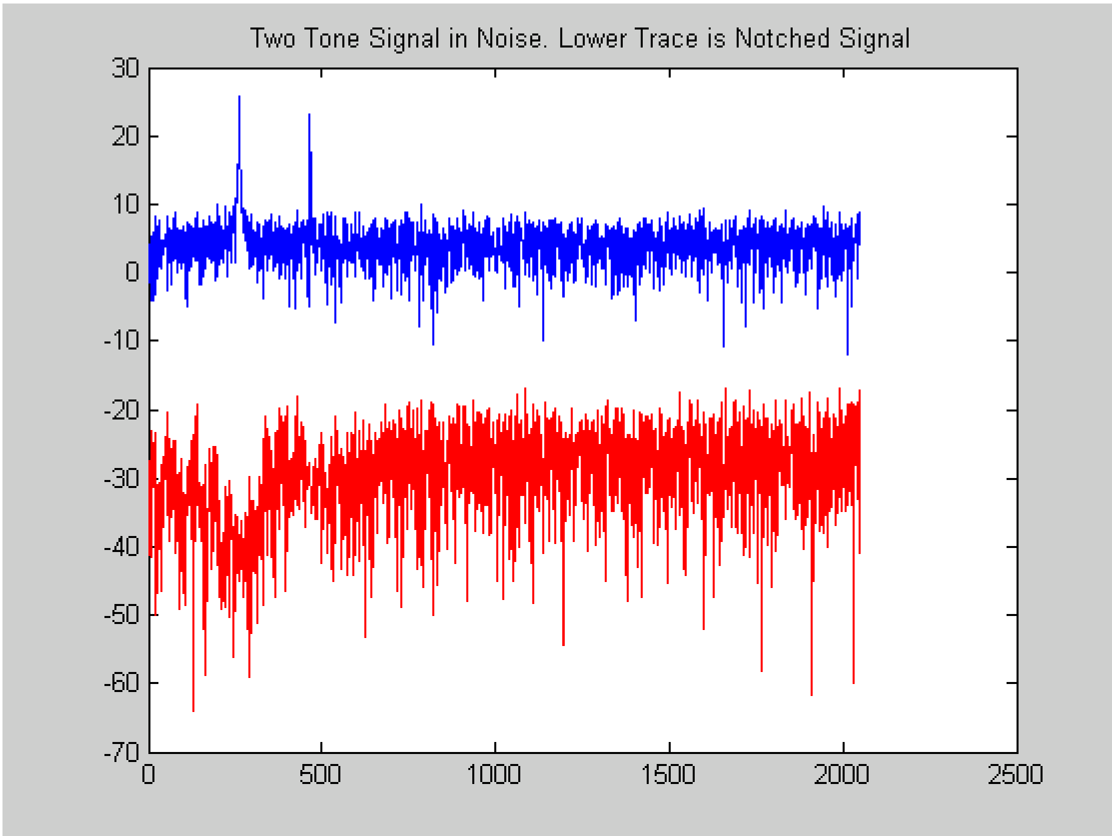


Figure 13 – Notched Power Spectrum

A serious drawback to the radio has been the way it operates as a CW rig, despite a Herculean effort by W5SXD. Frank Brickle, AB2KT, and author N4HY have come up with a technique to use Modulated CW (MCW) in order to gain full QSK without the drawbacks of using MCW. Since this is a software radio, we can afford to have an external circuit with a keyer chip and a tone generator that generates MCW. Some may be worried about spectral purity with this kind of excitation. However, we do not need to worry. We will do detection on the MCW signal inside the radio software rather than automatically transmitting it. We will then reconstitute the CW, with adjustable shaping and weight to be transmitted to the antenna. We will soon have RTTY and PSK31among the other modes already implemented. Rob Heard, in his own Delphi Version of the console, has implemented Slow Scan Television (SSTV) reception and is working on transmit capabilities. The full spectrum of narrow band communications on the ham bands is possible with this radio.

Recently, N4HY proposed an relatively easy scheme using the SDR to do frequency hopped spread spectrum using a compression-in-time algorithm that will enable the addition of synchrony signaling on every dwell while not losing or covering up the signal of interest.

Frank Brickle, AB2KT, has written an interesting article in a recent issue of *QEX*, which will lead inevitably to Cognitively Defined Radio. What this means is that the radio will detect a signal, classify it, and configure itself given the built in artificial intelligence to do so in the software defined radio.

AB2KT and N4HY are writing a full-blown console using Qt-Free as the GUI development engine and will be releasing the Linux/Alsa Sound/Qt console soon.

The following is a list of software developers listed in the latest beta version of the console software. The things they have contributed are too numerous to list but the radio would not be nearly as feature rich nor would it function as well without their contributions:

W5SXD, G6UVS, AA6YQ, W3IP, VE7APU, VK6APH, WK0J, N7TQM, N4HY, and AC5OG

New Object Oriented Architecture

While a firm groundwork has been established using the Visual Basic 6 (VB6) interface, it has become increasingly important to look at a new platform. With Microsoft making moves toward no longer supporting VB6[3], we began to look at building the SDRConsole in a more recent language. Rather than simply porting the current code, we decided to take a bold step and redesign the entire console from scratch.

Using the lessons learned from the VB6 design process, we began with a very high level view of the software and broke each section into smaller logical blocks. Examples of such blocks are Digital Signal Processing (DSP), DataStream and Hardware. These blocks would be further broken down to a size that is easily maintained. Dissecting the project in this way allowed us to break up the coding responsibility much more easily. Using a Unified Modeling Language (UML) tool called ArgoUML helped us to visualize our software model. Figure 14 shows a portion of an early prototype of this model. Given the open-source nature of our project, easing the ability for customers to contribute directly toward the development of this new platform would be crucial to the software's continued success. With open source code and customers contributing code in their own specific areas of expertise, we have a uniquely diverse development team.

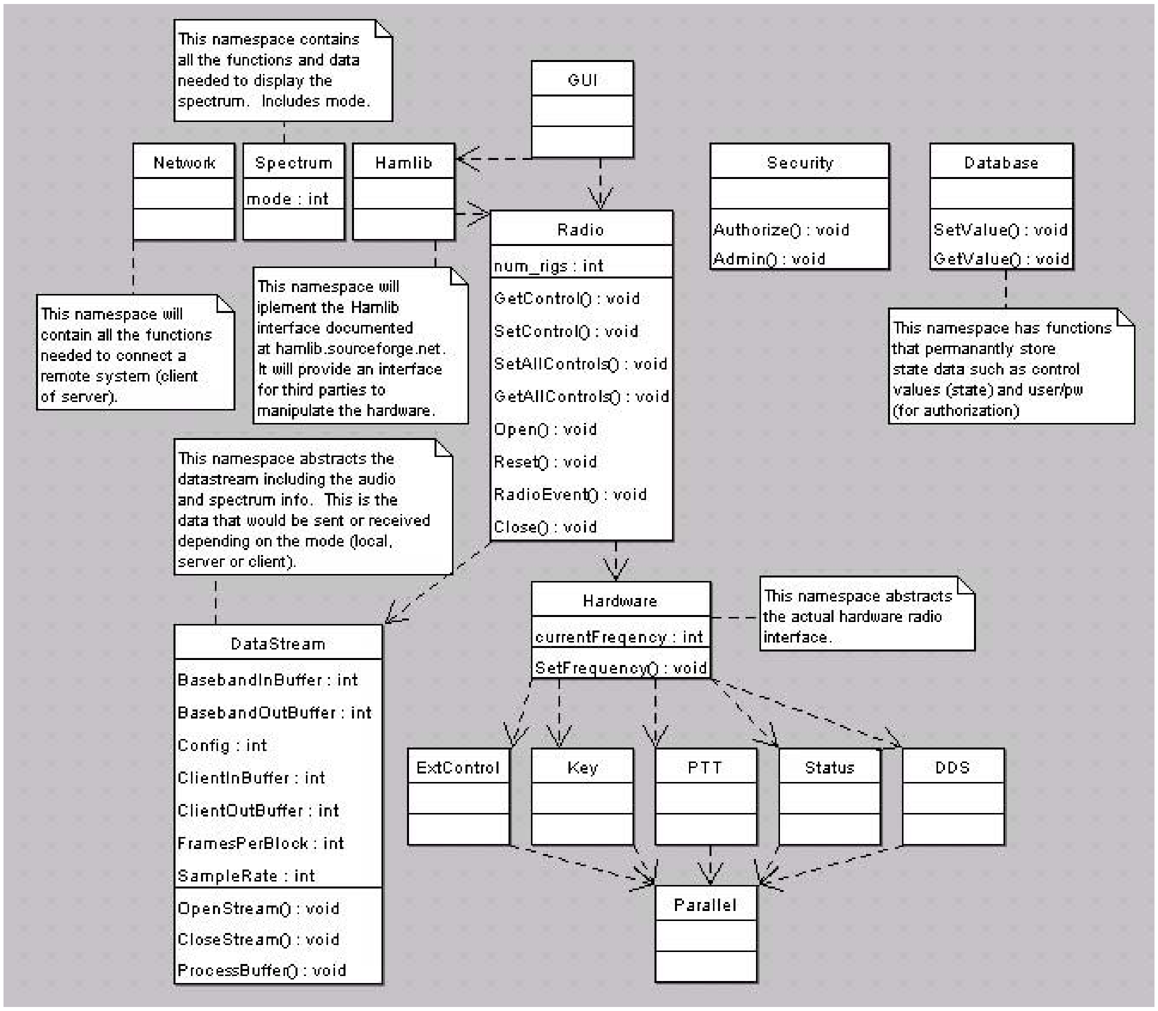


Figure 14 – UML Model

One of the major design points in our new software model was to provide support for both a binary executable interface as well as a web interface that could be accessed from any computer with access to the Internet. This would not be an easy undertaking, as we would have to consider such things as audio compression, data encryption and serialization. Despite the development cost, this feature is necessary for a cutting edge product such as the SDR-1000 and would open new doors of opportunity for remote radio applications. Imagine being able to pull up your radio interface and even transmitting using your PDA. This is the type of flexibility that we are aiming for with our new design.

In our search for an appropriate language, our options were somewhat narrowed by our strict criteria. While still wanting to offer an easy-access version for beginning programmers, our product would shine best in a multithreaded environment. We essentially needed something with the easy visual interface that Visual Basic offered while at the same time offering the power of C or C++. After a bit of research, C# seemed to be the logical choice. Further investigation revealed an extensive class library in the .NET Framework. With defined namespaces such as System.XML, System.Threading and System.Security, we would be able to quickly integrate powerful features such as RSA encryption, multithreading and serialization without spending months developing these libraries on our own[4]. Linux and C#.NET versions of the console are being developed by Flex Radio, N4HY, and AB2KT. We expect these versions to be in Beta testing within the next month.

One of the more exciting possible applications with the new object oriented architecture and the use of more modern development tools available in C#.NET and Linux is the easy ability to remote the transceiver hardware and to do the signal processing at the other end of the remote connection. An extremely exciting prospect for doing coherent combining of the signals from multiple radios is immediately available to the serious experimenter with minor modifications to the radio to allow for the injection of coherent DDS oscillator signals.

Having discussed the web-based access to the radio, it becomes obvious that not everyone is equally endowed with Internet connections. It would be very easy for the local server running, for example, a RealServer to save a known user's configuration, internet connection speed, and other factors so that when the unique user connects to the radio, the remote transmission to that user is configured appropriately for them. This information is easily stored in a database local to the radio and accessed upon connection.

In the early days when we were doing the initial development on the radio, some obvious expediencies came immediately to bear on the issue of getting the radio finished and software developed that would enable the experimenter to begin tinkering. AC5OG, as the developer, was not a DSP expert and not a real-time computing expert. A decision was made to use Intel's Signal Processing Library (SPL). This enabled fast, accurate, well written algorithms to be immediately available to the Visual Basic 6 console without having to be written from scratch, debugged, and optimized. However, as we move on to do other things with the radio and as Intel has dropped its support for SPL and substituted a fee for license based library known as PPL, we have decided to explore other options and some have become available for our experimentation with the new object oriented console.

We would like to re-use code across all platforms whether it be Linux, MacOS, or Windows. Recent developments have helped tremendously in that regard. A project that solves most of the really tough issues of dealing with audio and sound card issues was found in the PortAudio API. The PortAudio API project is on the web at http://www.portaudio.com. It has versions that enable one API to be used on Linux, MacOS, and Microsoft Windows. All versions of the code can have one interface to the sound system in the computer on which they are running. Eric Wachsmann has written a C# wrapper to talk to PortAudio for Microsoft Windows Visual Studio .NET 2003 and the API already comes native to run on Linux, and Unix (including FreeBSD which will run on the Mac).

We need a similar kind of library to do the primitive signal processing procedures that SPL did for us. In addition, we wish to begin doing the APA, NLMS-OCF, N-channel combining algorithm work and experiments not yet conceived by us but which we are fully aware will have features in common. The primary features will include a solid library to do linear algebra and matrix/vector manipulations as well as optimized fast Fourier transforms (FFT).

The latter was available for Visual Studio 6 as well as Linux and the Unices in the form of FFTW (see http://www.fftw.org). N4HY has recently ported FFTW-2.1.5, the most recent release version, to Microsoft Visual Studio (MSVS) .NET 2003 with all the project and solution files. This is available through a link on the Flex-Radio web site on the resources page.

The signal processing and linear algebra routines have been captured in a U.S. government supported open source effort known as VSIPL (see http://www.vsipl.org). Heretofore, no one known to us had ported this library to Microsoft Windows tools. It compiled and ran natively on Linux, Unix and MacOS (FreeBSD) systems. N4HY has managed to get all versions of VSIPL, which is written in C, to compile and make static and .dll libraries for MSVS.NET 2003. All library versions including using FFTW-2.1.5 as well as the native FFT in VSIPL, both static and dynamic have been made and tested. This library is also available as a link on the Flex-Radio resources page.

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The Easiest Satellites

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October 2004

Abstract

Reception of VHF weather satellite signals is the easiest, lowest-cost entry to satellite operation. The signals are strong and easy to receive with simple wire antennas and readily available scanning receivers. They nevertheless illustrate many aspects of satellite operation, including orbital prediction and the nature of the satellite ground track and coverage area. The downlink signals may be processed on a modern personal computer to produce images that are interesting in their own right, and often beautiful too.

1 Introduction

In AMSAT we are always looking for satellite systems that are useful to attract beginners to our specialized corner of amateur radio. Weather satellite reception can provide such an entry point: the signals are easy to receive on low-cost equipment, and provide interesting results to which newcomers can relate.

2 Satellites

The current active low-orbit weather satellites are all operated by the U.S. National Oceanic and Atmospheric Administration, NOAA. While there have been other low-orbit satellites in the past, particularly the Meteor series operated originally by the U.S.S.R. and later by the C.I.S., none of these satellites are currently operational.

The NOAA satellites are all in near-polar (98 degree inclination) sun-synchronous orbits. Their orbital planes rotate 360 degrees in one year, following the Earth's orbit around the sun. They thus image the same parts of the Earth at the same local time, a valuable characteristic for Earth-imaging applications. Operationally, this means that they pass over an observer's location at approximately the same local time each day.

Unlike many amateur satellites, the NOAA weather satellites do not perform store-and-forward operation. Instead, they broadcast imagery of the area they are passing over, in real time. They image a single scan line with a rotating mirror, while the other dimension of the images is created by the forward motion of the spacecraft as it orbits the Earth. The primary instrument on the spacecraft is the Advanced Very High Resolution Radiometer, AVHRR. This payload splits the incoming light into 6 spectral bands, digitizes them and transmits the raw data over the HRPT downlink (see Section 5). It also processes selected channels to create the analogue Automatic Picture Transmission (APT) downlink, transmitted on VHF. During the day the APT downlink carries a visible light channel and an infrared channel. At night APT switches both channels to infrared, one near-infrared, the other far-infrared.

3 Ground station requirements

The signals transmitted by weather satellites are easy to receive, and simple ground station equipment will provide good pictures. The downlink signals are in the 136–138 MHz space operations band, which benefits from its proximity to the 2 meter amateur band. It is thus easy to retune 2m ham gear to receive weather satellites, though there can be practical issues.

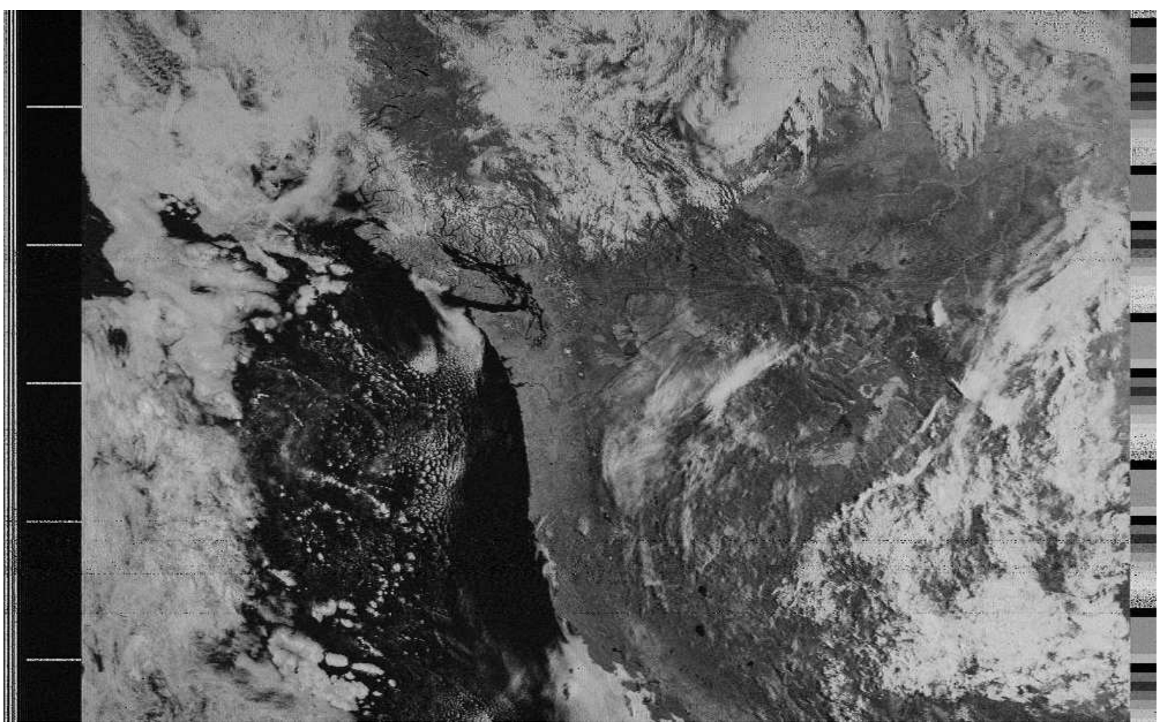

Figure 1: The west coast of Canada and the U.S.A., as seen by NOAA–16

The satellites transmit conventional FM signals. The bandwidth is unusual, however, approaching 50 kHz. This is wider than amateur and commercial narrow-band FM, but much narrower than FM broadcast. Taggart suggests several options (Taggart94), including replacing the standard NBFM filter in a receiver with a *cheap* 30 kHz model (which will have wide skirts), or removing a strategic filter outright and replacing it with a capacitor. I've tried both approaches, and have received weather satellite signals with a variety of receivers, shown in Figure 2. The Ramsey receiver (the board in the foreground) is a little wide and a bit drifty, but it's hard to beat the price! Unmodified ham gear will not generally work produce satisfactory images: it will produce loud signals, but the narrow bandwidth will eliminate much of the interesting detail.

Figure 2: Weather satellite receivers.

The high output power and low orbits of weather satellites mean that simple antennas will produce useful signals, particularly on high elevation passes. A dipole cut for 137 MHz will produce signals, but the single most important optimization is a circularly polarized antenna.

The simplest circularly polarized antenna is a pair of dipoles oriented at right angles, and fed 90 degrees out of phase, as illustrated in Figure 3. The antenna must have the same polarization sense

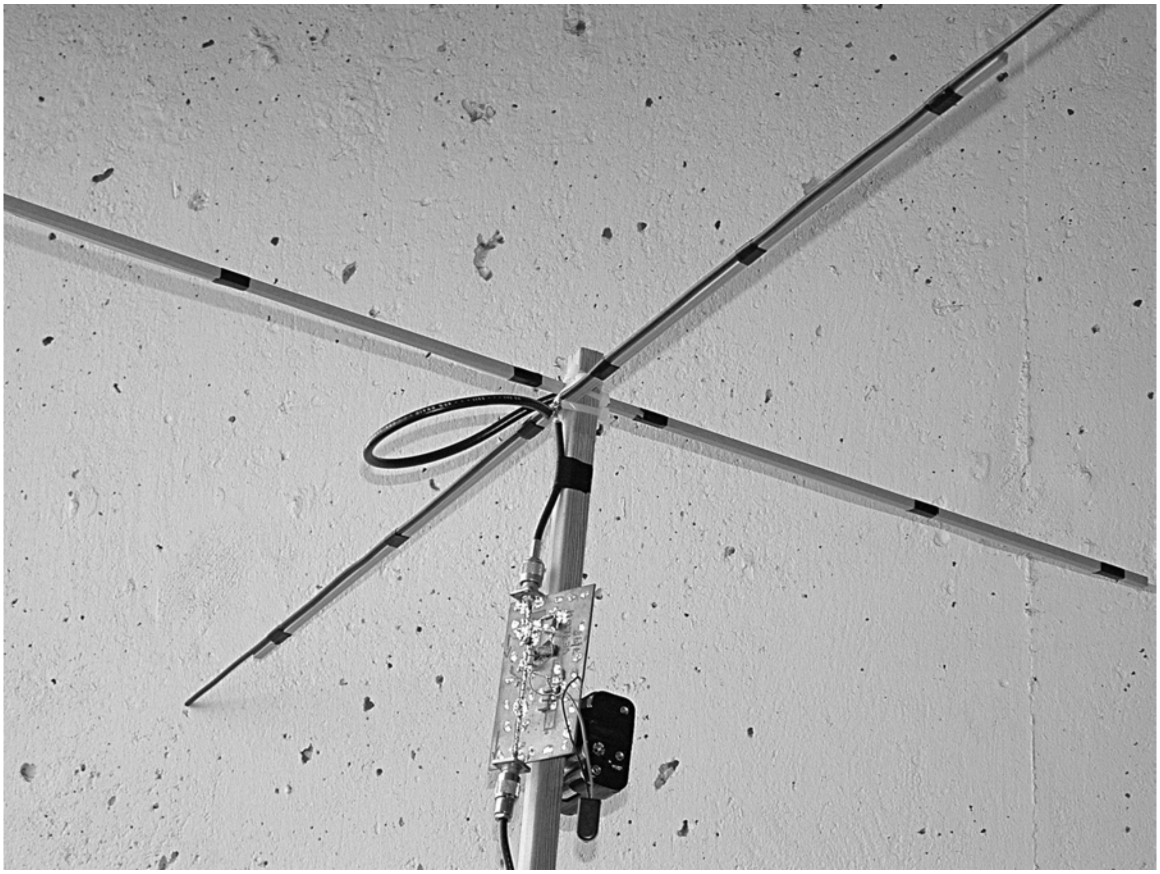

Figure 3: A crossed dipole antenna: a simple but effective antenna for weather satellites.

as the satellite, right-hand circular polarization. The antenna in the picture includes a simple dual-gate MOSFET preamplifier plus some band-pass filtering, important for the wide front ends of scanners in the often-hostile VHF RF environment.

Other circularly polarized antennas are possible, including the Lindenblad and the quadrifilar helix (Davidoff98, Taggart94, UHF97). An axial-mode helix antenna is entirely possible, but is large and unwieldy at this frequency. Users who wish to receive signals from distant, low-elevation passes usually opt for steered Yagi antennas.

4 Demodulation and image processing

Many devices have been used in the past to convert the APT downlink signal to pictures. Past satellite users used modified slow-scan television equipment, facsimile recorders with a rotating drum, and other mechanical devices.

Taggart describes some of these devices, but even in 1994 they were obsolete. Prior to the advent of today's fast computers and CD-quality sound cards, the preferred approach was to process the audio in an external unit, then feed digital data to the computer through the parallel port. I built Taggart's `WSH` interface, but modified it to take advantage of a bidirectional parallel port that could input a byte through what were normally its output lines. This worked well, and gave me my first pictures.

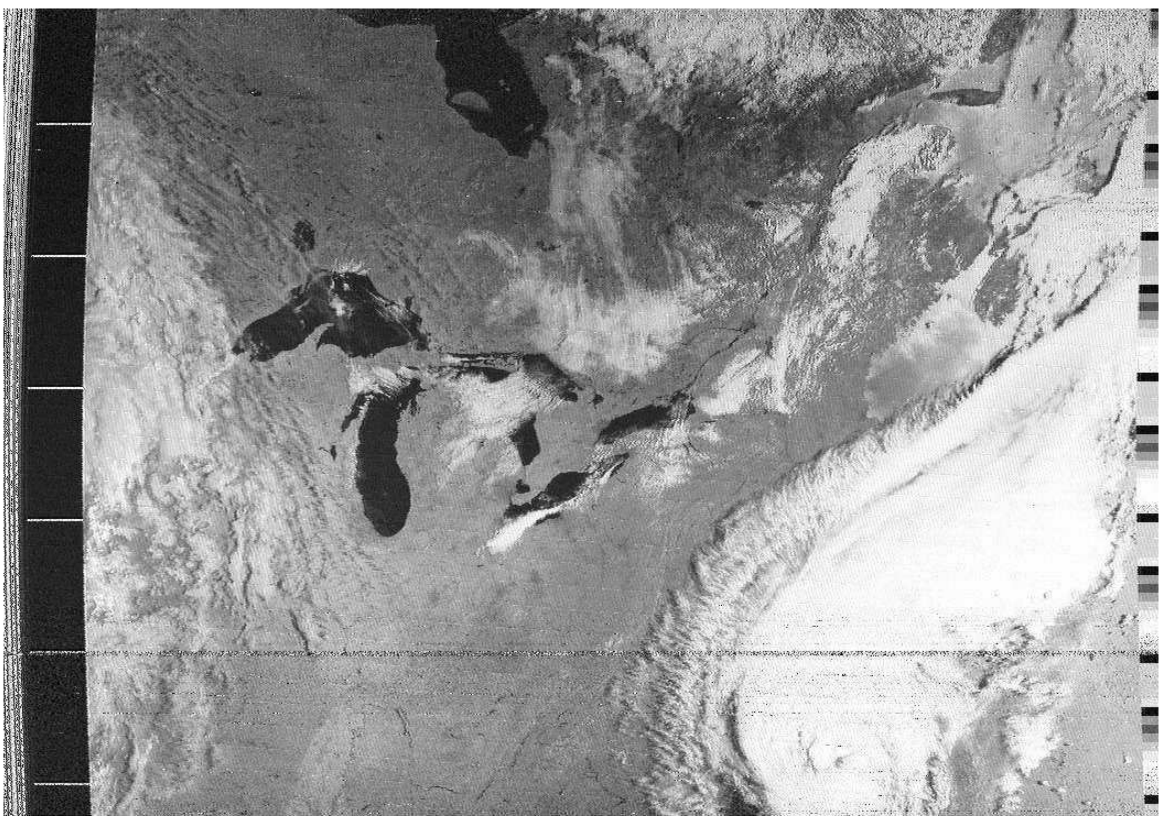

Figure 4: The Great Lakes basin, as seen by NOAA–14. The storm over the Carolinas is Hurricane Dennis (1999).

The modulation of the 2400 Hz APT subcarrier, double-sideband AM, lends itself to simple demodulators. My first attempt was, in effect, a DSP crystal set: a full-wave detector followed by a low-pass filter. It actually produced decent pictures, but now, like everybody else, I use a synchronous detector with a quadrature local oscillator. One of my graduate signal processing courses came in handy when I added LMS noise reduction to the system, for a marked improvement in image quality.

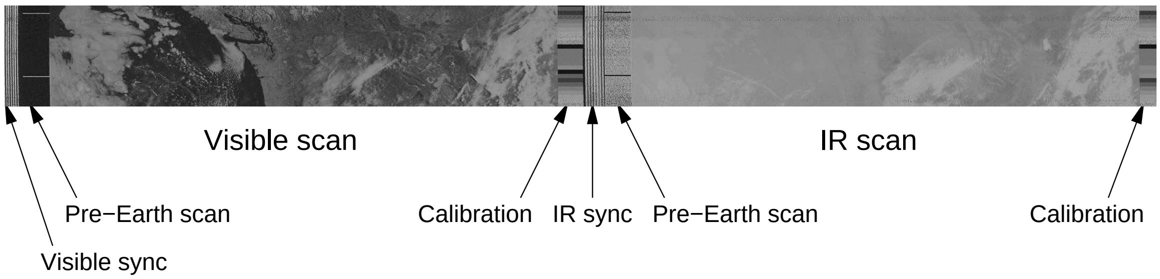

Figure 5: The format of an APT signal.

Software is available for all popular operating systems. It ranges from basic to fancy, with elaborate programs available that add gridding and boundaries, and that also attempt to colour the ground and water the appropriate colours. The format of the imagery (see NOAA00) is simple, as illustrated in Figure 5, sufficiently so that it is entirely feasible to sync and frame images by eye. Note that the pre-Earth scan (i.e. space) is black in visible light, but white (cold) in infrared.

On a practical note, I have always recorded the audio to a sound file and processed it later. This started out of necessity, with an 80486-based computer that wasn't fast enough to process signals in real time. Now I do it for convenience: there is already enough happening during a pass, and recording the audio means one less thing to worry about.

5 Other signals

The VHF APT downlink is not the only signal transmitted by the NOAA weather satellites. The other image downlink is the High Resolution Picture Transmission downlink, HRPT. This consists of the raw digital AVHRR data, transmitted at 665.4 kbps on frequencies near 1.7 GHz. Equipment for this transmission has been described in the amateur literature — see, for example, S53MV's receiver (Vidmar97). I have not yet attempted reception of these signals, which offer much higher ground resolution (1.1 km per pixel, as opposed to 4 km per pixel for APT). nor have I attempted reception of the signals from the geostationary GOES satellites, also in the vicinity of 1.7 GHz. Neither of these are suitable for beginners, and are beyond the scope of this paper.

6 Conclusions

APT weather satellite reception offers an attractive entry into satellite operation. It demonstrates a type of satellite operation that is accessible to beginners by providing a data product (pictures) that is low in initial equipment cost, easy to receive, and which may be understood (literally, at a glance) by any prospective satellite operator.

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Bias Tees for Satellite Receiving Systems, Emphasis on GPS Receivers

by

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Radio amateurs first used bias tees long before satellites were first orbited. Early VHF and UHF experimenters recognized the advantage of locating the receiver preamplifiers as close to the antenna feed as possible. To do this economically, power was feed up the downlead, which required two bias tees. One bias tee was used to insert the power on the coaxial cable and one was used to extract the power. Many preampliers and converters are now made with provisions for feeding the dc power via the down lead. However, that does not mean that the end in the shack is compatible with the design. Older receivers do not have the capability of injecting the power in the feed line. And, some do not provide the correct voltage. I became aware of the problems when I began experimenting with popular GPS navigation receivers. The result so far has been four different bias tee/dc-block combinations.

Having used a Garmin GPS45 navigation receiver from my car for many years, I finally decided that it was time to upgrade the system when the LCD display began to fail. After much searching around, I settled on a Garmin GPS12MAP receiver. Part of the selection reasoning was to have compatibility with my existing installation. The new receiver has the same physical dimensions so it fits into my existing holder, the power/data connector and wiring are the same, and the external power requirements are the same. But, I did not consider the output voltage from the external antenna jack. Yes, I did know that the external antenna connectors were different, but the problem turned out to be more than just a connector adapter issue. The external antenna I use in my car is an old Trimble unit with a SMB style connector. The old GPS45 receiver had a BNC antenna connector and the GPS12MAP receiver comes with a MCX connector. It doesn't take much thought to fabricate the proper adapter cables. After all, shield to shield and center pin to center pin is a no-brainer. I had previously experienced the same problem with a GPS12XL receiver, so I already had the necessary adapter cables made up. However, when I connected the Trimble antenna to the GPS12MAP receiver, there were no signals.

Back to the books. It seems the GPS12MAP uses newer low voltage external antennas such as the GA27C. The GPS45 and GPS12XL use 5V external antennas such as the Garmin GA27. Oh what a difference the "C" makes. Okay, so what is the output voltage from the GPS12MAP receiver? A simple test with a pigtail coax cable connected to the antenna jack and a multimeter revealed a no-load output voltage of 2.4V. With a 1000-Ohm load, the output voltage only dropped to 2.2V. With a 240-Ohm load, the output voltage plummeted to 1.6V. Obviously I could not expect my 5V external antennas to work. The choice was between spending more bucks for a new external antenna and finding another way to power the existing antenna straight from the car battery. I chose the latter.

The first thought was to just add an in-line switched capacitor voltage doubler powered by the voltage available from the GPS12MAP antenna connector, but I soon realized that the GPS receiver was not designed to supply the necessary current. So, that left just a regular in-line bias-tee. But, a regular bias tee would not work. The Garmin receivers, which have an internal patch antenna and an external antenna jack, sense the antenna lead current to decide when to switch to an external antenna. If there is no antenna lead current, the receiver continues to use the internal patch antenna. If the external antenna draws above some minimum value, the receiver switches to the external antenna. Fine, but how much current is needed before the receiver switches? In past designs, for 5V systems, the popular value of the load resistance has been around 240 Ohms from the center conductor to the shield, or ground. Yes 240 Ohms will work with the GPS12MAP, but it puts an excessive load on the receiver. I once again connected a pigtail to the external antenna jack and tried different load resistor values. Watching the satellite signal strength display, I could see when the receiver switched from the internal patch antenna because the signal strength bars started dropping. After all, there was no real external antenna, just the coax pigtail. The receiver switched with a 240-Ohm load and also with a 1000-Ohm load. The receiver also switched with a 10K Ohm load. It did not switch with 22K Ohm load. I did not feel I needed to do any more testing, and decided that a 5K to 10K-shunt resistor would be adequate. If you plan to use this bias-tee with one of the older receivers, use a 240-Ohm shunt resistor or perform a similar test to select the best value.

Okay, so I now knew enough to design and build the bias-tee. I knew the required antenna voltage, 5V, and the receiver switching load resistance. The basic schematic of a bias tee is shown in Figure 1. The only difference between that schematic and a normal bias tee is the need for the shunt resistor on the receiver port. There is a series RF pass, dc-block, capacitor between the receiver port and the external antenna port, and there is a blocking choke between the external antenna port and the power connector. The power connector also has a bypass capacitor to ground. Both the series capacitor and the bypass capacitor need only be large enough to present a low impedance to the 1,575.42 MHz GPS signal. Anything greater than 20 pF (~5 Ohms) is adequate. I decided to add some features to the plain design. The enhanced design is shown as Figure 2 and Photographs A and B.

Instead of just running the receiver load resistor to ground, I added a switch to ground the resistor when I selected external antenna and unground the resistor when I wanted to use the receiver internal patch antenna. The same DPDT switch is used to route power to the antenna when the external antenna is selected and to remove power from the antenna when the internal antenna is selected. I also added a simple three terminal voltage regulator, with the standard protection diodes and filter capacitors, to drop the car supply down to 5V. I used a T0-3 case regulator because I still have a drawer full of the older devices. The typical external antenna current drain is 25mA, so a low power regulator could have been used, but the device would be dissipating (13V-5V)*(0.025A) = 200mW which is a bit much in a warm automobile environment.

The blocking choke is just five turns of number 22 wire that was wound using a 1/2-Watt resistor as a mandrel and the turn spacing is about one wire diameter. The number of turns, wire size, coil diameter and other parameters for the choke are not critical. The choke is readily visible in the photographs. The series capacitor is just a 47 pF silver mica. The RF connectors are selected as needed. For my application, the receiver connector is a BNC and the external antenna connector is a SMB, use what you need. The bypass capacitors are 100 pF button bypass capacitors from a piece of WWII military surplus equipment. Okay, I have been around for a long, long time.

I know you expected some sort of microstrip circuit on expensive printed circuit board material with surface mount chip components and warnings of the need to follow an exact layout and maintain critical dimensions or nothing would work. But, here you see simple point to point wiring with ordinary components. Things are not that critical. Use short leads, good components and you should get reasonable results. I was going to say that I would not attempt this sort of wiring above 2 or 3 GHz, but actually I would try it and see if it would work, that is part of what amateur radio is all about.

I remember the 1296 MHz rigs built by K1CLL, Bill Hoisington, using RCA phono plugs as RF connectors. By the way, a number of commercial companies used RCA phono style plugs on their 1 GHz aircraft transponders.

The GPS antenna bias-tee unit worked the first time I fired it up. With the receiver inside and an external window mounted antenna, I had good reception with the switch in the external position and would lose almost all the signals with the switch in the internal position.

The second bias tee bias tee I needed was similar but with a difference. At work, I have an antenna distribution amplifier, which I use to connect a common GPS antenna to several receivers. In this case, the distribution amplifier outputs have 5V on the connectors. I needed a bias tee or other network to block the dc to the GPS receivers, but also provide the proper shunt resistor to force each receiver to accept an external antenna input. So, as can be seen in the schematic, Figure 3, the network is similar to the first except there is no choke for dc power insertion and I have made provision for two different shunt resistors. The 6.8 K shunt resistor is used for low current output receivers, and 240 Ohms is used for the older 5Voutput receivers. In this case a seven-turn choke was used, but again it is not critical. Photographs C and D show the simple construction.

The third bias tee I needed was similar to the second but once again had a slight variation. I was testing a dish antenna I had configured to receive the GPS WAAS signal from geostationary satellites. I wanted a dc block as in the second bias tee. There was no dc on the dish down lead, but I did not want any antenna shorting out the coax cable, which could damage some GPS receivers. And, since the bias tee would be used with my only WAAS compatible receiver, a GPS76, I only needed one value of shunt resistor. But, since I wanted the receiver to acquire the satellite with the internal patch antenna before I switched to the dish, I need to be able to lift the ground end of the shunt receiver to trick the receiver into switching to the internal antenna. The schematic for this third bias tee is shown in Figure 4, and the compact design is depicted in Photographs E and F.

I did build a fourth bias tee. This bias tee was built to be a universal GPS bias tee. The schematic is shown as Figure 5 and Photograph G. In this version, a switch is provided to allow a dc path straight through the network, which allows the receiver to supply power directly to an external antenna. Or, with the switch in the "Local" position, the receiver can be terminated with either one of two shunt resistors or left unterminated while the antenna can be supplied from a 5V, 2.5V or zero volts source. A 0-50 milliammeter is used to monitor the antenna dc current whether in the "Local" or in the "Pass" position. The two MICROLAB/FXR model FW-11N bias tees are connected back-to-back and are rated for 800 to 2300 MHz.   I purchased the bias tees secondhand. Mini-Circuits sells a number of wideband bias tees with and without connectors.

In summary, no one bias tee can optimally solve all problems for all receiving configurations, but with simple designs one can solve the problems without having to revert to strip lines or other microwave construction techniques.

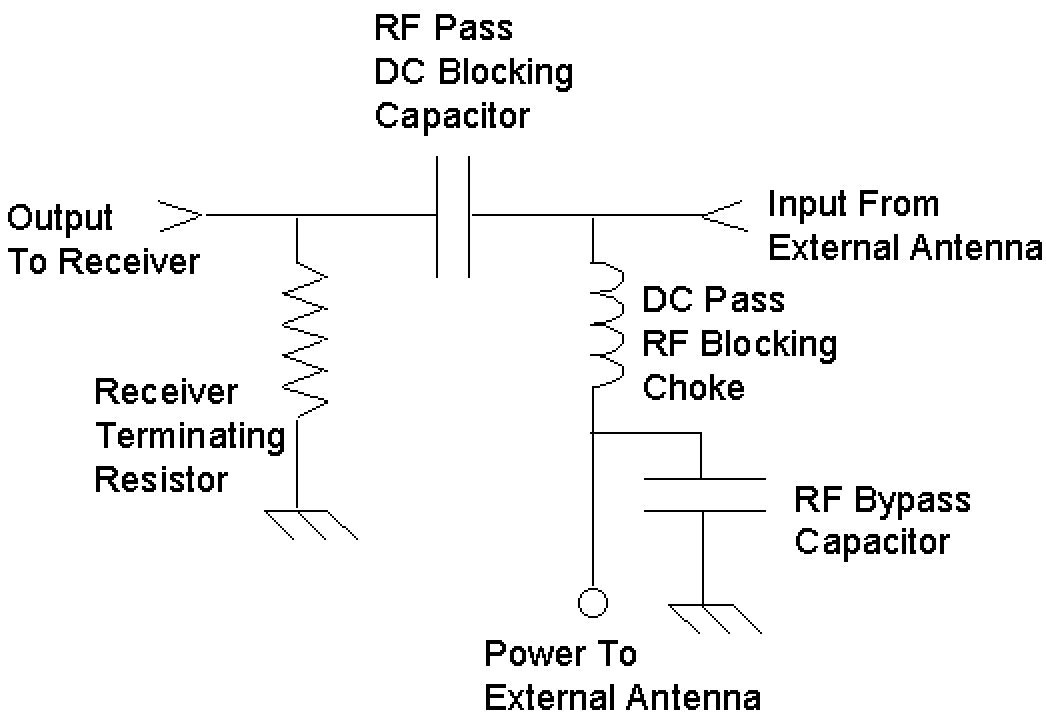

Figure 1: Basic bias tee circuit

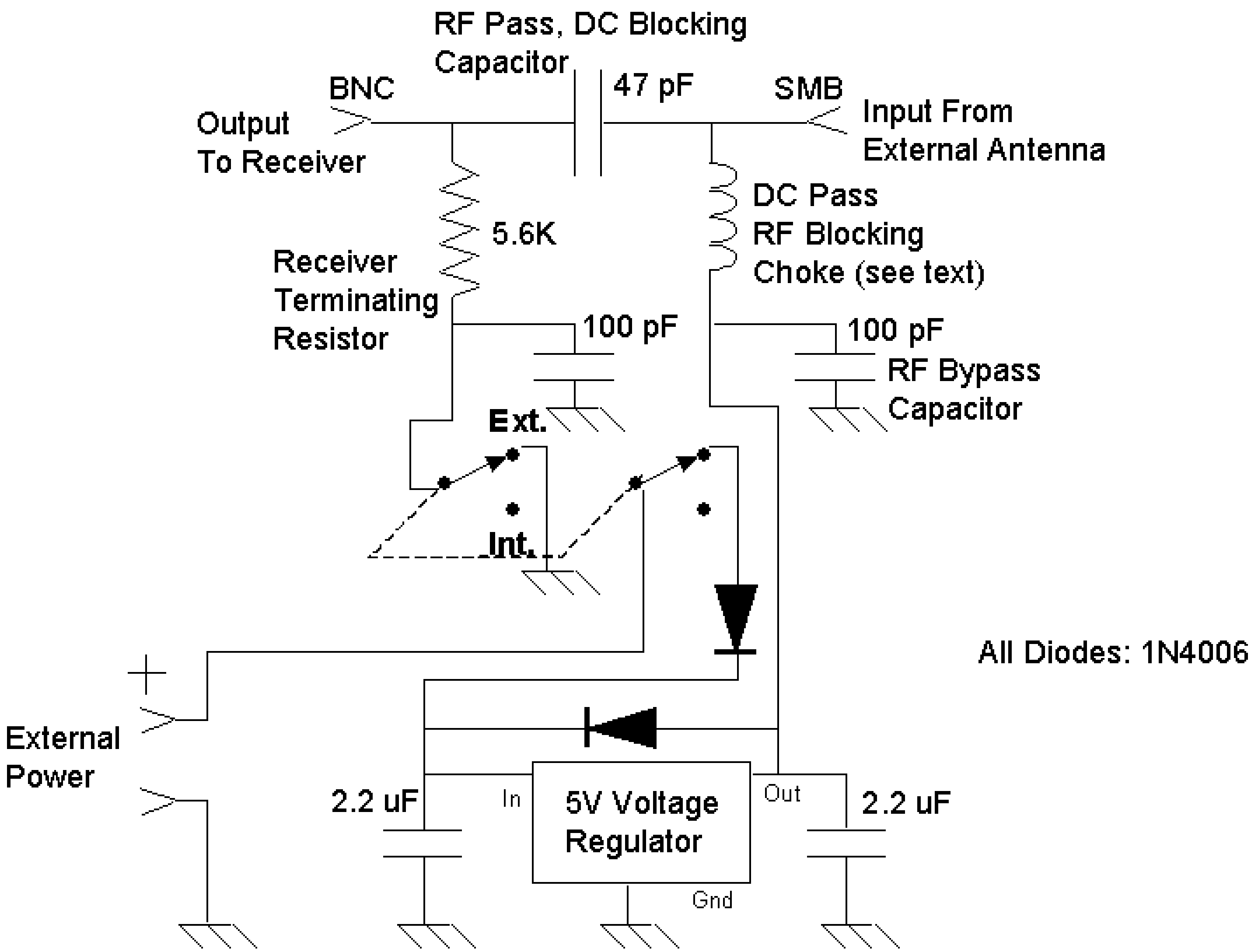

Figure 2: Enhanced bias tee circuit

Photo A: GPS12MAP Bias Tee, External View

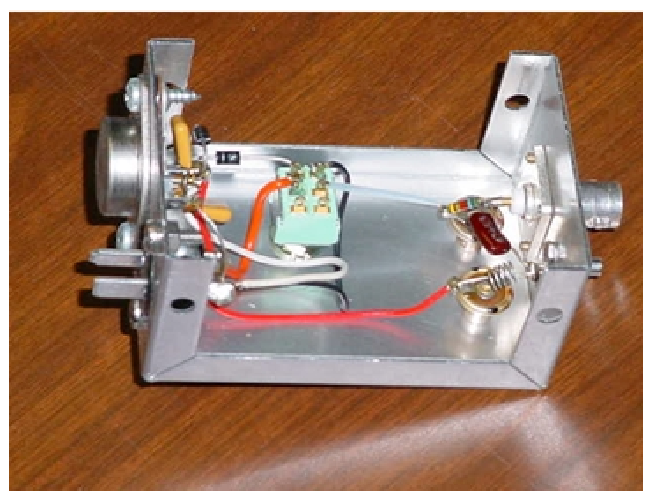

Photo B: GPS12MAP Bias Tee, Internal View

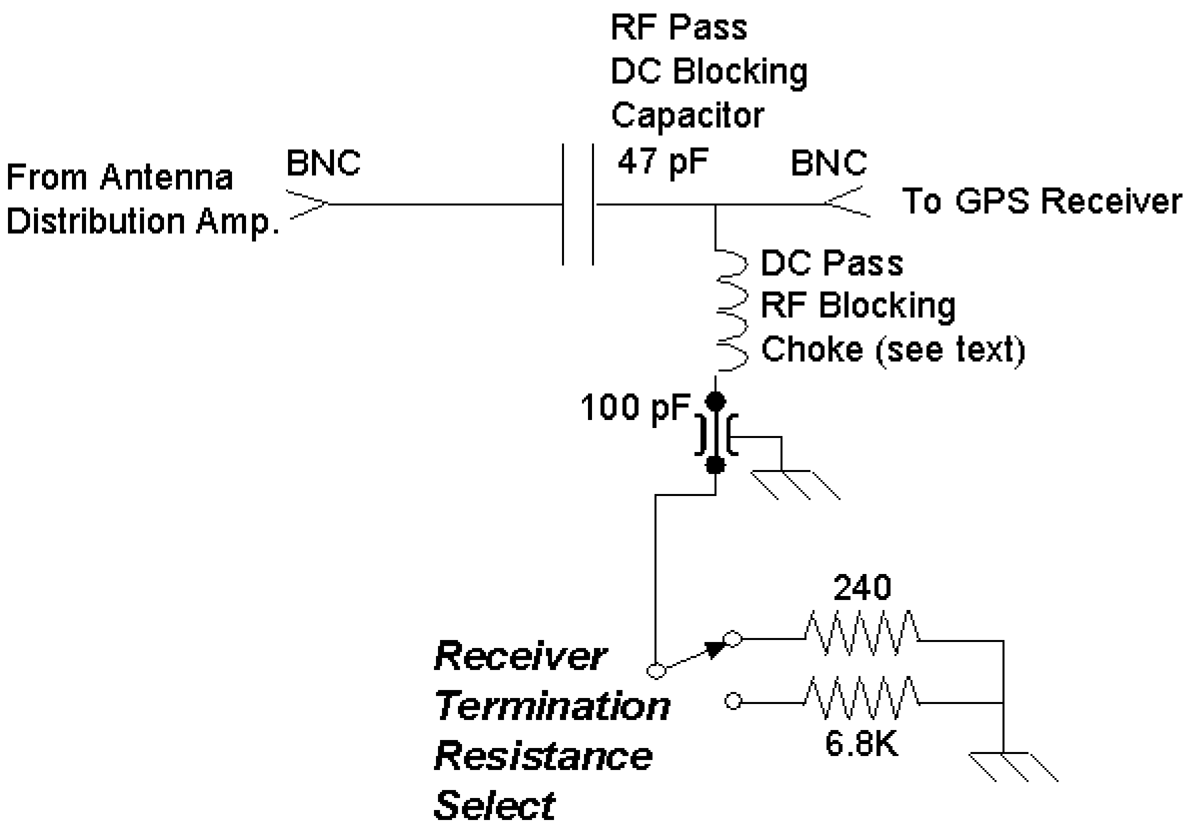

Figure 3: Bias tee for distribution amplifier

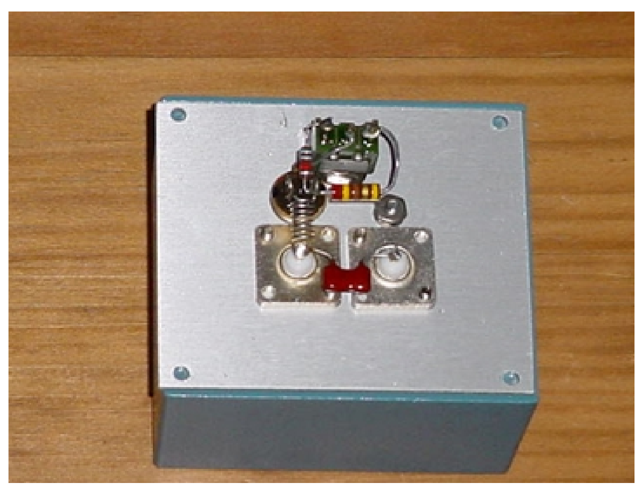

Photo C: Distribution Amp Bias Tee, External View **Photo D: Distribution Amp Bias Tee, Internal View**

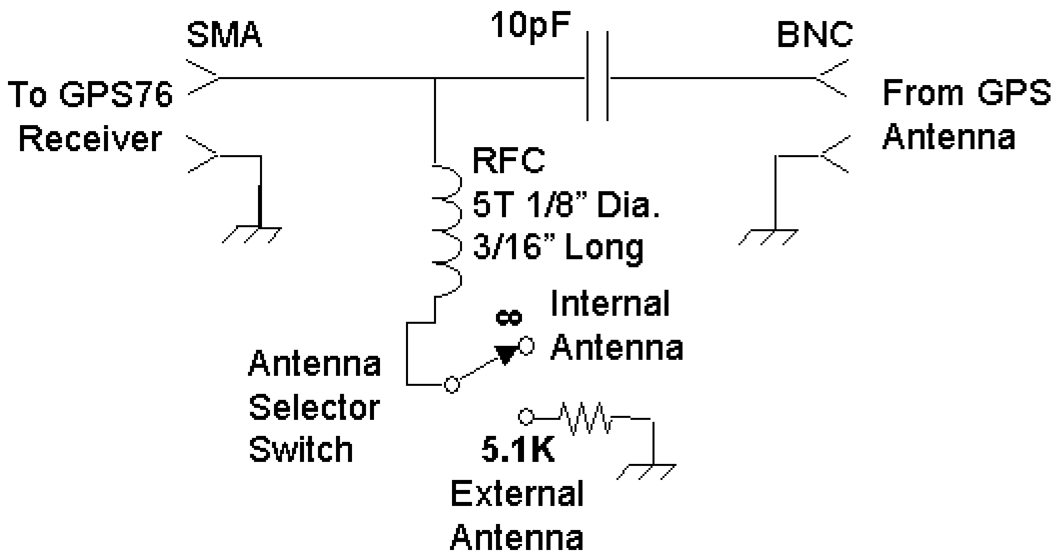

Figure 4: GPS76 receiver antenna bias tee

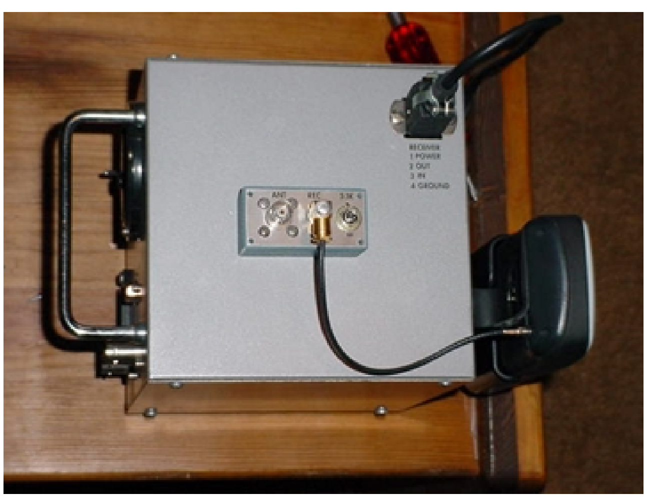

Photo E: GPS76 Bias Tee, External View

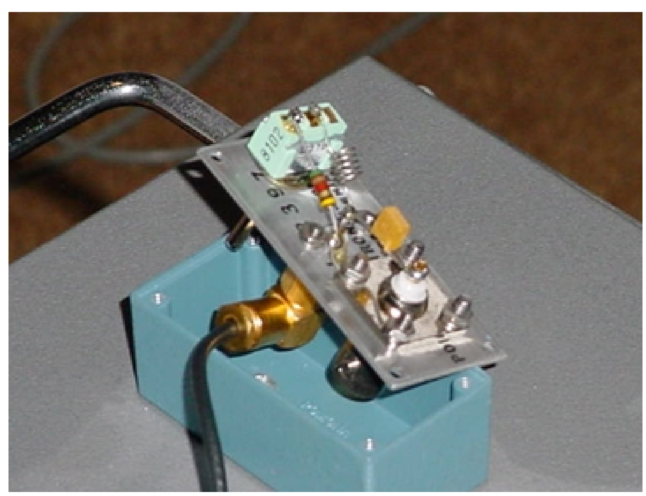

Photo F: GPS76 Bias Tee, Internal View

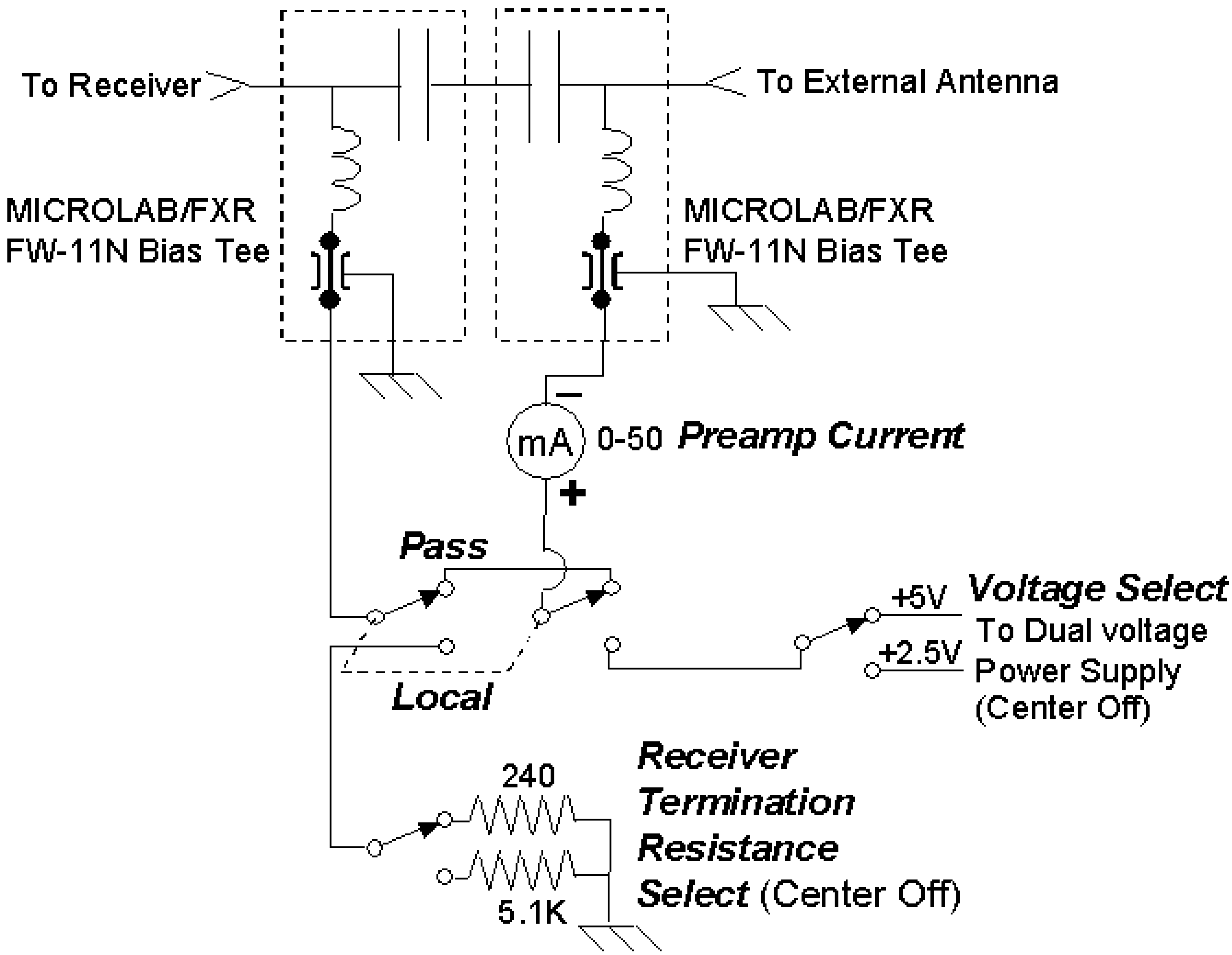

Figure 5: Universal bias tee circuit

Photo G: Universal Bias Tee, External View

From Sizzling Hot BBQ to Cool BUD-Lite

Taming the Grid Dish for Space Communications

Anthony Monteiro, AA2TX
aa2tx@amsat.org

Abstract

The three-foot, barbeque-grill (BBQ) dish antenna would seem to be an ideal solution for ham radio satellite communications on S-band. These antennas are widely available, light-weight, inexpensive, and specified to have about 24 dBi gain. However, when these antennas were used for receiving OSCAR-40, their performance was much worse than expected. This paper describes an investigation into the poor performance and how to dramatically improve it. Although OSCAR-40 is no longer operational, future ham radio satellites are expected to make greater use of S-band so there is still a need for a good, cheap antenna for this band.

Introduction

The three-foot, barbeque-grill (BBQ) dish antenna would seem to be an ideal solution for satellite communications on S-band. These antennas are widely available, light-weight, inexpensive, and specified to have about 24dBi gain. As OSCAR-40 was being prepared for launch, the combination of a modified Drake 2880 down-converter paired with one of these BBQ dishes was believed to be a terrific way to receive the new satellite on its 2.4GHz downlink without incurring a big expense.

However, when these antennas were used for receiving OSCAR-40, their performance was worse than expected, leaving many hams disappointed. To some extent, this was due to the failure of AO-40's high-power, S1 transmitter leaving only the lower-power, S2 transmitter operational. However, even with the lower-power transmitter, the BBQ grid dish looked, on paper, like it should have been adequate. So why was the performance so poor? This paper investigates the reasons for the poor performance and describes modifications that can dramatically improve it. Although OSCAR-40 is no longer operational, future satellites, including AMSAT-ECHO are expected to make greater use of S-band so there is still a need for a good, inexpensive antenna for this band.

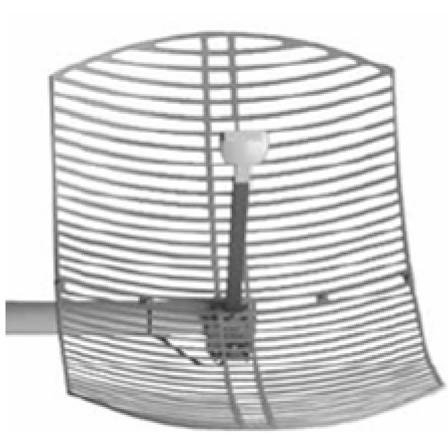

Figure 1. BBQ-grill Dish Antenna

An investigation by Scott Townley, NX7U, was helpful in understanding one of the key issues[1]. He modeled a BBQ-grill dish with a dipole feed using the NEC-2D antenna analysis program. His modeling shows that the dipole feed over-illuminates the dish, especially in the long dimension, causing significant side-lobes. These side-lobes pick up noise from the warm earth and cause the overall antenna temperature to increase.

In order to perform some actual tests, the author purchased a BBQ-grill antenna on eBay for $50. A photo of this antenna is shown in Figure 1. There are several manufacturers of these antennas and they vary a bit in their exact dimensions. However, all of them are about 39 inches by 24 inches, use a dipole feed, and are specified to have 24dBi ±1dB gain on S-band.

[1] NX7U analysis available at http://members.cox.net/nx7u/ao40/bbqdish/BBQGridNec.htm.

Baseline Performance Test

The author assembled a very low noise receive system to use in testing the antenna. This system consisted of a Down East Microwave 13ULNA preamp feeding an AIDC-3731AA down-converter. The output of the down-converter was fed through a JFW Industries Model 50DR-055 Step Attenuator into a Yaesu FT-817 radio used as the intermediate frequency (IF) receiver. The FT-817 is ideal for testing since it allows the automatic gain control (AGC) to be disabled which allows linear measurements to be made. The FT-817 audio output was fed into a Hewlett-Packard 400L AC Voltmeter.

The preamp was measured at 0.28 dB noise figure and 16 dB gain and the down-converter was measured at 1.37 dB noise figure and 37 dB gain. A 3-foot jumper of 9913FX coax was used between the preamp and down-converter. This combination has an excellent noise temperature of a mere 23K. For comparison, the AIDC down-converter alone, which is a very good unit, would be around 109K and a modified Drake 2880 down-converter has a noise temperature of nearly 1,600K.[2]

For testing, the antenna was pointed with an azimuth-elevation positioner made from a pair of Gemini TV antenna rotators on a tripod as shown in Figure 2. The light weight and low wind-resistance of the BBQ-grill antenna make this possible and would help to keep the total costs low for a permanent system.

Figure 2. Test azimuth/elevation positioner made from TV antenna rotators

[2]Drake 2880 with modifications as per Masa Arai, JN1GKZ. As tested at the AMSAT-UK colloquium, July, 1998 and reported by David Bowman, G0MRF. The Noise Figure is 7.8 dB and the gain is 15.5 dB.

The antenna was pointed at OSCAR-40 and the S+N/N ratio of the beacon was measured while the transponder pass-band was on. The beacon measured 15.5 dB above the noise (S+N/N) with the satellite range at 62,067 Km and an off-pointing angle of 5.5 degrees. The antenna gain was assumed to be 24 dB as specified by the manufacturer. Using the Microsoft Excel spreadsheet, ao40v2.1.xls[3] from Gene Marcus, the effective antenna temperature was calculated at 156K. This is a very high noise temperature for a space communications antenna. While one may delight in the *hottest* new radio equipment, this is not a good thing for a satellite antenna and it explains why the resulting performance has been poor.

A Better Feed

The author modeled the dipole feed using EZNEC[4] and concluded that it was not possible to make a simple modification of this feed that would not over-illuminate the dish.

To replace the dipole feed, the author designed a linearly-polarized, horn feed that would provide better illumination of the dish. For terrestrial communications, a -10 dB illumination taper at the dish edge is typically used because it provides the best gain. For satellite communications, a -13 dB or sometimes higher illumination taper is often used even though this causes a reduction in the gain of the antenna. This slight under-illumination of the dish causes an even greater reduction in the effective noise temperature and so produces a better signal to noise ratio for receiving signals from space.

The BBQ-grill dish poses a special challenge because it is not symmetrical. If both dish dimensions were tapered at -13 dB, the dish gain would be substantially reduced. Instead, the author estimated that the best compromise would be achieved with an illumination taper of -13 dB on the long dimension edges and about -10 dB on the short dimension edges of the dish. This was expected to cause only about a ½ dB reduction in gain compared to the dipole feed although some additional thermal shielding might be then needed if there was too much noise pickup from along the short dimension.

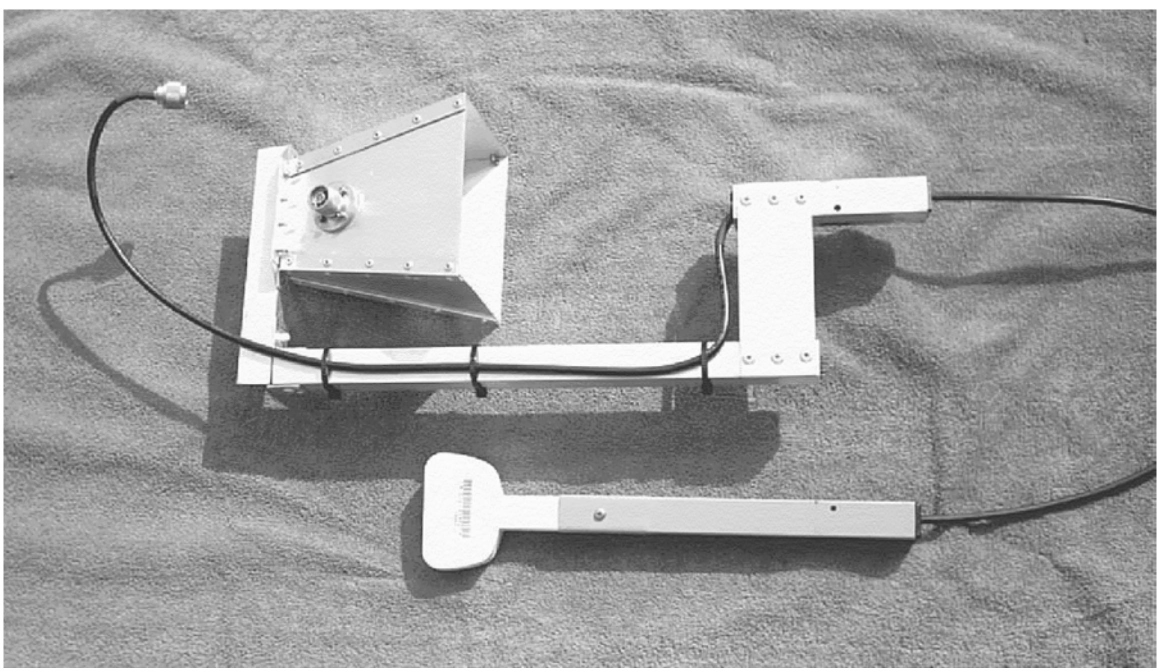

Figure 3. Horn (top) and dipole (bottom) dish feeds

[3] Spreadsheet ao40v2.1.xls is available at http://www.knology.net/~gmarcus/ao40/ao40v2.1.xls.
[4] EZNEC antenna modeling software is available at http://www.eznec.com/.

Though not necessarily ideal, the horn mounting arrangement was made compatible with the center clamp on the dish used to mount the dipole feed. This allowed the feeds to be easily and quickly swapped and facilitated comparisons between them. A photo of the horn and dipole feeds is shown in Figure 3. Note that the horn was fitted with a male N-connector to allow a preamp to be directly connected with no feed-line. The coax-pigtail connects to the output of the preamp. Details of the horn feed construction are in Appendix A.

Sun Noise Testing

To compare the feeds, sun noise testing was used. The basic procedure consists of pointing the antenna straight up to set the background noise level and then pointing the antenna at the sun and noting the increase in detected noise. This is an easy way to compare the feeds as the sun is a fairly stable noise source with no spin modulation, no off-pointing angles, and minimal range variation. The sun noise temperature is stable over several hours allowing a rather leisurely approach to the measurements. It is also easy to find in the sky; no tracking program is needed.

The dipole feed was fitted first and the sun noise was measured at +1.5 dB above the background noise. Next, the horn feed was set up on the dish and the sun noise was measured again. It measured a surprising +1.4 dB. The measurements were repeated to assure that there was no mistake.

This was a very interesting result. The horn feed was expected to cause the dish gain to decrease by ½ dB or so due to the slight under-illumination (-13 dB) of the long dimension. But the background noise level should have decreased much more and the sun noise should have been higher than with the dipole feed. That is not what happened. This could only mean that the high noise temperature of the dish is not caused just by over-illumination of the feed. There had to be another source of noise.

The author hypothesized that the noise was actually coming from the warm earth *through the dish surface*. Subsequent modeling with EZNEC showed that the dish surface is nearly opaque for co-polarized signals or noise but it is virtually transparent to cross-polarized signals or noise. Since the earth noise is randomly polarized, it seems that there was enough randomly polarized earth noise coupling into the feed through the dish surface to substantially increase the overall noise temperature. For the dish's intended applications (i.e. MMDS, WiFi etc.,) this would not matter. In terrestrial applications, the noise is the same in front or in back of the dish. But for space communications, the earth noise temperature of 300K is much higher than the space background noise temperature which is only around 8K at 2.4 GHz.

To test this theory, the author covered the dish surface with aluminum foil, holding it in place with packing tape. Then the measurements were repeated. This time, there was a substantial improvement with both feeds. The dipole measured +1.9 dB and the horn a little better at +2.0 dB.

Knowing that the horn illumination taper is only -10 dB at the center part of the dish, a set of thermal shields were fashioned out of aluminum foil and attached to the short sides of the dish, extending out a few inches. With these shields in place, the measurements were again repeated. Again, there was a significant improvement. This time the dipole feed measured +2.0 dB and the horn feed measured +2.4 dB of sun noise. All of these measurements were made within a few minutes of each other so the results were directly comparable. The results were clear, the dish noise can be dramatically reduced by covering the dish surface with a conductive material and by adding some shielding to the short sides of the dish.

With this in mind, the aluminum foil was removed and a more permanent approach was devised. Instead of the foil, aluminum window screening was attached to the dish surface with aluminum wire. The screen used was three-feet wide and it was centered on the short dimension of the dish, leaving a few inches hanging over each side of the dish. This excess screening does not conform to the parabolic shape of the dish and so does not contribute to gain but it was left in place to act as a thermal shield to reduce the noise with minimal effort. A photo of the horn feed mounted to the screened dish is shown in Figure 4.

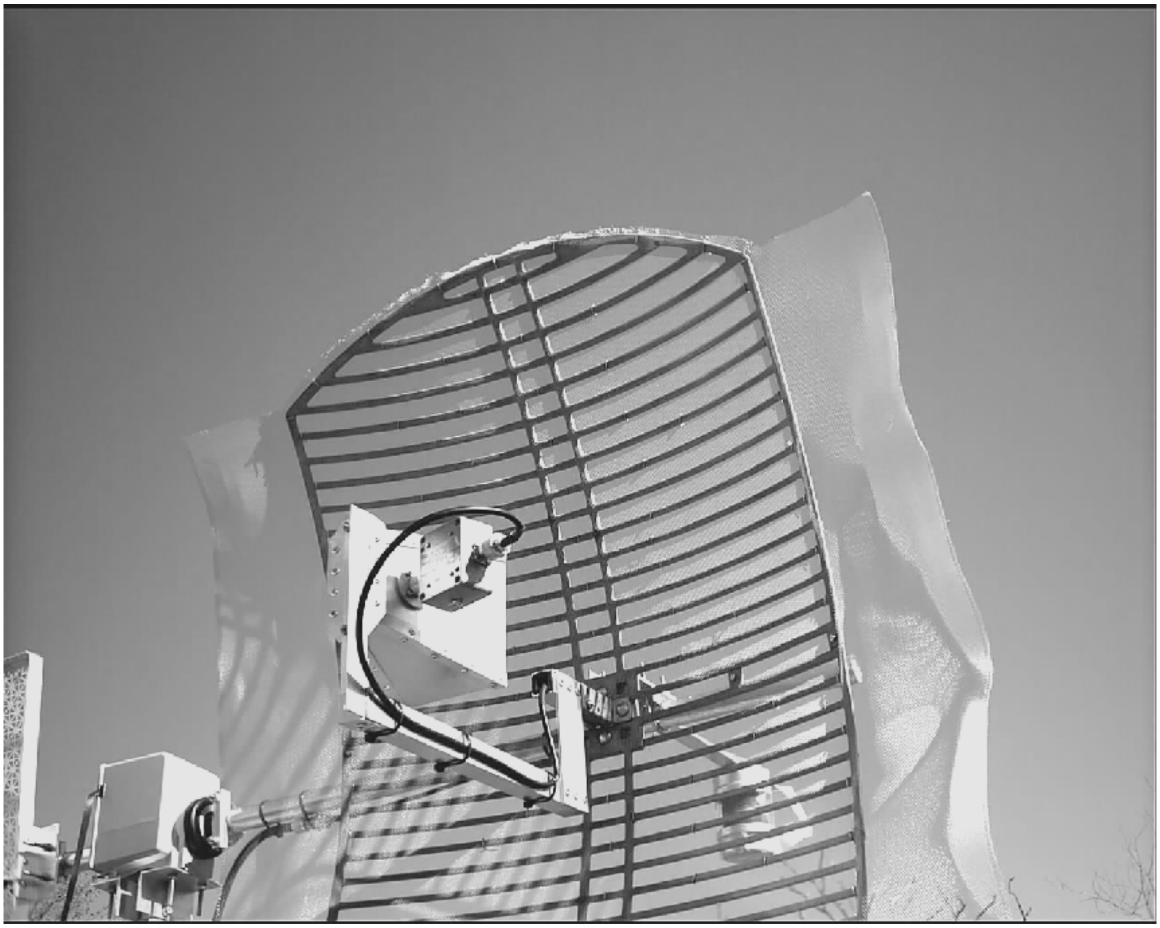

Figure 4. Horn feed mounted to screened dish

The “screened” dish was then tested again for sun noise. Again, there was an improvement in both feeds with the dipole feed measuring +2.1 dB and the horn measuring +2.5 dB of sun noise. A chart showing the measured sun noise for each configuration is shown in Figure 5. These measurements were all made during the same afternoon and the improvement, at first glance, might not appear to be that significant but in fact it represents a dramatic reduction in the dish noise temperature.

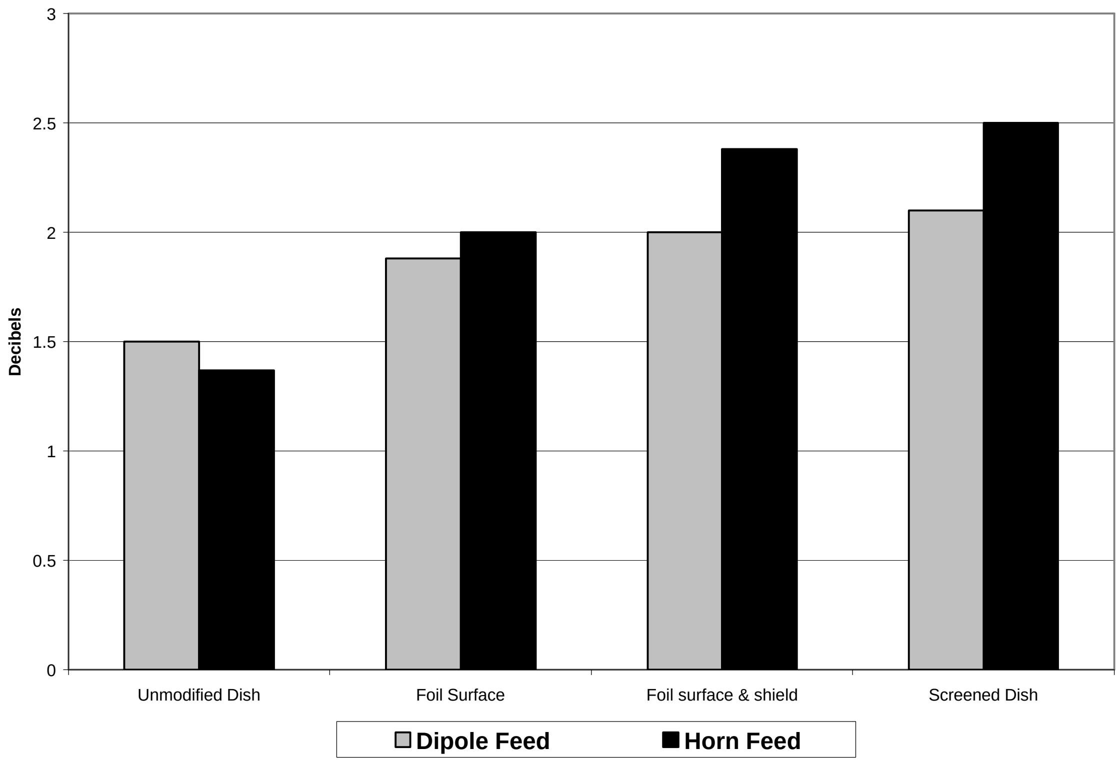

Figure 5. Sun noise comparisons

Modified Dish Performance

The newly screened dish antenna was again pointed at OSCAR-40 and the S+N/N ratio of the beacon was measured while the transponder pass-band was on. With the dipole feed, the beacon measured +17 dB above the noise (S+N/N.) With the horn feed, the beacon measured +18.5 dB above the noise (S+N/N.) This was measured with the satellite at 60,364 Km and an off-pointing angle of 12.6 degrees.

Again using the ao40v2.1.xls spreadsheet, the new effective antenna temperatures were calculated. For the dipole feed, the effective antenna temperature was reduced to 97K. This represents a pretty impressive reduction in noise temperature of nearly 60K. With the horn feed, the effective antenna temperature was reduced to only 50K which is a reduction of over 100K. To put this in perspective, the effective noise temperature of the antenna was reduced by more than the difference in temperature between boiling hot water and ice.

Make Mine a BUD-Lite!

The modified BBQ-grill dish, with 23.5 dBi gain and a 50K noise temperature is still not quite up to the *Big Ugly Dish* (BUD) performance standard. However, by using a reasonably low-noise preamp or down-converter right at the horn feed, it is possible to get to nearly BUD performance. A modest 0.5 dB noise figure at the front end is all that is required. Preamps and down-converters at this performance level are readily available at a reasonable cost. The resulting *BUD-Lite* configuration is light-weight, low-cost, and can be assembled from readily available components. The complete antenna weighs only about 7 lbs. and, with the low wind-resistance, would allow inexpensive TV antenna rotators to be used in a permanent system which would help keep the overall system costs low.

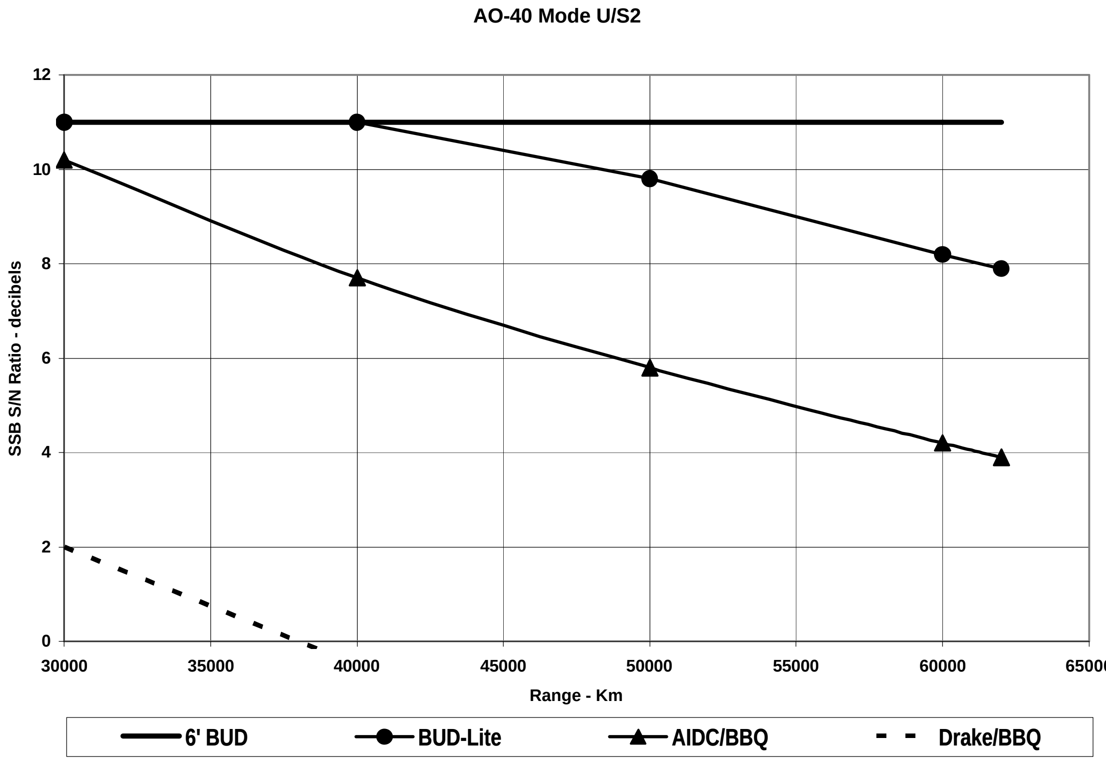

Figure 6. Configuration performance comparisons

Performance Comparisons

To help illustrate the relative performance that can be expected, a comparison chart was developed as shown in Figure 6. This chart shows the calculated signal-to-noise ratio of an SSB signal from OSCAR-40 plotted against the satellite range at a 0° off-pointing (squint) angle. The satellite was assumed to be in mode U/S2 and the SSB signals were assumed to be at the recommended level of -10 dB relative to the satellite beacon. Note that the LEILA[5] limit is actually +2 dB higher than the received signal level that is used in the chart.

Several configurations are shown for comparison. At the top of the chart is the performance of a 6-foot *big-ugly-dish* (BUD) with a circularly polarized feed and an AIDC-3731AA down-converter. With this configuration, the S/N ratio is limited only by the transponder noise all the way out to apogee. This is the *gold standard* by which the other configurations should be compared. Of course, not everyone can put up a BUD in their backyard (or apartment!) so other *compromise* configurations may also need to be considered.

At the bottom of the chart is the basic unmodified BBQ-grill dish with a dipole feed and a Drake 2880 down-converter. Recall that this was the system that was considered, at one time, to be ideal to receive AO-40. With this system, it should be possible to hear the beacon but the signal to noise ratio on SSB is so bad that even at a mere 30,000 Km, no reasonable SSB contacts would be possible.

The next step up was probably the most commonly attempted configuration with the BBQ-grill dish. This is the basic unmodified dish with its dipole feed into an AIDC-3731AA down-converter. This is not a terrible system out to about 40,000 Km. But as shown in the chart, the signal to noise ratio becomes pretty low as

[5] The LEILA device on AO-40 limits the uplink power that may be used.

the satellite approaches apogee. At 50,000 Km, the S/N ratio is down to only 6 dB and at apogee the S/N is below 4 dB which would be quite difficult to copy.

Finally, the line just below the 6-foot BUD is the BUD-Lite configuration. This is the screened BBQ-grill dish with the horn feed and a 0.5 dB noise figure front end. Note that up to 50,000 Km the signals from this antenna would be virtually indistinguishable from the 6-foot dish. Even at apogee, the SSB S/N ratio would still be around 8 dB. While not quite *arm-chair copy*, these signals would be fully readable and only slightly degraded from the big dish.

In the interest of fairness, it should be noted that the BUD-Lite performance remains pretty good up to about a 10° off-pointing (squint) angle. On OSCAR-40, all linearly polarized antennas suffered from an increase in fading due to spin-modulation at angles much above this. A real BUD with a circularly-polarized feed would have had significantly less fading at the higher off-pointing angles[6]. Of course, for many of us, a 6-foot dish is not a viable option anyway, so a small, cheap antenna system that works almost as well is a highly desirable option, even if it comes with some limitations.

Summary

This paper examined the unexpectedly poor performance of the barbeque-grill dish antenna and found that the antenna noise temperature was a very high 156K. This high noise temperature was apparently caused by both earth thermal noise passing through the dish surface and spillover from the dipole feed. The effective antenna noise temperature can be reduced by over 100K by adding aluminum screening to the dish surface and changing to a horn feed.

When combined with a low-noise front end, the antenna's performance in receiving OSCAR-40 approached that of a 6-foot *big-ugly-dish* (BUD,) earning it the moniker *BUD-Lite*. While OSCAR-40 is no longer operational, future ham radio satellites, including AMSAT-Eagle and P3E, are expected to make significant use of S-band downlinks so there is still a need for a good, cheap antenna for this band. For those of us who cannot install a real BUD, the BUD-Lite antenna configuration may be a worthwhile consideration especially since it can be assembled inexpensively from readily available parts.

[6] "What does Circular Polarization of the Antenna Add to Satellite Operations," by Franz J. Bellen DJ1YQ, *The AMSAT Journal*, Jan/Feb 2004, pages 26-28.

Appendix A
Constructing the AA2TX BBQ-dish Feed

Description

This BBQ-dish feed is a pyramidal horn designed to illuminate an Andrew Model 26, aluminum, die-cast, parabolic grid reflector. This dish is manufactured by Andrew Corporation but is apparently sold by many antenna vendors including Pacific Wireless. The dish is 39.25” across and 7.5” deep on its long dimension and 23.5” across and 2.75” deep along the short dimension. It has a focal point 12.75” from the dish surface.

This horn feed may be used with other 3’ x 2’ BBQ-grill dishes but make sure to position the mouth of the horn at the proper focal point of the dish which may differ from 12.75”. The horn feed is designed to provide a 150°-wide illumination pattern along the long dimension and a 102°-wide illumination pattern along the short dimension. The illumination pattern of this horn might not be optimal for another brand of BBQ-dish although it should still work satisfactorily if the required patterns are not too different.

Materials

Note that the horn dimensions are critical for proper operation, but the horn construction is not. The author constructed his horn entirely out of aluminum and used aluminum pop rivets to assemble it. Aluminum is ideal because no painting or other finishing is required to weatherproof it. However, other metals and construction techniques could be used. For example, copper sheet could be used and the horn soldered together but the finished horn would then need to be plated or painted to survive outdoors.

Note that the electro-magnetic design was done using SI (metric) units and all of the design dimensions are given in centimeters. However, all of the materials that were used in the construction are sold in “inch” dimensions so please be aware of the mixed units.

The horn was constructed out of 1/64” sheet aluminum. It is held in shape by a skeleton made from ½” x ½” by 1/16” angle stock. Aluminum, 1/8” pop rivets were used to attach the sheet aluminum to the angle stock. Stainless steel nuts and bolts were used to attach the horn to its mounting bracket.

In order to make the horn mounting bracket compatible with the dipole feed, a 5 ¼” long piece of 1” x 1” by 1/8” square, hollow tube stock was used to fashion a compatible mounting stub. This stub plugs into the clamp on the dish and is held in place with a stainless steel nut. The rest of the horn mount was made from this same tube stock as well as a few other odd scrap pieces of aluminum angle and bar stock. Needless to say, this part of the feed is not critical and the builder should feel free to use whatever is convenient for them.

Construction

The horn dimensions are critical so cut the horn panels as accurately as possible as shown in Figures 8, 9, 10 and 11. The 1.5 cm rectangular sections on the top, bottom, and side panels are bent outward to make a flange along the line shown with “bend” on each drawing. When the horn is assembled, these should stick out at a 90° angle from the axial length of the horn.

Horn side panel “A” has a hole 4.7 cm from the mouth edge to accommodate a probe that tunes out the horn reactance. The probe used was a 1.5” aluminum screw post but a #8 stainless or aluminum screw may be used instead. If a screw is used, it should be adjusted so it sticks 1.5 inches into the horn. No other adjustment should be necessary. Drill the hole in the side panel to accommodate the material used for the tuning probe. The hole should be centered on the panel as shown in Figure 9.

Horn side panel “B” must be drilled to accommodate the type of N-connector you use. The center hole of the connector should be centered on the panel as shown in Figure 10. Before attaching the N-connector, solder a 3 cm piece of #12 (AWG) of insulated copper wire to the connector center conductor at a 16° angle. After soldering, cut the wire so the total length that sticks out from the connector mounting flange is 2.1 cm. This forms the coupling probe. Attach the N-connector to the side panel so that this coupling probe is parallel with the back panel of the horn.

Four ½" x ½" x 1/16" angle stock sections are cut to run along the edge of the horn approximately 15.7 cm long. These will need to be filed or carefully cut to fit the side seams. The angle stock is used on the outside of the horn panels and was attached with pop-rivets to the horn panels. The horn side panels, angle stock

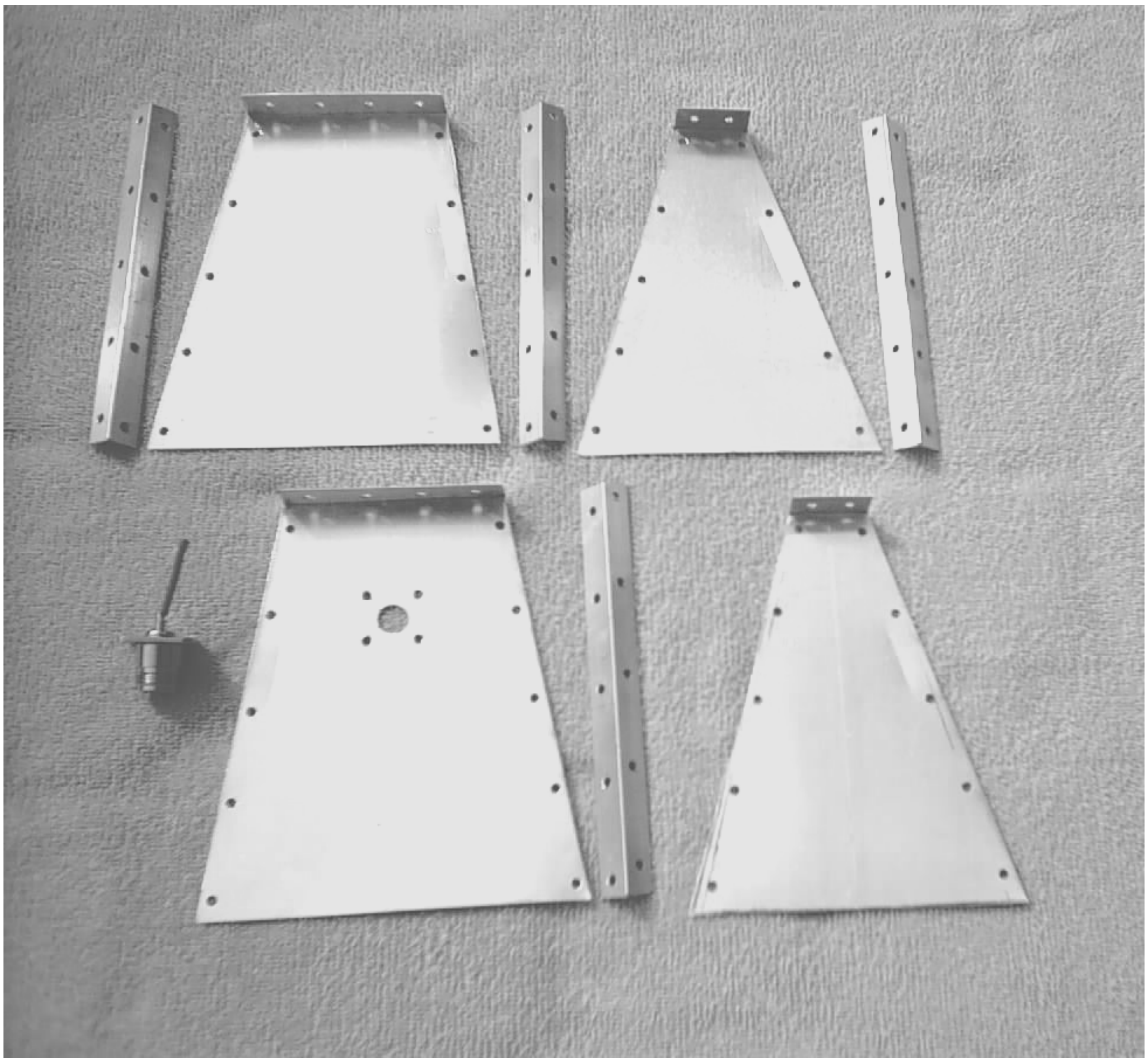

Figure 7. Horn side panels, angle-stock, side seams, and N-connector with probe before assembly

side seams, and N-Connector with coupling probe are shown as they looked before assembly in Figure 7.

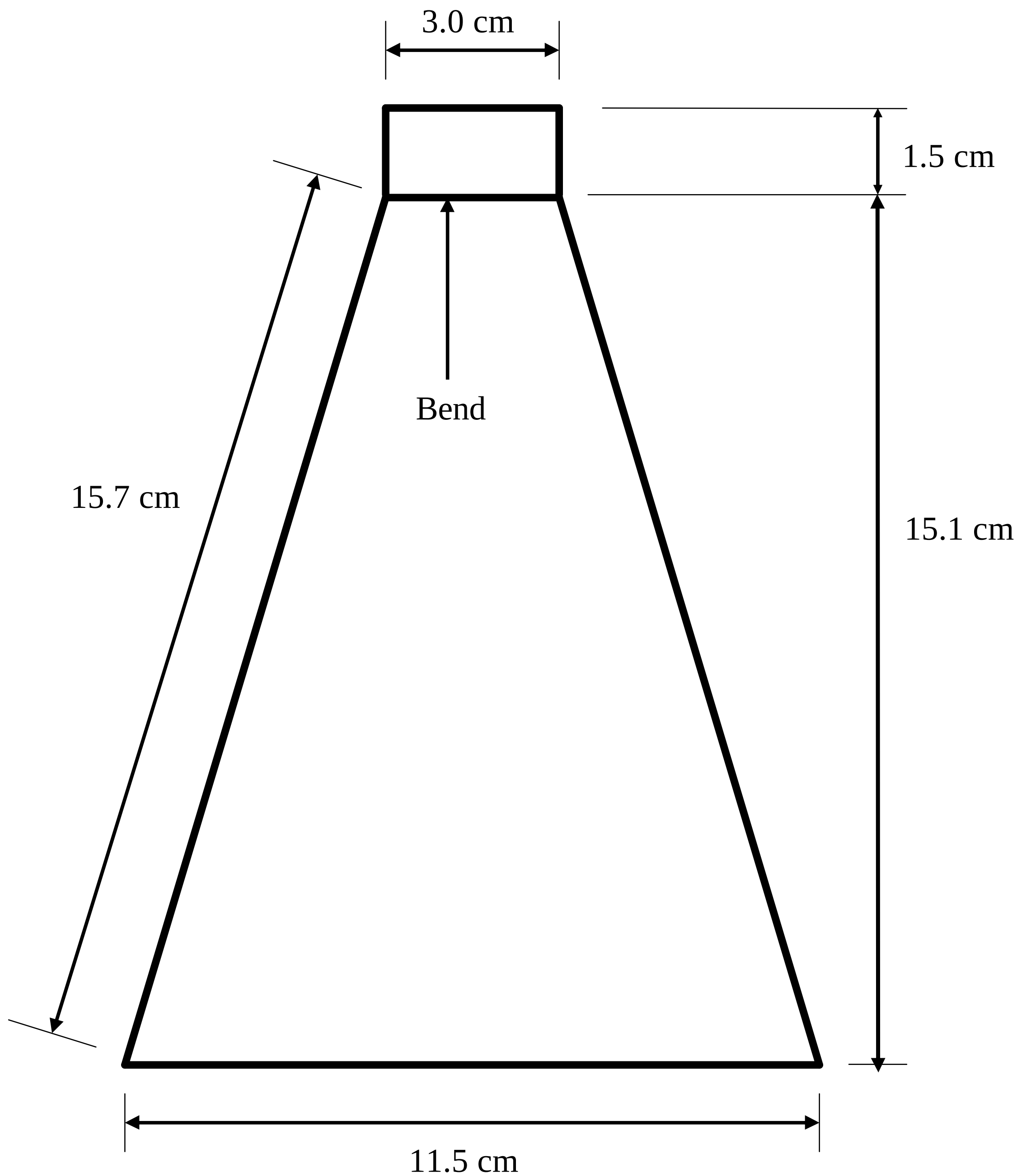

Figure 8. Horn top and bottom panels

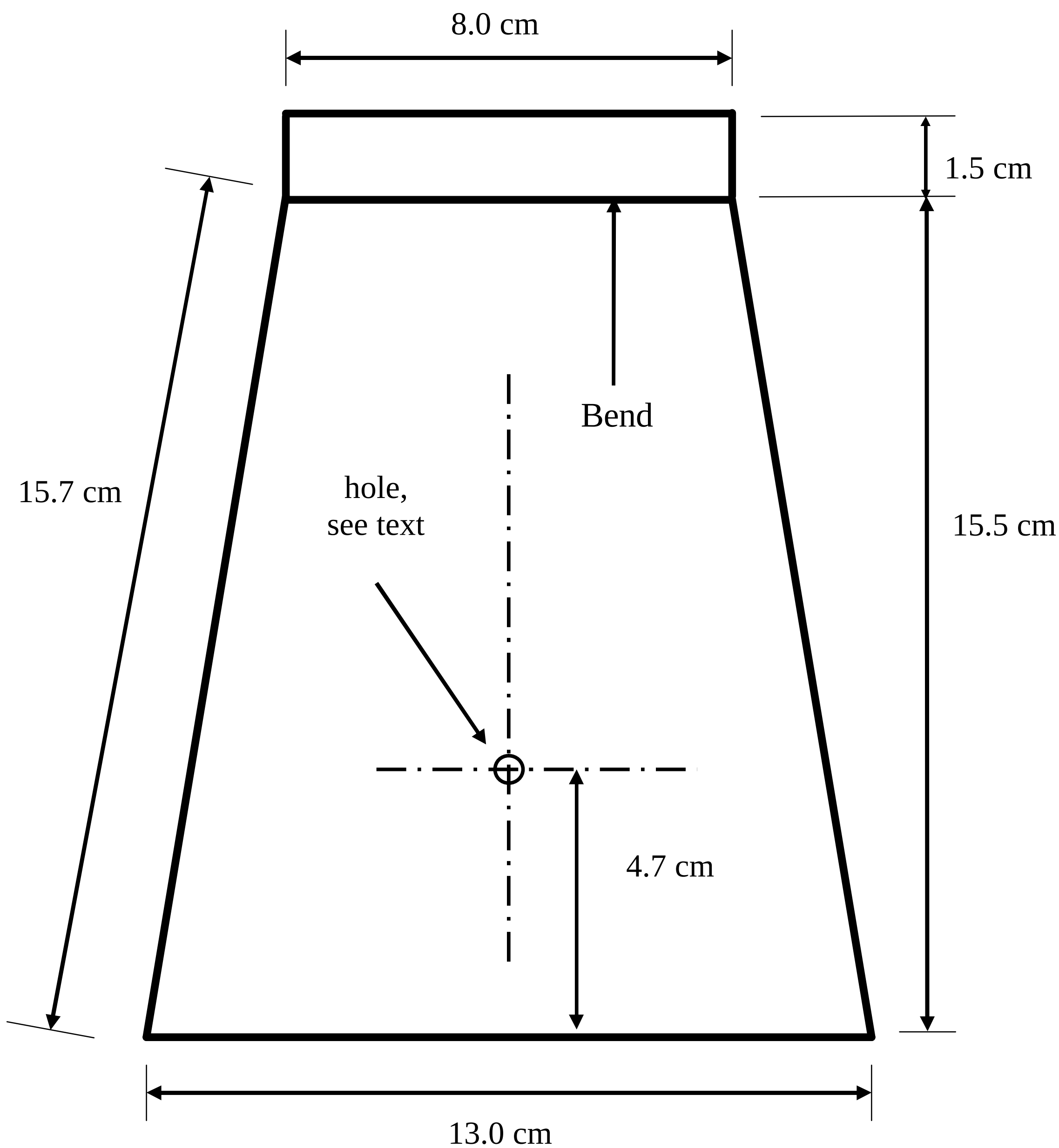

Figure 9. Horn side panel “A”

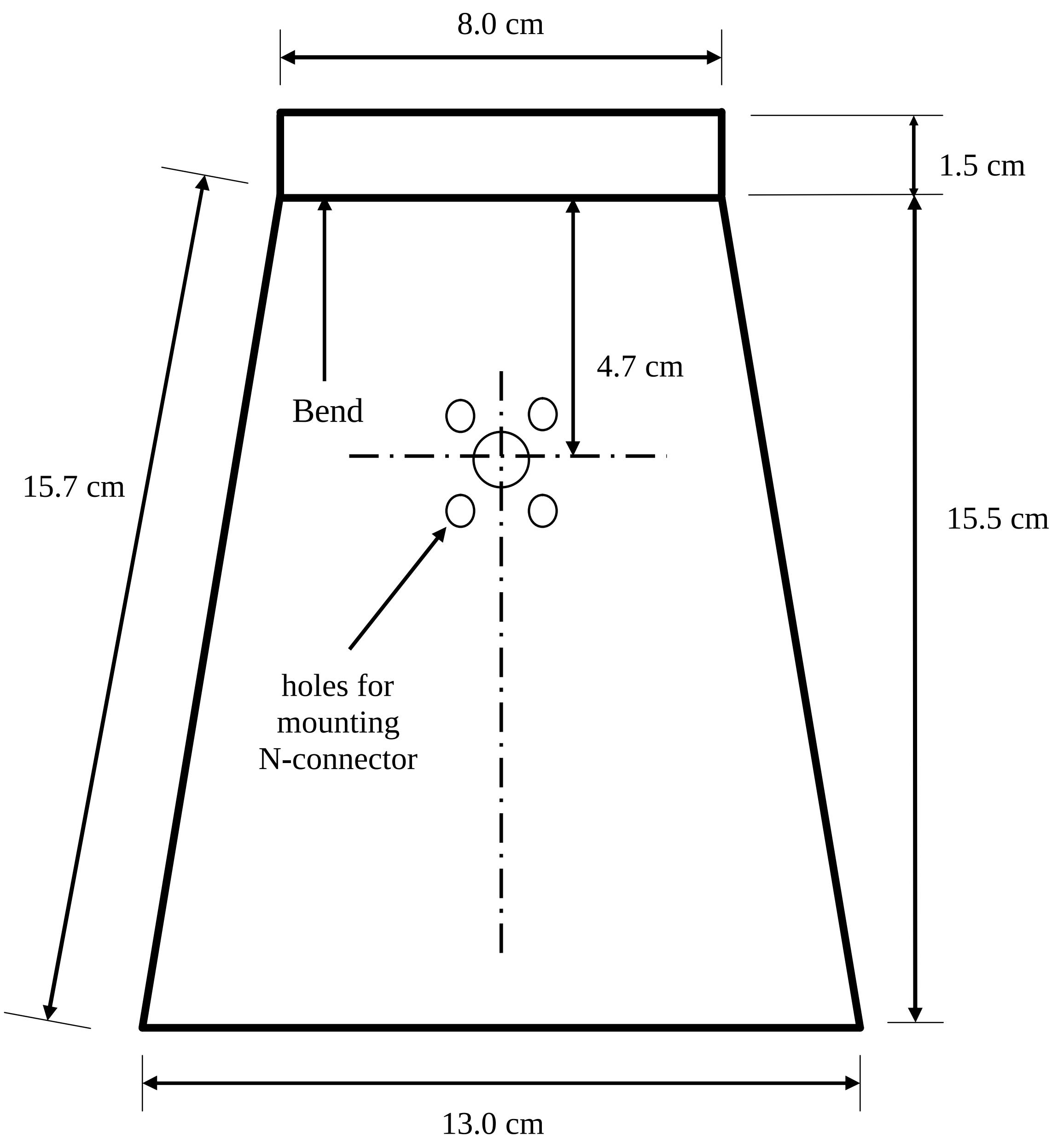

Figure 10. Horn side panel “B” with N-connector

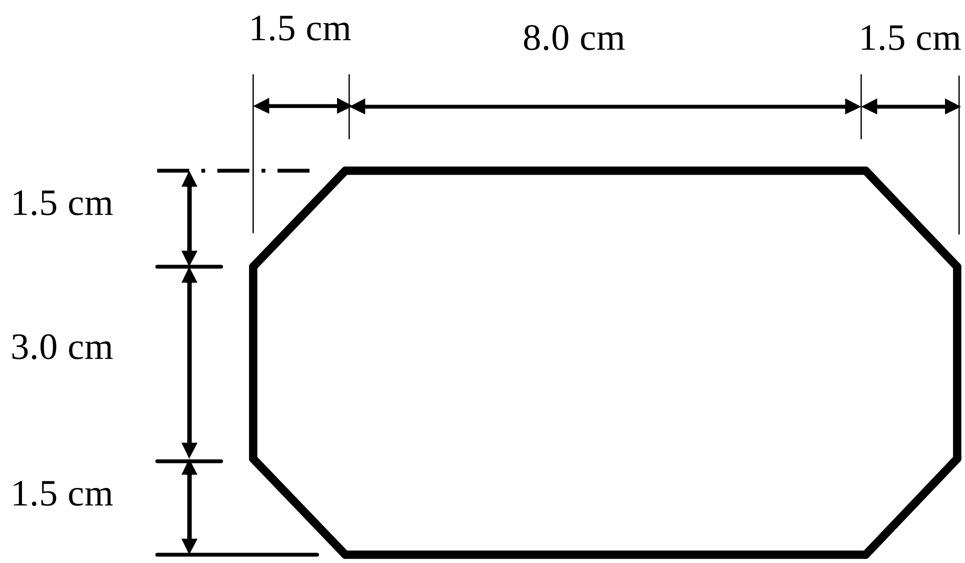

Figure 11. Horn back panel

The back panel attaches to the flange made from the bent part of the side panels. Pop rivets were used to attach the long sides and #6 nuts and bolts were used on the short sides to provide a way to mount the horn to its mounting bracket. After assembly, the horn should look as shown in Figures 12 and 13.

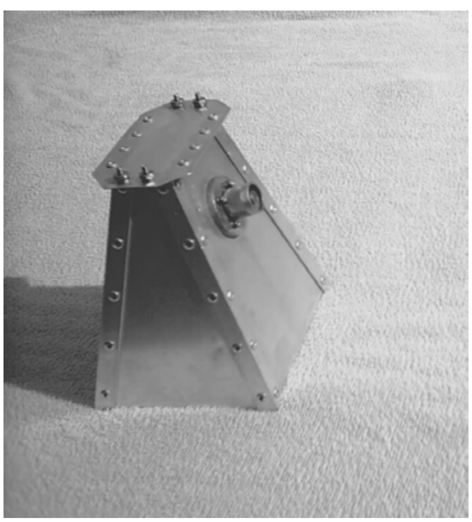

Figure 12. Completed horn

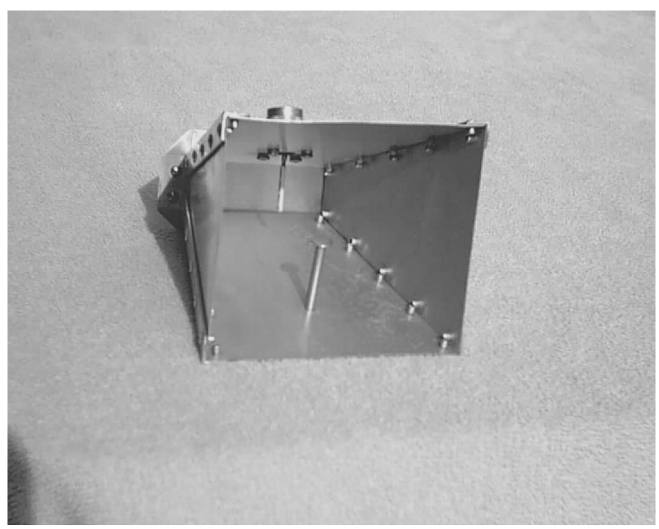

Figure 13. Looking into horn mouth

Mounting the Horn

The horn mounting bracket is not critical and any type of construction may be used. For the Andrew Model 26 reflector, the horn mouth must be positioned 12.75” from the dish surface (i.e. at the focal point.) It is important that any metal used in a bracket, that is in front of the horn mouth be perpendicular to the horn coupling probe, cross-polarized from the horn E-field. Otherwise, distortion of the horn radiation pattern may result. The author assembled a mounting bracket from scrap aluminum and as shown in Figures 14 and 15. An LMR-240 coax jumper is used to connect to the preamp. The completed horn is shown mounted to the dish in Figure 16.

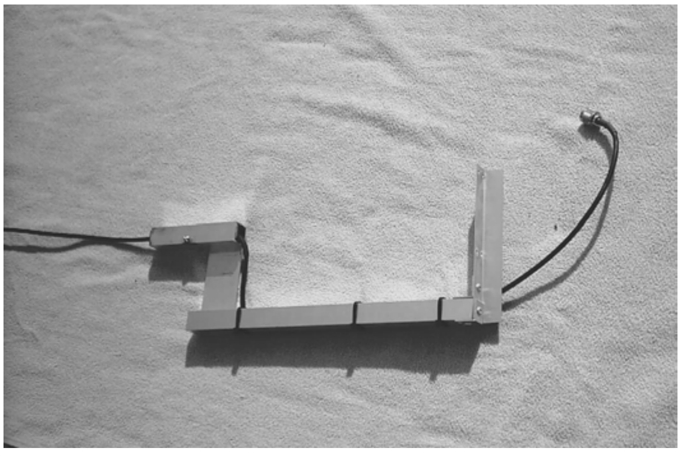

Figure 14. Horn mounting bracket

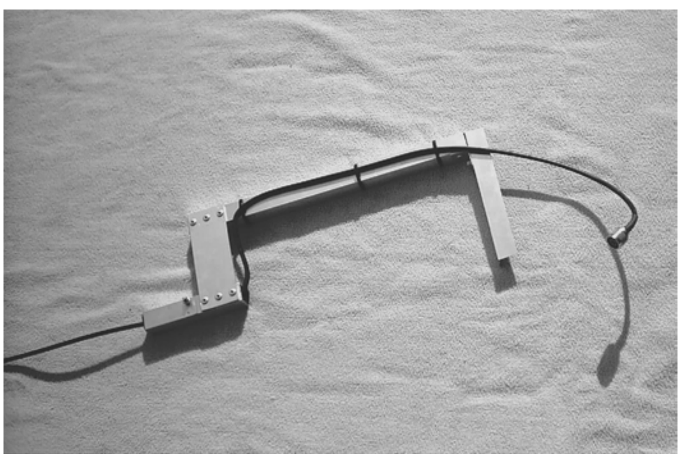

Figure 15. Horn mounting bracket

Figure 16. Completed dish antenna with horn feed

The horn return loss was measured at -20dB which should be fine for any preamp or down-converter. The photo in Figure 16 shows the completed antenna with a Down East Microwave 13ULNA preamp mounted to the horn feed.

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Abstract. Finding an affordable launch opportunity is key to the success of any amateur satellite project. The Department of Defense (DoD) Space Test Program (STP) provides launches, at no cost to the experimenter, for DoD-sponsored experiments that demonstrate DoD relevance and technical merit. Amateur satellite builders seeking an STP launch must find a DoD or Federal sponsor and present their proposal for review by the DoD Space Experiments Review Board (SERB), which ranks proposed space flight experiments. The STP has launched several amateur satellites, and undoubtedly offers opportunities for future amateur satellites, perhaps even for AMSAT's Eagle.

Introduction

Amateur satellite activity is limited by, more than any other factor, the ability of amateurs to place satellites into orbit. Amateurs have repeatedly demonstrated tremendous resourcefulness in designing and constructing satellites on very limited budgets. Who else but amateurs could even conceive that a handful of guys with a $2000 budget could actually build their own satellite, much less have it successfully placed into orbit[16]? Or that a team composed largely of undergraduate woman could proudly point to *their* own on-orbit satellite[13]? However resourceful they might be, amateurs have not yet developed their own orbital launch capability. In the interim, they must scrounge free or reduced-cost rides on "professional" launches. The Department of Defense (DoD) Space Test Program (STP) is one potential source of free flights. In fact, this program has already launched several amateur satellites, including the two mentioned above. Of course, obtaining free rides into orbit isn't easy. But, "you can't win, if you don't play." This note offers some thoughts about competing for STP-sponsored flights. Preceding that, it describes the DoD Space Test Program itself and the process by it selects the experiments that it will support.

The DoD Space Test Program

The DoD Space Test Program STP "provides support to the DoD space research community by centrally financing the launch and initial operations costs for experiments with military relevance whose scope ranges from basic research to advanced development[18]". Of even greater interest to amateurs, the STP "provides spaceflight for qualified DOD sponsored experiments at *no charge to the experimenter*" [emphasis added][21]. What is this Space Test Program? And, more importantly, how can amateurs join the "DoD space research community" and have their satellites designated as "DoD sponsored experiments" and launched into orbit at no cost?

The STP was established in 1966 to provide flight opportunities to the Defense research and development community. By early 2000, the STP had launched 410 payloads on 150 missions[14]. These payloads included "free-flyers" (spacecraft deployed by the Space Shuttle or by an expendable launch vehicle), secondary (or piggyback) payloads hosted on another spacecraft, and experiments flown on the Space Shuttle (either in the pressurized Middeck of the crew cabin or in the cargo bay). More recently, STP experiments have flown on the International Space Station (ISS). The STP is proud of what these missions have accomplished. Lt. Col. Perry Ballard states that "Every operational DOD space system originated as an STP experiment – STP is the future of DOD Space[3]".

Fortunately for amateurs, the DoD has a broad view of who qualifies for STP support: "DOD experiments normally originate in the Service (Army, Air Force, Navy, NASA) laboratories or research institutions (colleges, universities, think tanks, etc.) but are in no way limited to these institutions[21]". The title of Lt. Col. Ballard's presentation makes the STP's broad intent clear: "The DOD Space Test Program and University Satellite Projects: Launch Opportunities". Of course, the STP has limited resources and can't satisfy every request for a free launch. It is the responsibility of the Satellite Experiment Review Board to identify the experiments that best advance the objectives of the STP and warrant STP support.

The Satellite Experiment Review Board

The Satellite Experiment Review Board (SERB) is tasked with maintaining the DoD Experiment Priority List, which ranks proposed space flight experiments. The STP flies as many of the highest-ranked experiments as its budget and other resources permit.

The SERB Review Process

The first step towards a STP-sponsored space flight is to find a sponsor. Any DoD organization may sponsor an STP experiment, as may non-DoD Federal agencies. While experiments *can* originate outside of the DoD and other Federal agencies, this is clearly the exception rather than the rule. The process by which an outside organization finds a sponsor appears to be largely informal. This undoubtedly involves convincing the potential sponsor that your experiment will support the objectives of the organization and the STP. In spite of these challenges, several university satellite programs have been successful in finding sponsors.

The sponsoring agencies are expected to rank the experiments that they submit to the SERB. For some agencies, this involves an evaluation process modeled on that used by the DoD SERB. The Navy SERB maintains an informative, publicly accessible Web site that describes its activities, processes, and evaluation criteria, which are similar to those of the DoD SERB[24].

The DoD SERB review process culminates in a review meeting during which the proposed experiments are ranked. Each presenter has 15 minutes to make his or her case. The SERB provides a five-slide outline that summarizes the concept (objective and description), justification (military relevance, need for spaceflight and comparison to alternatives), and a few other details about the proposed space flight experiment. The sponsoring agency must also submit a DD Form 1721, "Space Test Program Flight Request". The heart of this 11-page form is two pages on which the experimenter must summarize this same information.

The SERB Web site[19] includes a summary of the process that is used to rank proposed experiments; a more detailed description is contained in Air Force Instruction 10-1202(I), "Space Test Program (STP) Management"[17].

The process by which experiments ranked highly by the SERB are matched up with space flight opportunities is beyond the scope of this paper. What is important to understand is that the STP will provide substantial funding and other support to the experiments that it believes demonstrate DoD relevance and technical merit.

STP Evaluation Criteria

The DoD SERB ranks proposed experiments based on three criteria: military relevance, the quality of the proposed experiment, and the priority assigned by the sponsoring agency[20]. These factors are weighted 60%, 20% and 20%, respectively, to compute a composite score for each experiment.

DoD Relevance

DoD relevance is the most heavily weighted evaluation criteria. SERB presentations are expected to demonstrate DoD relevance by explicitly referencing the U.S. Space Command's Long Range Plan and other documents. Fortunately, as is discussed below, "DoD relevance" is an extremely broad concept. In similar circumstances, the writer typically has wide latitude in making his or her case for DoD relevance.

Technical Merit

The SERB wants to sponsor experiments that are likely to be successful, that will generate results that can't easily be obtained without a space flight, and that don't replicate data that are likely to be generated by other experiments. While the written rating criteria don't mention it, the reputation and demonstrated competence of the research team are often important in the evaluation of research proposals in similar environments.

Agency Ranking

The DoD SERB will consider the ranking placed on a proposed experiment by the sponsoring agency. Outside organizations would be prudent to consider how an agency is likely to rank their experiment when they approach potential sponsors.

Competing for an STP Launch

To mangle an old aphorism, "there's no such thing as a free launch". Creating a successful STP proposal, like writing any major research proposal, is a lot of hard work, requiring hundreds of hours of labor. The proposal must convince the SERB that the project has strong DoD relevance and outstanding technical merit. Competition is fierce; the STP can provide space flights for only a small number of the experiments that it deems worthy of support. However, the process of creating even an unsuccessful proposal will be beneficial – the experimenter will have a refined, reviewed proposal that can be submitted in other forums.

Writing Research Proposals

Writing research proposals is hard work, and creating a successful STP proposal is no exception. The researcher must craft an concise, articulate, compelling story about how his or her project will alter the course of history, or at least the small part of history that is of interest to the customer (i.e., the agency soliciting the proposals). Direct, concise presentation is mandatory. The reviewers are likely to be reading dozens of proposals, and will naturally favor those that they can understand quickly and easily. DD Form 1721, "Space Test Program Flight Request", provides two pages in which the researcher must describe the proposed experiment, its relevance to DoD requirements, and why the project is unique. Although the researcher *can* submit additional sheets, reviewers undoubtedly prefer succinct stories. Conversely, a researcher's inability to describe his experiment and its significance in an understandable, one-page abstract often evokes suspicion or skepticism. A one-page abstract can sometimes determine the future of a project. NASA is currently reviewing 750-word abstracts to determine which organizations will even be permitted to submit multi-million dollar proposals in response to the Human & Robotic Technology Broad Agency Announcement[6].

In addition to being well written, a proposal must embody a thorough understanding of the needs of the customer (the sponsoring agency) and of the current state of the relevant area of science or technology.

DoD Relevance

The following quote from the justification for the STP's Fiscal Year 1998 budget provides a sense of the breadth that "DoD relevance" encompasses:

> SPT missions are the most cost effective way to flight test new space system technologies, concepts and designs, providing an inexpensive way to:
>
> - Demonstrate the feasibility of new space systems and technologies
> - Provide early operational capabilities to evaluate usefulness or quickly react to new developments
> - Perform operational risk reduction through direct flight test of prototype components
> - Improve operational design by characterizing the space environment, event or sensor physics proposed for an operational system/system upgrade
> - Develop, test, acquire advanced payload support hardware for Launch Vehicles/Shuttle/ISS
> - Demonstrate and develop responsive R&D space capabilities[18]

Fortunately, agencies have a strong interest in ensuring that researchers understand the challenges for which the organizations need solutions. For example, NASA's Small Business Innovative Research (SBIR) solicitation is a laundry list of technologies that NASA would like contractors to develop[7]. The DoD, NASA, and other Federal agencies release dozens of research solicitations every year that similarly detail numerous space-related research challenges. Agencies document their technology needs in a variety of other formats, including long-range plans and technology roadmaps. The space-related technology needs of the DoD and other

Federal agencies are so great that they provide numerous opportunities for a researcher to demonstrate relevance. A few hypothetical experiments may help illustrate how proposals might tie experiments to unmet technology needs.

- **The integration of satellite services with mobile, wireless terrestrial networks.** Emerging DoD networks, such as Warfighter Information Network – Tactical (WIN-T) and the Future Combat Systems (FCS) network will integrate satellite services to extend connectivity. However, precisely how satellites, particularly those in low Earth orbit, should be integrated with mobile, wireless ground units is not well understood. An amateur satellite could provide a large-scale testbed for proposed satellite/terrestrial network architectures.

- **The use of the Internet protocols in space.** NASA is exploring the use of the Internet protocols to communicate with near-Earth spacecraft and to enable researchers to access on-orbit experimental data from Internet-attached computers[8]. Some of the IP-in-space experiments performed by the NASA Goddard Space Flight Center were conducted on a flight computer onboard UoSAT-12, known in amateur circles as UO-36[11,12]. Presumably, future amateur satellites could support more advanced IP-in-space experiments.

- **Integration of satellites with digital public safety communications.** A recent Air Force solicitation requested proposals to use space communications to support interoperability between public safety agencies, Federal agencies, and the DoD. An amateur satellite ought to be able to support experiments that explore the use of satellite communications to interconnect clusters of digital public safety radios with amateur radio networks.

The challenge for amateur satellite builders is to identify a documented, unmet technology need, show that solving that need is important, and convince the SERB that his experiment is likely to provide a solution.

Technical Merit

The last thing that the SERB wants to do is to waste a valuable launch opportunity on an experiment that is unlikely to provide some useful benefit. Experimenters should convince the SERB that their experiment is well conceived, and that the project team has a excellent grasp of the current, relevant science or technology.

Past STP Support for Amateur Satellites

Amateur satellites[1] *have* been launched through the Space Test Program, including:

- **PANSAT (PO-34)**[23] The Petite Amateur Navy Satellite (PANSAT) was designed and built by the Naval Postgraduate School. Its main objective was to provide students with real-world experience developing and managing a space system. PANSAT also provided store-and-forward services using spread spectrum communications.

- **ASUSat1 (AO-37)**[2] AUSat1 was designed, built, tested, and operated by students at Arizona State University. It carried an amateur transponder and other instruments.

- **OPAL (AO-38)**[15] The Orbiting Picosatellite Automated Launcher (OPAL) microsatellite was designed and built by students at the Stanford University Space Systems Development Laboratory (SSDL). This 51-pound satellite deployed six picosatellites, including the two mentioned in the introduction of this paper. It also carried a number of other instruments and experiments.

- **JAWSAT (WO-39)**[9] The Joint Air Force Academy - Weber State Satellite (JAWSAT) deployed four other satellites, including ASUSat1 and OPAL. The project included several universities, aerospace companies, the Air Force Academy, the Air Force Research Laboratory, and NASA.

- **Starshine 3 (SO-43)**[10] Starshine 3 was an optically reflective spherical satellite designed by the U.S. Naval Research Laboratory and built by volunteers. It carried 1,500 mirrors that were polished by approximately 40,000 students at 1000 schools in 30 countries.

- **PCSat (NO-44)**[25] PCSat was built by students at the U.S. Naval Academy. It continues to forward AX.25 Unnumbered Information (UI) packets.

- **Sapphire (NO-45)**[26] The Stanford AudioPhonic PHotographic InfraRed Experiment (Sapphire) satellite was designed and built by students at Stanford University, and pre-flight integration and post-launch operations were provided by students at Washington University. Its primary mission was to space-qualify micromachined infrared sensors, and also carried a digital camera and a voice synthesizer.

Of course, these terse descriptions don't provide any insight into why the SERB ranked these projects highly. But, a couple of characteristics stand out. First, all of these satellites had substantial student involvement in their design, construction, testing and operations, including undergraduates and graduate students at universities and military academies. Second, they all included one or more scientific experiments or technology demonstrations. This theme is reiterated in Lt. Col. Ballard's presentation: "Basically, STP has committed to the AFA and USNA that if they build a satellite around a SERB experiment we will launch it".

Attracting, inspiring, and developing the next generation of space engineers and scientists is a persistent theme of NASA and the DoD. NASA's mission is, in part, "to inspire the next generation of explorers ... as only NASA can". Early last year, the Air Force's top two space officials told a Senate subcommittee that the development of a "space cadre" was one of their top priorities[4]. All of the amateur satellites launched by the STP have clearly supported this theme.

An STP Launch for AMSAT Eagle?

Should AMSAT pursue an STP launch for Eagle[5]? Absolutely! The work required to create a strong proposal is substantial, the competition is intense, and the odds are long. But, the payoff is so great that, in my opinion, AMSAT would be remiss if it didn't try. The information provided here should provide a good starting point for the preparation of a strong STP proposal for Eagle. It might even put Eagle into orbit!

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Technical, Security, and Regulatory Considerations When Planning the Use of Simplex Telecommand Systems in Small Satellites

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1.0 Introduction:

The availability of low cost transmitter/receiver hardware in SIMPLEX operation[2,3] has come to the attention of many of the universities developing small satellite systems. The concept of using this telecommunications hardware, upgraded for space use, is attractive and has many advantages for low-cost systems. Among the advantages are:

- A potential reduction in the size, mass and average power of the telecommunications hardware on board the spacecraft
- The economy of using only a single frequency for both transmit and receive
- The potential of using a companion radio (a carbon copy of the spacecraft version, but with bigger antennas) for the satellite ground station
- The need for only one simple antenna on the spacecraft
- The potential to operate a common network of satellites (constellation) using half duplex, space-to-space relay techniques

These advantages are compelling. However, one must consider these advantages in the light of other important considerations. It is our intent here to outline the overall "cost" of using simplex telecommunications equipment on board a small satellite system. These recommendations made (and insights provided) are based on many years of AMSAT experience in operating small satellite systems. There are network reliability, satellite security, and regulatory factors that should be considered before final choices for the

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1 With editorial assistance from: Tom Clark (W3IWI), Arthur Feller (W4ART), Graham Shirville (G3VZV), Ray Soifer (W2RS) and Jim White (WD0E).

2 "*Simplex operation:* Operating method in which transmission is made possible alternately in each direction of a telecommunication channel, for example, by means of manual control." [RR 1.125] Simplex operation may use either one or two frequencies.

3 See the ANNEX for definitions of related and other useful terms.

telecommunications equipment and method of operation are determined for any particular satellite system.

2.0 Technical Considerations:

There are several purely technical factors that should be considered before a satellite project chooses to use a *simplex* telecom system. Some of the issues may be well understood, however, there are others that may be less obvious.

2.1 The Doppler Effect:

The apparent shift in frequency caused by the velocity of a satellite relative to an observer is proportional to both the absolute frequency of the transmitter and the satellite's velocity. It is worth noting, by the way, that not only the carrier frequency is shifted but, the modulating frequency is also Doppler-shifted. The appropriate relationship here is:

$$f' = f_o\left(1 \pm \frac{v}{c}\right)$$

where: f ' = Doppler-shifted carrier or modulation frequency

f_o = nominal carrier frequency or mean modulation frequency

v = satellite velocity relative to the observer (It is noted that this is normally a vector quantity). The use of the "±" here is to denote the two extreme Doppler shifted values.

c = velocity of the carrier wave = speed of light

It's important to get a feel for the magnitude of the Doppler shift in frequency that occurs between a ground station and a satellite. Take, as an example, a satellite in a circular orbit at 600 km altitude. To first order, the speed of the satellite is constant and equal to 7,558 m/s. If the satellite had a transmitter operating at exactly 100 MHz, the Doppler-shifted frequency as the satellite moves directly toward the ground station observer would be 100.002521 MHz. As the satellite moved directly away from the observing ground station the observed transmitter frequency is 99.997478 MHz. It can be seen, with a little thought, that the worst-case Doppler shift for a direct overhead pass in this example satellite would be ±2521 Hz or a total shift of 5042 Hz.

Continuing with this example, the following table gives the worst case or largest value of Doppler shift that can occur in frequency bands commonly in use within the amateur-satellite service. The same orbit is assumed.

Carrier Frequency	Max. Doppler Shift
29.500 MHz	±0.744 kHz
145.8 MHz	±3.68 kHz
437.5 MHz	±11.03 kHz
2405 MHz	±60.63 kHz

Table 1

As can be seen, the maximum Doppler shift is small at low frequencies such as within the 29 MHz band. The frequency shift experienced during a typical pass (perhaps amounting to only 70-80% of the maximum shift) is on the order of one kilohertz. This is a small fraction of the modulation bandwidth of most contemporary digital radio systems. However, if the use of the most popular band at 435-438 MHz is contemplated, the Doppler shift over a pass is typically as large as 18 kHz (note that it could be as large as 22 kHz) for LEO missions. When popular modulation methods for data transmission such as 9600 bps "G3RUH FSK" are used, the Doppler shift in frequency is approximately equal to the entire channel bandwidth and the bandwidth of the ground station receiver filter. This requires the radio or the operator to retune the receiver several times during a pass in order to keep the signal centered in the passband. If higher frequencies such as 2400 MHz are to be used, the Doppler shift and time rate of change of frequency caused by Doppler are large indeed. The change in frequency can be as large as 120 kHz, which is approximately six times the bandwidth occupied by this same type of data system. The time rate of change at the center of the pass (time of closest approach or TCA) is on the order of 1.0 kHz/sec.

This then brings up the first set of issues that must be dealt with if a simplex radio system is to be employed:

a) It is important that both the satellite transmitter/receiver system and the ground station system (whether it is a companion radio or not) are capable of handling the Doppler shift in frequency. Most terrestrial radios are not capable of adjusting for Doppler shift since satellite systems and very high-speed aircraft are about the only vehicles that travel fast enough to require this capability. The vendor of the transceiver may not have contemplated this application. One means of dealing with this problem is to increase the bandwidth of the receiver filters on both ends of the link so that even with the Doppler shift, the modulation bandwidth of the transmitted signal still stays within the receiver filter bandwidth. This has a penalty associated with it. The extra bandwidth adds thermal noise (Pn = kTB) and this noise reduces the S/N (or Eb/Nt) of received signal.

b) If the satellite transmitter is normally OFF and is commanded ON, there must be a means (automatic or manual) for adjusting the receiver center frequency to account for the change in frequency since the last transmission. To the receiver this will appear as a "jump" in frequency between two ON periods. If the transmitter is commanded ON only once during a pass then the Doppler shift introduces an uncertainty in terms of where the center frequency (f') will be located at any given instant in time when the transmitter comes ON.

c) Some receiver systems are required to be "locked" to a carrier (usually, but not always located in the center of the modulation spectrum) prior to demodulation of data. Such a system is known as a *coherent* system. These systems must be able to acquire and track a changing carrier frequency. If the simplex system contemplated for use employs coherent technology, it should be verified that the frequency tracking range of the carrier acquisition and tracking loop is large enough to accommodate the maximum Doppler shift in frequency. It would be very useful if the receiver could automatically acquire the carrier by using a sweeping loop or equivalent technology.

It's important to realize that when a simplex system is used, the satellite receiver will experience the same Doppler shift on the command uplink. Any correction made to the downlink frequency must be made to the uplink as well, and in the OPPOSITE direction. In this situation, the use of simplex can be helpful as the measured downlink Doppler frequency shift can be applied as a correction on the command uplink.

2.2 Energy Management:

For most very small satellite systems, energy management is a first-order system design parameter. In order to maintain a positive energy budget, which will allow the spacecraft battery to remain fully charged, it may be necessary to cycle the transmitter ON and OFF. The RF transistors used for the power amplifier chain of a spacecraft transmitter are critical devices in many ways. The transistors or integrated circuits employed in that application should have the highest DC-to-RF conversion efficiency possible. At VHF and UHF frequencies, these devices could have efficiencies as high as 85% (given the current state of technology). However, RF devices employed in most commercial radio products operating in this frequency range and designed for terrestrial use do not achieve this level of efficiency. Values in the 30% range are more typical and efficiencies can be as poor as 15%. So, independent of the issue of simplex utilization, the telecommunications engineer for a satellite project should seek the most efficient RF transmitter design possible as a first-order design consideration.

The amount of power required to complete the data link is given by the system link analysis (or budget) and at a given data rate and for a given LEO orbit, that value is fixed once a minimum elevation angle for communications has been selected. If the reference orbit given above is used (600 km circular orbit) and if a typical UHF ground station is employed (13 dBi antenna gain and 425K system noise temperature) then at 437.5 MHz, approximately 2 watts of RF power will be required to complete the link with 4 dB of link margin. [NOTE: For a small Earth station, a 4 dB link margin is not very much. A margin of 10 dB should be the design objective of a low cost ground station.] It has been assumed that the system has a 9600 bps data rate (using G3RUH FSK) and that a 10° minimum elevation angle must be supported. If the transmitter portion of the radio is 33% efficient and 2 watts of RF output is required, then the input power requirement is 6 watts DC. This implies that 4 watts of power are dissipated as heat during periods when the transmitter is ON.

For transmitter amplifier chains that have only modest efficiency and if data rates as high as 9600 bps must be sustained, it is clear that several watts of power must be dissipated by the transmitter when it is on the air. Since the satellite systems using this radio equipment are themselves very small, the transceiver must be highly miniaturized. So the power density (measured in watts/cm^2) in the vicinity of the amplifier chain is necessarily high.

A transmitter designed for terrestrial use can depend on three methods for the dissipation of the heat it generates:

- Convection: Heat transferred from the device to the air around it.

- Conduction: Heat transferred from the device to primary structure and then convected or radiated away.

- Radiation: Heat transferred from the device and converted into IR energy as a black body radiator.

If the same transmitter is to be used in space, dissipation via convection is no longer possible as all of the air goes away (unless some sort of pressure vessel is employed – an old Russian satellite thermal design trick).

[**NOTE*:*** *In order to get a feel for this problem, take a 1 watt resistor of 4.7 ohms and place it across the leads of a current-limited power supply. Turn on the supply and limit the current to .45 amps. You should find the voltage is about 2.2 volts. This set of conditions will cause the resistor to dissipate approximately 1 watt. Wait a few minutes and carefully touch the resistor with your finger. You should find it's at least warm to the touch if not quite hot. If you were to repeat the exercise but, now place the resistor into a vacuum chamber (bell jar) and pump all of the air out, you would find the resistor would be very hot indeed and depending on the conductive nature of the leads used to connect the resistor within the vacuum chamber, the resistor might eventually fail. Now, what would happen if the current were increased to .90 amps (double the original value)? At this point the 1 watt resistor is dissipating 4 watts and in about the same volume of material as the 2 watt RF transmitter operating at 33% efficiency. The satellite designer must solve the problem of successfully dissipating this heat without destroying the transmitter and/ or the satellite. AND, this problem must be solved without using convection as a heat dissipation mode.]*

The satellite system designer must determine:

a) If the system can conduct the heat away from the transmitter and toward the radiating surfaces of the spacecraft sufficiently well so that the transmitter does not overheat during the ON period.

b) If the system has sufficiently large surface area and sufficiently high thermal emittance properties so that the average temperature of the satellite is not exceeded during ON periods of the transmitter. [Note that the thermal equilibrium temperature achieved passively by the satellite (and given by the radiance equation) depends upon the total surface area of the satellite and the thermal emittance of each surface. If the surface area of the satellite is very small then the equilibrium temperature can be quite high, especially if one has up to 4 watts of additional heat from the transmitter that must be dissipated.]

It is now appropriate to discuss the next set of issues related to the simplex operation of the system. The ON duration of the transmitter must be chosen. Several outcomes are possible:

a) It may be that the ON duration of the transmitter is driven by the need to maintain the temperature at acceptable levels per the above discussion. This is bad, as will be pointed out shortly.

b) It may be that the ON duration of the transmitter is driven by the need to maintain a positive energy balance for the spacecraft system.

c) It may be that the ON duration of the transmitter is driven by the desire to transmit only during the time when the satellite is within range of the command station.

d) Ideally, conditions b) and c) are mutually satisfied.

The above outcomes are in ascending order of desirability. If it is possible to maintain a positive energy balance for the satellite system by turning the transmitter ON only during periods when you can communicate with the spacecraft and IF it is possible to keep the transmitter on during the entire pass, this is the optimum outcome from both a technical and a frequency regulatory point of view. From a satellite security perspective, it may be desirable to turn ON the transmitter only when the satellite is in range of your ground station AND only for as long as it is necessary to download your data. In fact, it is worth noting here that other satellite systems licensed to transmit in other services are nearly always REQUIRED to keep their transmitters OFF except when in range of their respective ground stations. It is only in the Amateur Satellite Service that this is even an option. But, it is an option rapidly decreasing in popularity due to the rapid increase in satellite systems occupying Amateur Radio spectrum and the consequent need for them to share frequencies.

2.3 Failure Modes:

Outcome (a) is particularly bad. If the transmitter can be turned ON only for very short periods so as to avoid overheating and if this process is continuous around each orbit, a new failure mechanism arises. Not only are the transistor die heating up when the transmitter is turned ON and OFF, but the bond wires are also rapidly heating up and they also quickly cool down. Since the bond wires are tiny and transport significant current and have very low thermal inertia they heat and cool very rapidly. Like any piece of metal that is rapidly and repeatedly heated and cooled, the bond wires are subject to expansion/contraction stresses that can (and usually will) lead to a failure of one of the bond wires inside the transistor or integrated circuit. If plastic parts are used, the bond wires are embedded in a plastic material. It is often true that the thermal coefficient of expansion (TCE) of the bond wires and the plastic around them are quite different. If this is the case, the failure will occur all the sooner. So, the worst thing that can be done in this regard is to cycle the transmitter ON and OFF with a short period and with plastic parts which have a poor TCE match between the bond lead and the plastic.

The author learned this lesson the hard way. One mission, for which I had direct responsibility, used a VHF transmitter that had an ON duration of 30 seconds (which was long enough to download a long frame of data from the satellite instrument) and an OFF duration of 2 minutes (which was long enough to collect the data from the instrument for the next transmission period). The transmitter operated in this mode continuously. Despite the fact that this failure mode was anticipated prior to launch and that care was taken to fully heat-sink the transistors in the power amplifier chain, the transmitter failed after about 1.5 years in orbit. The transmitter should have lasted for many years in orbit. It was not possible to prevent the thermal exercising of the bond wires.

The lesson here is to avoid rapid cycling of the transmitter unless you are certain that it is rated for this type of service. Minimize the total number of ON/OFF cycles for the mission. Turning ON and OFF the transmitter 6 to 8 times per day during passes is not a big problem. Turning ON and OFF the transmitter every two minutes, continuously around the orbit, every orbit of every day, in order to maintain thermal equilibrium is establishing a failure mode that cannot be avoided.

2.4 System Security:

Secure operation of satellites has not been a first order design priority in the amateur-satellite service. There have been no known cases of anyone willfully commanding an amateur satellite without authorization and only a few cases where individuals have attempted to interfere with another station's uplink signal. Where this has occurred, it has been related to signals associated with the normal communications function of the satellite and not the command or telemetry functions.

Still, some precautions have always been taken to avoid the temptation that may exist for someone else to commandeer a satellite. The standard precautions are:

a) Never publish or, in any other way, cause to have known the command receiver frequency of the spacecraft. This should only be known by a very limited number of people within the project.

b) Do not publish or reveal the details of the command system data and modulation formats.

c) The spacecraft flight computer (or in a simpler case, the command decoder) should use some sort of password or ID (coded in hardware or firmware). This is to be done at the physical layer of the protocol.

d) At a higher link layer in the software add some additional password-like security.

One might note that because of these precautions we probably wouldn't know if someone was trying to "hack" one of our spacecraft. It would be prudent to assume that regardless of the frequency or radio service, modulation technique or protocol, there are a finite number of people with the desire and capability to hack the satellite. The purpose of security techniques is to make it difficult for them to be successful usually by withholding the needed information.

In addition to the above precautions, many satellites have used fully uploadable software. The only unchangeable code is that used to do the uploading itself. The theory is that if a hacker does find the information needed to hack your satellite one can upload new code with a different set of codes or a different protection technique. Most very small satellites do not have this capability so must have an "unhackable" command scheme that will protect it for the duration of the mission.

These precautions are quite simple and have always worked to date. Still, there has been much talk about using TCP/IP protocol to control satellite systems. Also, there has been considerable discussion about remote commanding using the Internet. Once a satellite system has been "connected" to the Internet and if the spacecraft employs standard data protocols, then clearly the satellite flight computer becomes an extension of the net. This action would open up the satellite system to the entire world of hackers. Such thoughts might cause some rethinking of how important it is to protect amateur satellite systems.

Let's, however, return to the radio frequency domain for it is here that the simplex system is most vulnerable. If someone wanted to directly tamper with a satellite's operation, there would be two ways to proceed:

a) Obtain all of the information necessary to command the spacecraft and develop a system that operates on the command frequency used by the spacecraft and then transmit a valid command to the spacecraft, thus changing its state of operation.

OR

b) Obtain knowledge of the satellites command frequency. This could be obtained by anyone living or operating near the command station site since the emissions from the command station during routine commanding could be heard (detected, decoded, analyzed) from many kilometers away and in any direction from the command station via *ground wave*. Once the command frequency is known, the "bad guy" only needs to transmit a CW carrier toward the victim satellite at a power level (EIRP) adequate to interfere with that of the real commanding ground station. This is formally called a "denial of service" attack.

In case (a), the "bad guy" must work very hard because he has to implement all of the features the real command station has, including the security features. This is very difficult and there is little real motivation for someone to do this. Still, if someone were to do this, they would have the ability to cause maximum chaos up to and including the ability to "kill" the victim spacecraft. What prevents this from happening regularly is the lack of information necessary to accomplish it and the difficulty of obtaining that information.

In case (b), the "bad guy" only needs to detect the presence of your command link or know it because someone let it leak out. In addition, this person would need to know the orbital elements for the satellite. This set of information, available to all on the Internet, will allow him/her to know when the satellite is passing over the "bad guy's" ground station. By transmitting a simple carrier in the general direction of the victim satellite and at an adequately high EIRP level, the "bad guy" can *deny access* to the satellite by the real command station. If, at a particular time, a critical command was to be sent (such as one that turns a particular subsystem ON or OFF for energy balance purposes), then by denying the real command station access to the satellite, damage to the satellite could occur - up to and possibly including causing the "death" of the satellite. NOTE: This is very easy for the "bad guy" to do. He needs only a little information to cause the victim very considerable potential grief.

A case (b) access denial event could occur at any time the real command station and the "bad guy" station are in mutual visibility of the satellite AND provided that the interferer's EIRP is higher. In effect, if the "bad guy's" location was within several hundred kilometers of the victim satellite's real command station, the interferer could prevent the spacecraft from being commanded by the real command station during virtually all of each pass. This situation is also somewhat difficult to recover from without another command station in another part of the world planned for in advance. Most small satellite programs have only one ground station. Quickly establishing another ground station outside the bad guy's footprint with all the needed capability is costly, time consuming and difficult. There may be licensing issues associated with the new station as well.

There is something else to be said about case (b). Many, if not most command receivers used by the small satellite community employ frequency modulation (FM). FM receivers are cheap, non-critical to use and they are less prone to audio distortion due to an offset in frequency as could result from a Doppler-induced error in the command station's uplink frequency. FM systems, however, have one feature which helps the "bad guy" in our above scenario. FM receivers exhibit a phenomenon known as the *capture effect*. Let's assume two FM-modulated carriers are present and both are centered on the receiver's bandpass filter but that they are of different signal amplitudes. The receiver will enhance the signal-to-interference ratio of the stronger signal and reduce the signal-to-interference ratio of the weaker signal at the output of the FM demodulator. This behavior is quite non-linear and is known as the capture effect. This effect is more pronounced for FM receivers that have a high modulation index (that is, they have a high deviation compared with the tone frequencies used to represent a "1" or a "0"). For a high-deviation FM receiver, the weaker signal may be virtually fully suppressed even if it is only 1 dB weaker than the "winning" signal. For low-deviation receivers (as may be found in the amateur radio service) the stronger signal might have to be 6-10 dB stronger than the weaker signal but, if that condition is met, the weaker signal will simply disappear from the output of the receiver. This information thus allows quantification of how easy or hard it would be for an intentional interferer to overcome the desired command signal. By the way, having a signal 6 dB (a factor of 4) stronger than that used by the command station may not be a difficult task for the "bad guy" to accomplish. This can be done with a power amplifier device and/or a larger antenna.

Given the above set of explanations, the issue of simplex operation vs. security can now be discussed. It is clear that a case (b) scenario is far more likely than case (a). So much so, that case (a) can be ignored for purposes of these discussions. Let's assume that a simplex transceiver is used in the satellite such that the command channel is shared with the telemetry downlink channel. That is, the satellite might normally be in receive mode but, occasionally (upon command, via timer or under computer control) the receiver is turned OFF and **ON THE VERY SAME FREQUENCY** the transmitter is turned ON. If the "bad guy" knows *only* that the satellite is using a simplex system for telemetry and command, then it is already clear to him/her that the transmitter is broadcasting the command frequency. Now the "bad guy" is able to use a combination of automated and manual means to block the command frequency and deny access to the real command station and even the Doppler correction information is automatically provided to the interferer. This is a terrible scenario for satellite security! One could not possibly make it easier for an intentional interferer to be successful.

There is one variation on the pure simplex case that can occur and it is the next worst case. Sometimes the receiver is offset in frequency from the transmitter by a fixed amount. Standard amateur radio transceivers operating in the 144-148 MHz band, for instance, have a standard offset of 600 kHz (plus or minus, depending on the part of the band where operations occur). So, a "bad guy" would naturally look for the command frequency at 0 kHz, +600 kHz and –600 kHz from the transmit frequency in trying to jam the command frequency. There are standard offsets used in other frequency bands as well.

After these warnings, if it is still deemed appropriate to operate a simplex radio for telemetry/command, then the following practices can be recommended to provide some measure of security:

a) Use a transmitter capable of using the highest reasonable output power and the highest practical gain antenna at the satellite command station. This will give the command station the ability to generate a high EIRP and the largest link margin. This high power level should not be used unless it is strictly necessary to do so, but it will also help prevent an intentional interferer from capturing the command link. [NOTE: It is common practice in the amateur service and amateur-satellite service to use only the MINIMUM power necessary to maintain communications (and in some countries, including the United States, this is the law). However, it is also extremely important to be able to control the emissions from every satellite. Therefore, if intentional interference were to occur, it only seems prudent to be capable of generating a high EIRP in order to overcome a *denial of service* attempt. Such high power should only be used when necessary.]

b) Use additional command stations located in other parts of the world. This is appropriate in any case but, such a strategy makes access denial much more difficult.

c) Do not rapidly cycle between receive and transmit modes during any given pass. It is tempting to do this as the telemetry downlink could be used to acknowledge each command before the next command is sent. This is logical but is not in the interest of security. The “bad guy” can simply key his interfering transmitter based on detecting the trailing edge of the satellite’s telemetry signal (just as the satellite goes into the command receive mode). It is better to send commands at the beginning of the pass before the telemetry transmitter is turned ON and then verify that an entire batch of commands has been accepted. This, of course, means the command station must transmit to the satellite blind (i.e., without hearing the satellite at the time of acquisition-of-signal) and this requires operational confidence. Once one turns ON the telemetry transmitter, leave it on until the end of the pass (or until sufficient data has been collected) and make sure that there is a safe hardware or firmware timer that will eventually turn the transmitter OFF if the command station is denied access to the satellite. This will prevent the satellite from fully discharging the battery if the transmitter OFF command is not received. Notice that this recommendation is in keeping with the recommendation made in Section 2.2 above. That is, in general, do not cycle the transmitter ON and OFF rapidly. Operationally, all of this is not very attractive. It’s much more likely the command station will want to first look at telemetry, then send some commands, and then once again, look at telemetry. However, a denial of service attack is likewise, undesirable. This is one more reason why simplex communications is a poor option.

d) Do not use an FM receiver with a high modulation index UNLESS the command station being used can be sure of “winning” against an intentional interferer. Such a receiver “increases the stakes” in the access denial game.

e) Do not tell anyone without a firm need to know about the details of your command system. The command receiver frequency is **THE** most sensitive of all pieces of information. By “details of the command system” it is meant ANY information about how it works. A potential bad guy can accumulate seemingly unimportant bits of information from a variety of sources and develop knowledge sufficient to attempt an attack. One of the fundamental precepts of this type of security is to make the job of interfering with your operation look so difficult that no one is tempted ever to try.

f) Do not use a standard frequency offset (i.e., one common in amateur use) between the command receiver and the telemetry transmitter.

3.0 Regulatory Considerations:

This section has been left until last but, it is the most important set of reasons as to why serious consideration should be given as to how SIMPLEX operation is employed on any amateur satellite – indeed any satellite at all.

In principle, it must be agreed that simplex operation saves spectrum since two functions share the same radio channel. This is a very positive feature of simplex operation.

The problem lies with other regulatory considerations based upon failures similar to those in AMSAT operations discussed earlier.

3.1 Interference Control:

Both national and international regulations governing ALL satellite operations in space require that transmissions from any spacecraft (amateur or otherwise) be under positive control at all times.[4] A critical part of this control function is the ability to rapidly and effectively terminate some or all transmissions from your spacecraft.

It is not the intention of this paper to interpret the meaning of the words used in these regulations. That has been done elsewhere and will, no doubt, be done again in the future. However, it is a simple argument to make (and fundamental to the way radios work) that when the satellite's receiver is OFF and its transmitter is ON, the command station cannot successfully command the satellite. In that literal sense, the command station does not have effective control of the spacecraft in the case of simplex operation. In simplex operation, when the transmitter is ON and the receiver is OFF, it is obvious that the system depends upon some form of timer or logical process to terminate the transmitter's operation and return the command receiver to its "normal" state AFTER some event has occurred.

The failure of this mechanism leading to unintended transmitter emissions and uncontrollable interference is the root of the real regulatory concern.

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[4] "Space stations shall be fitted with devices to ensure immediate cessation of their radio emissions by telecommand, whenever such cessation is required under the provisions of these Regulations." [RR 22.1.]

There is a second part to this concern. Even if the transmitter and the receiver could operate separately and even if the receiver could be turned ON while the transmitter is transmitting and even if they did not share the same antenna and even if the transmitter and receiver were not on the SAME frequency (but, they were operating in the same frequency band)…then IF the transmitter became "stuck" in the ON position, it is highly unlikely that the receiver could be accessed by the command station to turn OFF the transmitter. This is because the transmitter is so physically close to the receiver that it "overloads" the receiver front-end transistor devices. It is no exaggeration to say that the signal level reaching the command receiver input terminals from the on-board transmitter is typically on the order of 100 dB (that's 10 orders of magnitude) stronger than a command signal arriving from the ground. If one was to attempt a filter design that would attenuate the transmitter at the receiver's frequency say, 500 to 1000 kHz away, within the 435-438 MHz band and by an amount equal to 100 dB, it would be found that the filter is larger than the spacecraft (certainly larger than a "CubeSat"). So, the second concern is ANY type of satellite malfunction that causes the transmitter to become turned ON permanently and thus deny real access to the command system by the ground command station (even if the transmitter and receiver are separate but share the same frequency band).

In Section 2 above, it was noted that to successfully complete the downlink for a satellite in a circular reference orbit of 600 km altitude and at 9600 bps FSK it will require about 2 watts of RF power. That, in turn, implies a DC power requirement that could be as high as 6 watts (and is at best 3.5 watts) whenever the transmitter is ON. Certainly other functions on-board the spacecraft will require additional power. It is understood that very small satellites cannot sustain a positive energy budget if the transmitter is stuck ON. That means the satellite's battery will discharge. If careful attention has been given to the system design there will be protective hardware and/or software that will detect a battery low voltage condition and "shed" the major loads (i.e., turn them OFF). The "most major" of all such loads is surely the telemetry transmitter. If less care has been taken in the design, then the battery simply discharges and some logic states will change along the way and maybe the transmitter logic will reset as the batteries are discharged. This whole set of logical conditions may be modified by eclipse events that can occur on top of the battery discharge taking place…which was caused by the stuck transmitter. This is to say nothing about whatever the satellite experiments or payload may do to add to the set of logical conditions that must be considered. The question then is…what happens next? If the satellite is designed to allow the battery to become fully charged before the major loads can be switched ON, then all could be fine. But, the question that must be asked is, under all possible logical combinations of conditions that could occur on-board the spacecraft…when power is restored, will the transmitter remain OFF until commanded to do otherwise? The key to all of this is very careful design consideration AND VERY THOROUGH FUNCTIONAL TESTING of the satellite in all of its modes prior to launch.

3.2 Recommendations to Enhance Compliance with the Radio Regulations:

The following recommendations are made to those who still find simplex operation an imperative:

a) **Under no circumstances should a satellite be designed so that the transfer of a simplex radio system from its transmit mode to its receive mode is controlled only by a flight computer or a flight controller and its software (and most particularly software executed from RAM).** If such control is executed by flight computer software and it is logically backed up by a hardware timer that could be OK. The most reliable way to control the transfer is by using a simple hardware timer/logic solution ONLY. This is, admittedly the most conservative way.

Another solution would possibly be to place a second command receiver in another frequency band. This receiver could have, as its sole purpose, the resetting of the flight computer should it fail to perform the transfer from transmitter ON to transmitter OFF. Even placing the timer in firmware can be risky. Some FLASH ROM devices are radiation soft in the write mode. That is, they fail due to radiation damage (total cumulative dose) at low levels and the write function fails before the read function. This cannot be detected from the ground when it first occurs. So, if you were to write to the memory to change some function, the area of memory lost could be larger than the area being addressed. In this way, the firmware timer function could be lost. Certainly, not all FLASH RAM has this problem and by using FLASH known to be good for space, the designer could make this solution reliable. EPROM solutions are also bad, as EPROM is also prone to radiation problems. A controller/timer using radiation hard fusible-link ROM is a good solution. Also, an FPGA solution is good provided that the gate array is radiation tolerant.

b) The spacecraft system design should assure that if the battery is ever discharged fully, for whatever reason, (but, most particularly because the transmitter was "stuck" ON) that after the flight battery has recharged and the system is ready for service again, the transmitter does not come ON again until it is commanded to do so. A good spacecraft system design will "gracefully" turn OFF all loads, starting with the transmitter so that the battery is never allowed to go completely flat (to 0 voltage). For many battery technologies, reaching such a low voltage state can cause what is known as *cell reversal*, and that condition is usually system-fatal.

c) The spacecraft system design should assure that no combination of commands can cause the transmitter to become latched in the transmit mode, regardless of whether the system may recover once the battery discharges and then recharges. That is, one must not assume that battery discharge/recharge is the means of protection against a transmitter latch-up condition. A spacecraft known to work in this way should never be launched AND this would not satisfy the ITU Radio Regulations which require all satellite transmitters to be under positive command control at all times.

d) As a part of the spacecraft design process and as a part of the system level paperwork done for the project, the spacecraft should be thoroughly functionally tested to verify all of the modes of operation and all commands within each mode. Most particularly, it should be verified by test that no command sequence can be issued that will latch the transmitter ON and that after recovery from a battery under-voltage condition the spacecraft system returns to service with the command receiver ON and functional and with the transmitter OFF. Verification of this should be documented in a system LOG and it wouldn't be a bad idea if a letter were to be written for the file from the telecommunications engineer to the project manager verifying that these successfully completed tests were witnessed to occur. That letter should be signed by the telecommunications engineer and endorsed by the project manager. Thorough system level functional testing of the spacecraft is the most important recommendation the author can make. There are many space projects which have been launched by amateurs and professionals where testing has been abbreviated or eliminated due to the pressures of time. THIS IS A BIG MISTAKE. In almost every case, the project has lived to regret it. Murphy's law says,…"If something can go wrong it will." If you don't think this is a valid law, then you haven't built enough spacecraft yet. Don't test Murphy. Test the spacecraft so that design errors don't get into space.

4.0 The Relative Risk of TX ON vs. TX OFF:

Many will say they have heard this author say, "Never turn your transmitter OFF if you don't have to." This is a true statement. It is difficult and sometimes impossible to figure out what is wrong with a "sick" spacecraft if the transmitter is not ON as any data is far better than no data. Even an unmodulated carrier from a spacecraft gives far more information than no signal at all.

It is also very difficult to command a spacecraft blindly and especially the very first time it "comes over the hill." So, it is reasonable during the commissioning phase of a space mission to consider leaving the transmitter ON more of the time.

When using a simplex system, unfortunately, you are evoking the "unless you have to" clause associated with the above little rule. From a regulatory standpoint and from a common sense standpoint it is important to have positive control. Spectrum is valuable and spectrum used for space is very valuable because of the surface area of the Earth covered by the satellite's transmissions. In many ways a simplex system works against the principle of positive control. Therefore, there is a consequence. The consequence is that you will most likely have to command the satellite without knowing where to point antennas and there will be some uncertainty regarding the AOS time for the spacecraft. This is particularly true in the first few days or weeks following launch, when definitive orbital elements for all objects placed into orbit have not yet been firmly established. Assuming that all of the above rules can be followed, it should still be possible to program the flight computer to turn ON transmitter just prior to AOS at the satellite ground station and then OFF some minutes later (say, just before LOS). So, all is not lost if that flexibility exists. The transmitter could be turned OFF a few times during a pass by program control to allow commanding but, remember the "bad guy"!

A preferred telecommunication implementation for small space systems is a full duplex system that allows simultaneous command and telemetry transmission at will. There need not be any obvious relationship between the command frequency and the telemetry frequency. An alternative to turning the transmitter entirely OFF is to reduce its power (and data rate) so that at least some signal is present to track. Such an approach also reduces the potential for interference to others since the power level radiated by the satellite is lower and a lower data rate emission requires less bandwidth. This technique may require a larger ground station antenna system but then, that's a system trade you must make.

And, the subject of a low power beacon or telemetry link gets to the very last point. A part of the, "Never turn OFF the transmitter if you don't have to" rule also has to do with interference to others. A good reason for not keeping the transmitter ON when the satellite is not in view of the command station is the crowded state of the radio spectrum today. In the early days of amateur satellites everyone – everywhere – wanted to hear the very few (usually one) satellites that were available.

With the advent of the university satellite programs it has become an "every university for itself" kind of affair. So, one university's data are another university's interference. There are several cases where, in order to coordinate the frequencies for two or more satellites, the same frequency has been recommended. In such a case, successful coordination assumes that widely separated command sites will be used by these co-frequency projects and that the spacecraft transmitters will be used only in range of their respective ground stations.

So things are not as they used to be. Interference conditions nowadays dictate that satellite transmissions should be of short duration. Thus, it is no longer possible for everyone, everywhere to participate in the use of every satellite. For many of us this is an unfortunate state of affairs.

5.0 Conclusions:

It must be acknowledged that there are several advantages to employing a simplex telecommunication design in very small satellites. However, the telecom link employed in a space system is not only critical to the operators of the system, but also to others who share the same frequency band. One must recall that the amateur satellite service is allowed in the 435-438 MHz frequency band only on a secondary basis. This means we must give way to other services that are primary services in the band. In the United States and in many other countries, this band is allocated on a "primary" basis to radiolocation (RADAR), usually for the government (military). If interference is caused to a primary service, we are compelled to cease all radio transmissions. This, in turn, means that it is absolutely imperative that each space system in the amateur-satellite service be capable of controlling its emissions. That burden is harder to confidently shoulder when a simplex system is used.

In addition to the regulatory imperative, there are other security and technical issues that have been raised in this paper. An effort has been made to point out solutions to these issues based on experience. It has been noted that the preferred solution is to employ a full duplex telecom system where data (commands and telemetry) may flow in both directions simultaneously and at the will of the command station operator.

Finally, it might be worth noting that, while flying a component designed for a terrestrial application appears attractive at first glance, after reviewing the modifications that must be made to the hardware and software in order for it to be flight worthy (both from a reliability AND a DESIGN point of view), it may turn out to have been wiser to design the unit “from scratch” to begin with. It’s also true that you learn more by doing it that way. Unfortunately, this option is nearly always put aside as being too difficult, and the real problems of using terrestrial technologies in space are frequently “swept under the carpet.”

The author hopes this paper had provided some insight into the subject of simplex operation of small satellite systems.

- end -

ANNEX – USEFUL TERMS DEFINED

Administration: Any governmental department or service responsible for discharging the obligations undertaken in the Constitution of the International Telecommunication Union, in the Convention of the International Telecommunication Union and in the Administrative Regulations. [CS 1002.]

Radiocommunication service: A service as defined in this Section involving the transmission, *emission* and/or reception of *radio waves* for specific *telecommunication* purposes. [RR 1.19.]

Simplex operation: Operating method in which transmission is made possible alternately in each direction of a *telecommunication* channel, for example, by means of manual Control[5]. [RR 1.125.]

Duplex operation: Operating method in which transmission is possible simultaneously in both directions of a *telecommunication* channel. [RR 1.126.]

Semi-duplex operation: A method which is *simplex operation* at one end of the circuit and *duplex operation* at the other. [RR 1.127.]

Amateur service: A *radiocommunication service* for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest. [RR 1.56.]

Amateur-satellite service: A *radiocommunication service* using *space stations* on Earth *satellites* for the same purposes as those of the *amateur service*. [RR 1.57.]

Station: One or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary at one location for carrying on a *radiocommunication service*, or the *radio astronomy service*. Each station shall be classified by the service in which it operates permanently or temporarily. [RR 1.61.]

Terrestrial station: A *station* effecting *terrestrial radiocommunication*.
In these Regulations, unless otherwise stated, any *station* is a terrestrial station. [RR 1.62.]

Earth station: A *station* located either on the Earth's surface or within the major portion of the Earth's atmosphere and intended for communication:

– with one or more *space stations*; or

– with one or more *stations* of the same kind by means of one or more

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[5] 1.125.1, 1.126.1 and 1.127.1 In general, *duplex operation* and *semi-duplex operation* require two requencies in *radiocommunication*; *simplex operation* may use either one or two.

reflecting *satellites* or other objects in space. [RR 1.63.]

Space station: A *station* located on an object which is beyond, is intended to go beyond, or has been beyond, the major portion of the Earth's atmosphere. [RR 1.64.]

Telecommand: The use of *telecommunication* for the transmission of signals to initiate, modify or terminate functions of equipment at a distance. [RR 1.134.]

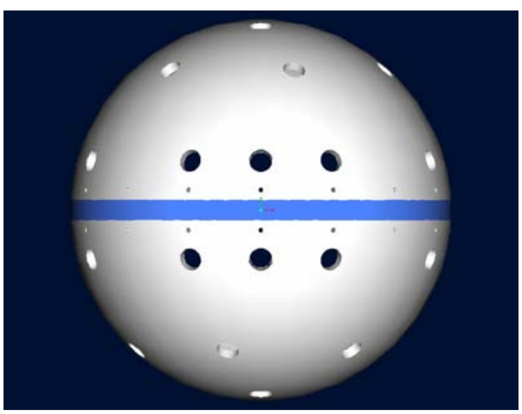
Space telecommand: The use of *radiocommunication* for the transmission of signals to a *space station* to initiate, modify or terminate functions of equipment on an associated space object, including the *space station*. [RR 1.135.]

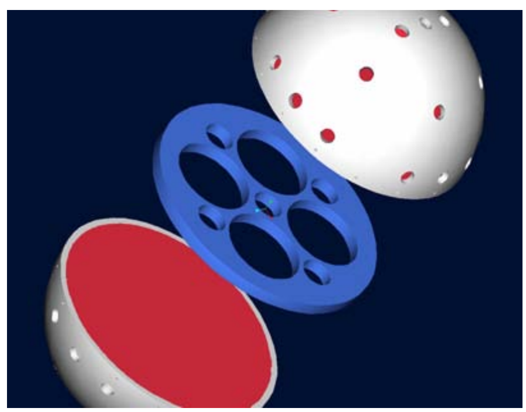
ANDE - Telemetry/Command and Comms

US Naval Academy Satellite Lab
Bob Bruninga, WB4APR
Present Team: Midn's Aaron(04), Villalbi(04), and Weisenberg(04)
Midn's Kelley(03), Keller(03), Harris(03), Patterson(02), & Ensign Sillman(02)
Antenna Designers/Modelers: Bob WB4APR, Phil KF8JW, Bobby WB8FEW, Bob KC8QPM & Rick K8CAV

Status: ANDE is in flight-build status. The midshipmen have completed two of the flight battery boards and the final engineering design model of the communications system. This summer (2004) we will finish the flight boards and begin integration. Launch is currently manifest on mission STS-116 after the shuttle returns to flight currently scheduled for December 2005. The design is fully disclosed on our WEB page[1].

ANDE stands for Atmospheric Neutral Drag Experiment and is a 19" passive sphere with optical corner reflectors and 6 Lasers for precise orbit determination. The Naval Academy has been given the opportunity to construct a digital communications transponder for use in the Amateur Satellite Service to fit inside the ANDE sphere similar to what it is flying on the PCsat and PCSAT2 missions as long as it did not use any external antennas nor perturb the perfect sphere in any way. The PCsat-like follow-on packet communications mission will continue the interest of students worldwide by letting them communicate via the satellite and capture telemetry relative to its temperature in the space environment. The communications system in ANDE operates fully within the rules of the Amateur Satellite Service [2].

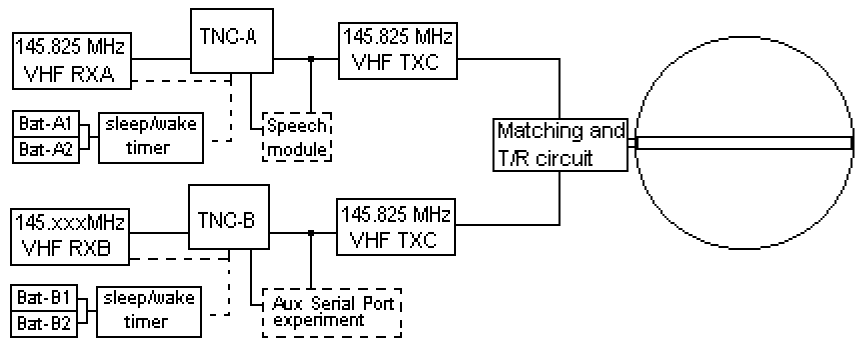




COMMUNICATIONS DESIGN DETAILS: The bulk of the mechanical details of ANDE is being designed and constructe at the Naval Research Labs in Washington DC. The Naval Academy is only responsible for the communications and power system portion of the design. The communications, telemetry, command and control is all based on the off-the-shelf Kantronics KPC-3 TNC as shown below. What makes this design unique is the absence of any external antennas as required by the minimum drag needs of the science experiment. We solved this by cutting the sphere in half so that we can use it as a dipole antenna across the two halves.

ANDE COMMS Block Diagram

WB4APR



RF System: ANDE has two independed AX.25 Packet Command and Telemetry systems. The primary system operates like PCsat providing Telemetry on 145.825 and supporting users communications. The secondary is on unpublished frequenceis.

Antenna: Both systems are matched to the ANDE Sphere as a dipole antenna.

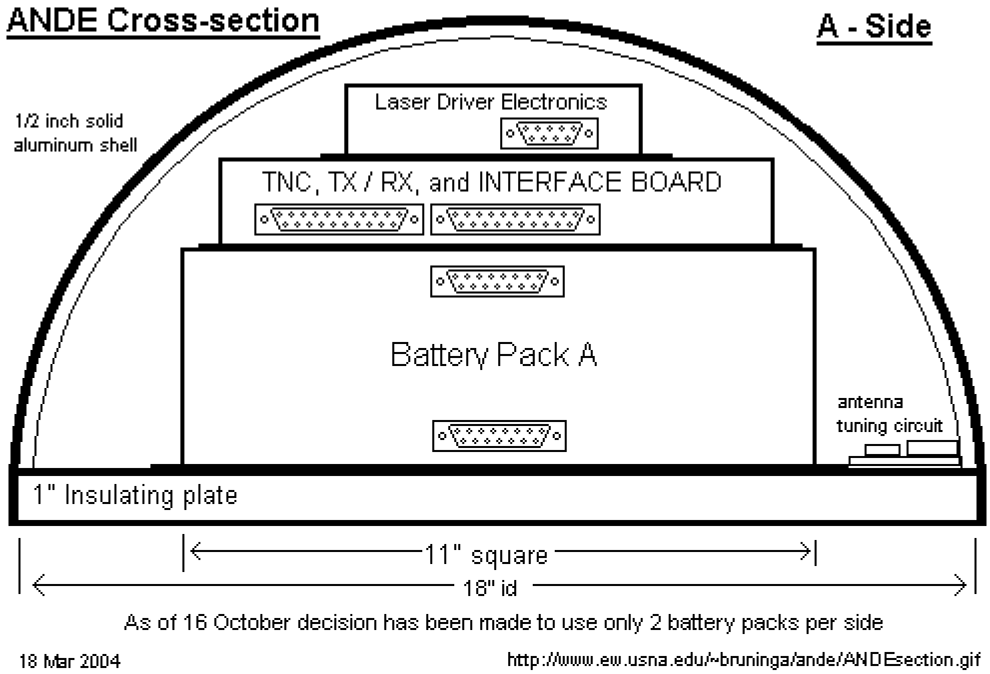
Telemetry: Each system A or B has several common telemetry items and a few items that are unique to each side.

Power: To save power, both systems sleep 90% of the time. The A side wakes for 1.5 secs out of every 15 and the B side wakes for 1.5 secs once a minute. If either detects activity, they will remain awake for a minute since the last signal heard.

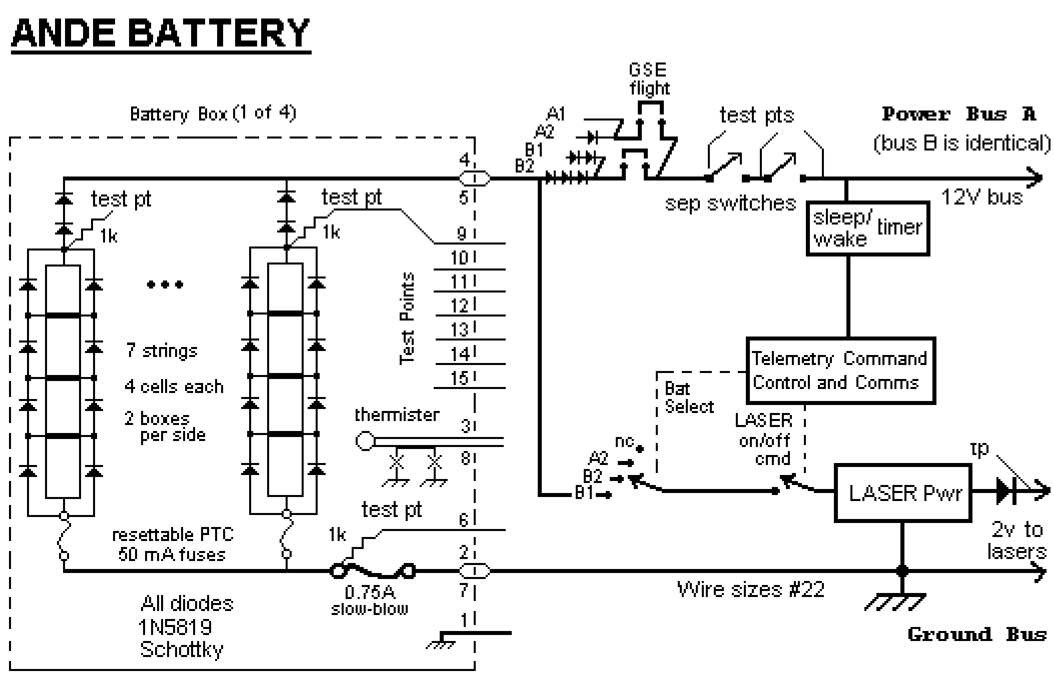
24 Feb 2004 http://www.ew.usna.edu/ande/ANDEblock.gif

The communications system consists of a Kantronics KPC-3+ TNC, a Hamtronics transmitter and receiver and a custom interface board to hook it all together. These are all mounted in a 1" tall box on top of the battery boxes. The mission is simply to serve as another in-space digipeater in support of the APRS and UI-Digipeating mission. The only uniqe feature is the requirement to keep the transponder off most of the time when it is not in use to save power. This is done by a 2 second/20 second sleep-wake timer followed by a 1 minute wake timer. Whenever the satellitie wakes up and detects packets, it will remain awake for the next minute. But after hearing nothing for over a minute, it will go back to sleep.

For reliability, the TNC powers up in factory defaults with no backup RAM that could be corrupted with radiation. This has the advantage of simplicity and reliability, but has the disadvantage of not being able to remember its configuration past the time it goes out of view of activity. Since the primary mission of the APRS/UI digipeater is real-time relay, there is little impact of this design. But we do hope to do some occasional trans-Atlantic store and forward experiments occasionally by uploading over the USA and then downloading over Europe before it goes back to sleep.

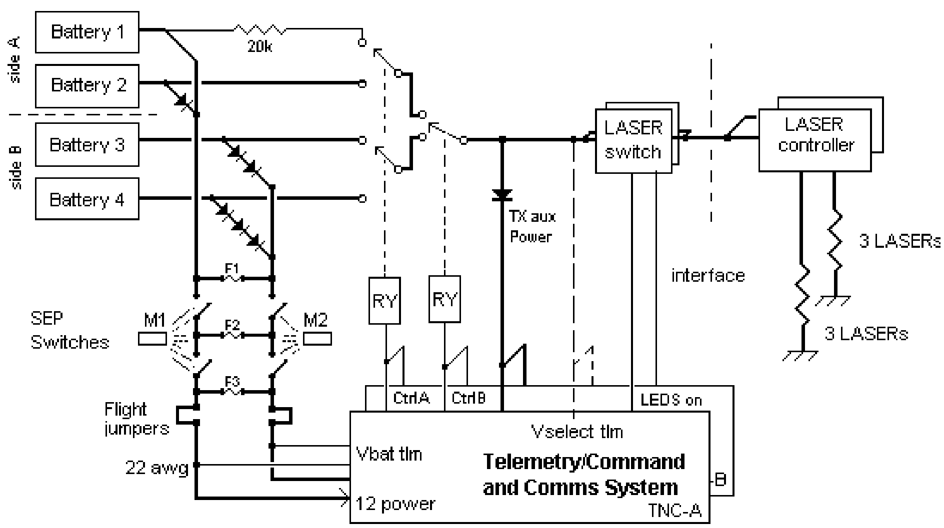


Lithium Primary Battery Power System: Another unique requirement of the comm system was to operate for up to 1.5 years on primary batteries without any solar cells or external charging. Thus, ANDE runs on 112 "D" cell Lithium thionylchloride cells arranged in 4 packs of 7 strings of 4 cells in series. To meet the man safety requirements for launch on the shuttle, extensive testing has been conducted.



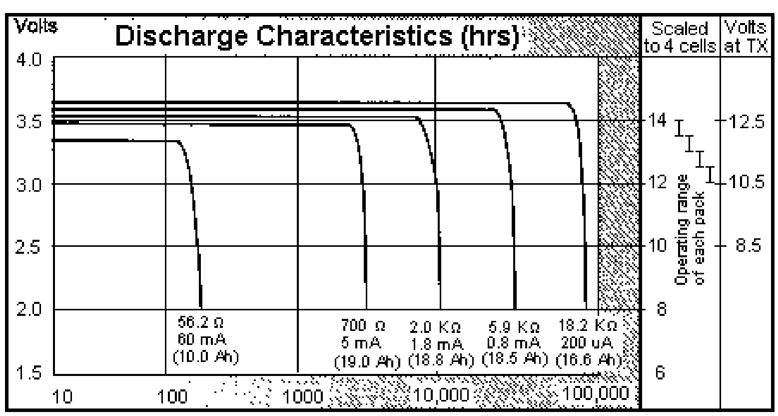
Since Lithium Cells have a very flat discharge characteristic, we needed to have some mechanism to measure the remaining capacity of the cells as they were used during the mission. The next page details how we used battery switching and a set of series Schotky diode voltage drops to be able to monitor the usage of the battery packs.

BATTERY MANAGEMENT SYSTEM Block Diagram



The TCC system is always redundantly powered by all battery strings. But the LASER load and TX is separately powered from one battery pack at a time so that we can measure one pack at a time under load for assessment of life remaining. All power system wiring is #22 awg.
The C1-C3 lines are the 3 command switches per TNC controller. A is primary, B is backup.

REV-1 The standby and Transmit load was further divided among the battery packs by additional 0.4 volt Shottky series diode voltage drops per pack. A1 has no drops, A2 has one drop, B1 has 2 drops and B2 has 3 drops. Thus battery A1 will provide most current initially, then A2, then B1 and finally B2. When B2 is practically dead at 3.0 volts per cell, then the voltage available to the transmitters will still be 10.8 volts and transmitter power will be down about 6 dB from original power.
Current sharing is about 90% to 1st string, 10% to next, etc.



20 Jun 2003
15 Sep 2003 Updated with cross connect fuses
5 Feb 2004 Added REV-1 power

		Project:	ANDE	**Title:**	Battery Management
Dwg No:	USNA-ANDE-EP04	**Midn:**	Kelly	**Date:**	1 April 2004
Web:	http://www.ew.usna.edu/~bruninga/ande/ANDEbat-mg13.gif	**USNA Satellite Lab**		**Engineer:**	Bob Bruninga

ANDE POWER SYSTEM ENERGY BUDGET 1 Apr 2004

The following paragraphs detail the power system budget:

BATTERY SYSTEM:	Lithium-primary
Battery Mass:	11.2 Kg
Battery Construction:	112 Cells Tadiran TL-5930 Each cell is 93 g and 33 x 62 mm
Battery volume:	7562 cu cm
Battery configuration:	28 4-cell strings in parallel
Battery volts:	12 volts (14.4v no load)
Battery safety:	Every 4-cell string fuzed individually
Battery capacity:	532 AHrs (7448 WHrs at 14 volts)

ANDE Telemetry/Command system:

System	nominal current	dutycycle standby	10% ontime with-users	result USAGE	Average CURRENT	Percent
Rcvr A	35 mA	10% [1.5s ON]	10%	20%	7 mA	20%
TNC A	20 mA	10% [15s off]	10%	20%	4 mA	11%
XMTR A	600 mA		20%	2%	12 mA	34%
LASERS	350 mA	3% over Maui	10%	0.3%	1 mA	3%
Timers	3 mA	100%	100%	100%	3 mA	9%]
Volt TLM	0.2	100% ea (2)	100%	100%	0.4 mA	1%]
Temp TLM	0.7	10% ea (6)	100%	20%	0.4 mA	1%]
5v ref	0.9	10%	100%	10%	0.1 mA	0%]
Counter	1.2	100%	100%	100%	1.2 mA	3%]
Rcvr B	35 mA	3% [1.5s ON]		3%	1 mA	3%
TNC B	20 mA	3% [45s off]		3%	0.6 mA	2%
XMTR B	600 mA	0% backup only	0%	0%	0 mA	
Timers	3 mA	100%	100%	100%	3 mA	9%]
Volt TLM	0.2	100% ea (2)	100%	100%	0.4 mA	1%]
Temp TLM	0.7	3% ea (6)	100%	3%	0.1 mA	1%]
5v ref	0.9	3%	100%	3%	0.03 mA	1%]
Counter	1.2	100%	100%	100%	1.2 mA	3%]
Total					35.5 mA	

Growth compared to original proposal 12%

Battery life: 532 AHrs/36 mA = 15,000 hours = About 600 days.

The total life is drastically dependent on the usage duty cycle. The above figures assumed a worse case scenario. Typical and target values could allow for more than 1.5 year life and still support nominal communications via the PCsat-style operations... The side B is dormant except for its 1.5 second wakeup every 45 seconds. Unless the A side fails, the B side is not used for transmitting otherwise.

MULTI-PACK BATTTERY DESIGN: Since the battery discharge curve is totally flat to 97% of battery life, the only energy usage data will be obtained by using each pf the 4 battery packs to exhaustion to run the LASERs. This will give 4 energy benchmarks during the mission

The digital communications relay will operate within the ITU regulations for operations in the Amateur Satellite Service, to provide digital communications for amateur satellite operators, educators and possible remote environmental sensors worldwide. This mission will augment the communications mission of PCsat by adding a second and third satellite to the constellation for comms support of remote travelers at sea, cross country travelers, expeditions, or any other travelers far from any existing digipeater infrastructure. The PCsat and ANDE downlink from such users is fed into the existing worldwide internet linked APRS system by a few permanent ground stations. ANDE would join ISS, MIR, PCsat and several other on-orbit experiments that have been conducted over the years leading up to this exciting capability.

The Space segment of the ANDE communications mission has been demonstrated a number of times in space via PCsat, ISS, MIR, SPREE, Sunsat, UOU-22 and others. It is also a spin off of a previous launch opportunity that we had in 1998 called NATsat that almost got launched on SEA-LAUNCH.. The ANDE Communications mission is a project to produce a viable payload in a very short time frame using off the shelf components where possible.

APRS is the Automatic Position Reporting System that has grown to include over 27,000 user stations worldwide mostly linked by the terrestrial digipeater network. Licensed students at the Naval Academy in the Amateur Radio Club have used APRS for tracking their boats and a variety of other vehicles including the annual running of the Army/Navy game football to the stadium in Philadelphia, and various local events. The ANDE Communications transponder would be operated under the rules of the Amateur Satellite Service and the rules of the FCC to help extend APRS coverage off shore and to remote areas outside of the existing infrastructure.

References:

[1] ANDE web page: http://www.ew.usna.edu/~bruninga/ande.html
[2] ITU application: http://www.ew.usna.edu/~bruninga/ande/ande-itu.txt

An Experimental Space Surveillance RADAR Transponder for the RAFT1 CubeSat

Robert Bruninga, WB4APR (Bruninga@usna.edu)
Anthony Monteiro, AA2TX (aa2tx@amsat.org)

Abstract

"…Now we have another great launch where eight microsat's were placed into orbit, and everyone is scrambling to come up with some Keps that reflect who is who up there. The tracking folks do a great job, but from what I remember from last years operation was that it will be a while before it is straighten out up there. I'm sure the trackers have no problem finding the large stuff, like the booster stage and shrouding. But when it comes to the microsat, well that's another issue. There small in size and probably close together right now. First they will have to find them, and then try to figure out who is what. I can recall from last years launch that it took the better part of a MONTH before it was settled…"
- From the AMSAT-Bulletin Board[1], 29-JUN-2004.

The US Naval Space Surveillance System (NSSS) RADAR provides critical orbiting object data to NORAD which generates the Keplerian elements needed to track satellites orbiting the earth. The advent of CubeSats, MicroSats, PicoSats and other small satellites launched in clusters, has caused a difficulty in identifying specific satellites in orbit since the number and very small size of these satellites is beyond the tracking ability of the NSSS RADAR.

This paper describes a RADAR transponder, currently being developed by a team of AMSAT members, which will be part of an experiment to determine if small satellites can help identify themselves. These RADAR experiments are the primary mission of the RAFT1 CubeSat shown in Figure 1. RAFT1 is being developed by midshipmen at the US Naval Academy Satellite Lab under the leadership of AMSAT member, Robert Bruninga, WB4APR. The NSSS Radar experiment is the primary mission and the satellite also carries an amateur radio payload as a secondary mission. RAFT1 is scheduled to be launched from the Space Shuttle in 2005.

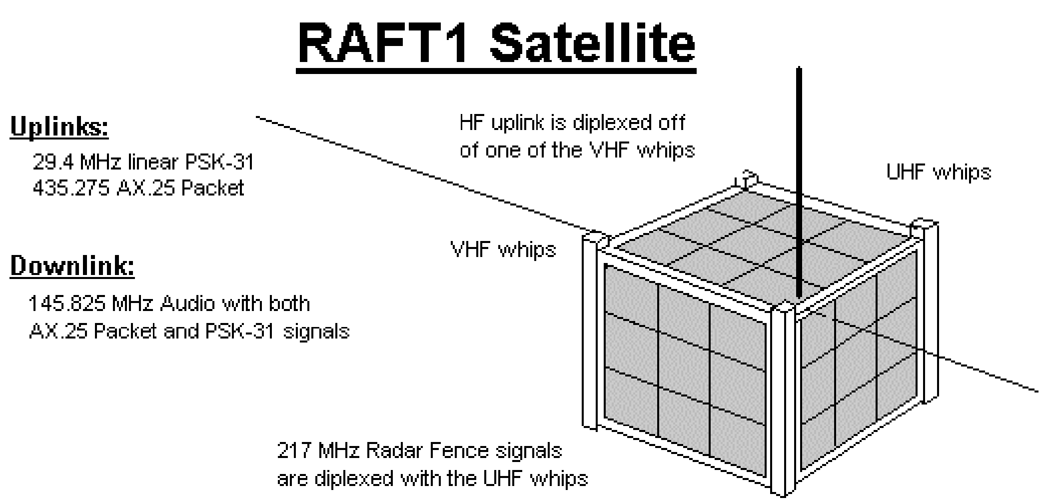


Figure 1. RAFT1 CubeSat

Introduction

The US Naval Space Surveillance System (NSSS) RADAR provides critical orbiting object data to NORAD to generate the Keplerian elements needed to track satellites orbiting the earth. The advent of CubeSats, MicroSats, PicoSats and other small satellites launched in clusters, has caused a difficulty in identifying specific satellites in orbit since the number and very small size of these satellites is beyond the ability of the NSSS RADAR to distinguish them.

The RAFT1 CubeSat project was developed as a response to these issues and was approved by the Department of Defense (DOD,) Space Experiments Review Board in 2002. This satellite will conduct experimental interactions with the NSSS RADAR to determine if an active transponder could assist in tracking and identifying very small satellites. As shown in Figure 1, RAFT1 includes a 217 MHz RADAR Transponder, a VHF downlink and uplinks on HF and UHF. The NSSS Radar experiment is the primary mission and the satellite carries an amateur radio payload as a secondary mission. RAFT1 is being developed by midshipmen at the US Naval Academy Satellite Lab under the leadership of AMSAT member, Robert Bruninga, WB4APR.

A block diagram of the satellite is shown in Figure 2. The NSSS RADAR experiment includes a direct-conversion receiver and a beacon oscillator operating at the NSSS RADAR frequency around 217 MHz. The beacon oscillator provides a signal to help the RADAR ground receivers positively identify the satellite. The output of the 217 MHz receiver is fed into a VHF FM downlink transmitter operating at around 145 MHz which will allow the actual RADAR transmitter signal to be monitored by ground stations as the satellite passes through it.

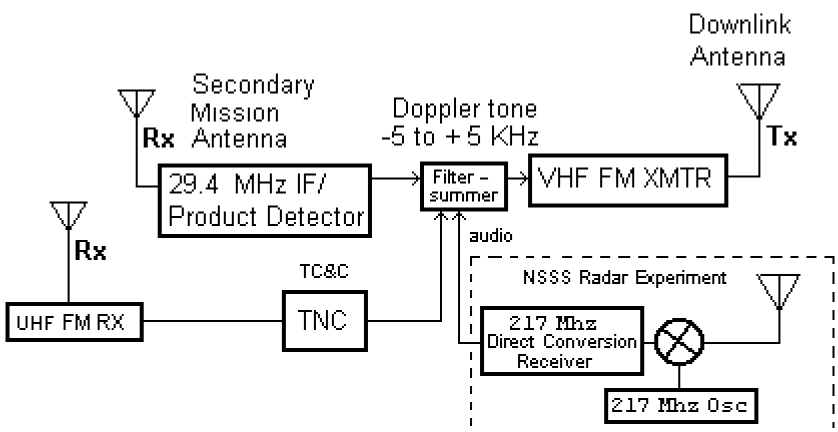


Figure 2. RAFT1 Satellite block diagram

RAFT1 has a UHF FM receiver, operating in the 436 MHz band, and it feeds a customized AX.25 Terminal Node Controller (TNC.) This TNC provides the satellite Telemetry, Command, and Control functions as well as providing a digital transponder for use in the Amateur Satellite Service. The output of the TNC is fed to the VHF FM transmitter for the downlink.

RAFT1 also includes a PSK-31 receiver operating on 29.4 MHz. The PSK-31 signals are combined with the audio output of the TNC and fed into the VHF FM transmitter. The TNC and PSK-31 transponder can operate simultaneously as they use different parts of the audio spectrum. For more details of the RAFT1 satellite program, please see The RAFT web site[2].

While most of the electronic subsystems needed for the satellite are available off-the-shelf, no current manufacturers provide the equipment needed to interact with the NSSS RADAR. A team of three AMSAT members in the Boston area, David Goncalves W1EUJ, Joe Fitzgerald KM1P, and Anthony Monteiro AA2TX, volunteered to help by designing and building the 217 MHz RADAR Transponder Unit. Additionally, Tom Kneisel, K4GFG, has been assisting the team in understanding the operation and requirements of the NSSS RADAR.

NSSS RADAR Fence

The Navy Space Surveillance System (NSSS) is a network of RADAR transmitting and receiving stations that all operate at around 217 MHz. The transmitting sites generate a continuous-wave fan beam, called the *Fence* that is very narrow in the North/South direction but extends straight up, from East to West across the entire southern United States.. Any object that crosses the *Fence* will generate an echo that will be detected by the receiving stations. The NSSS includes three transmitting stations and six receiving stations as shown in Figure 3.

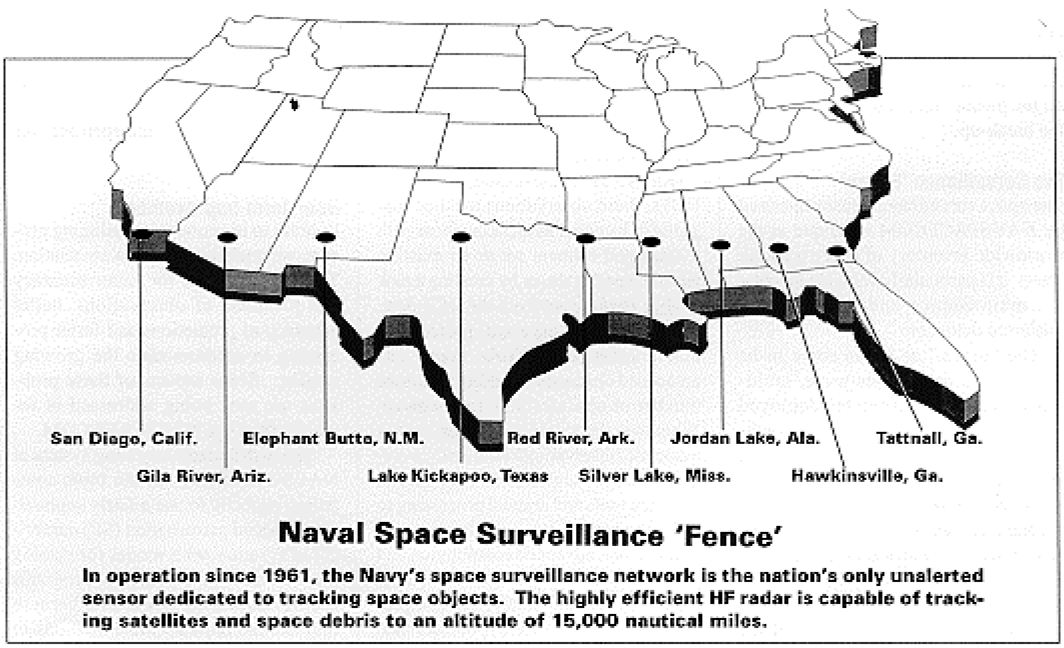


Figure 3. NSSS Transmitting and Receiving Stations[3]

The main transmitting station is in Lake Kickapoo, Texas. It consists of a linear array of 2,556 inverted-V antenna elements, each with its own 300 watt power amplifier, over a reflector screen and it generates a total effective isotropic radiated power (EIRP) of over 6,000 megawatts. A photo of part of the antenna is shown in Figure 4.

The Lake Kickapoo transmitter operates at 216.980 MHz. The other transmitting sites are much lower power but help to fill in the east and west edges of the *Fence*. They are at Gila River, Arizona on 216.970 MHz and at Jordan Lake, Alabama on 216.990 MHz.

The six receiving stations are at San Diego, California, Elephant Butte, New Mexico, Red River, Arkansas, Silver Lake, Mississippi, Hawkinsville, Georgia, and Tattnall, Georgia. The NSSS receiving stations each have an interferometer antenna array and use a variety of signal processing techniques, including measuring the Doppler-shift, to extract the orbital vectors from the received echo. For more information about the NSSS RADAR, please see the web pages by Tom Kneisel[4] and P.A. Crossley[5].

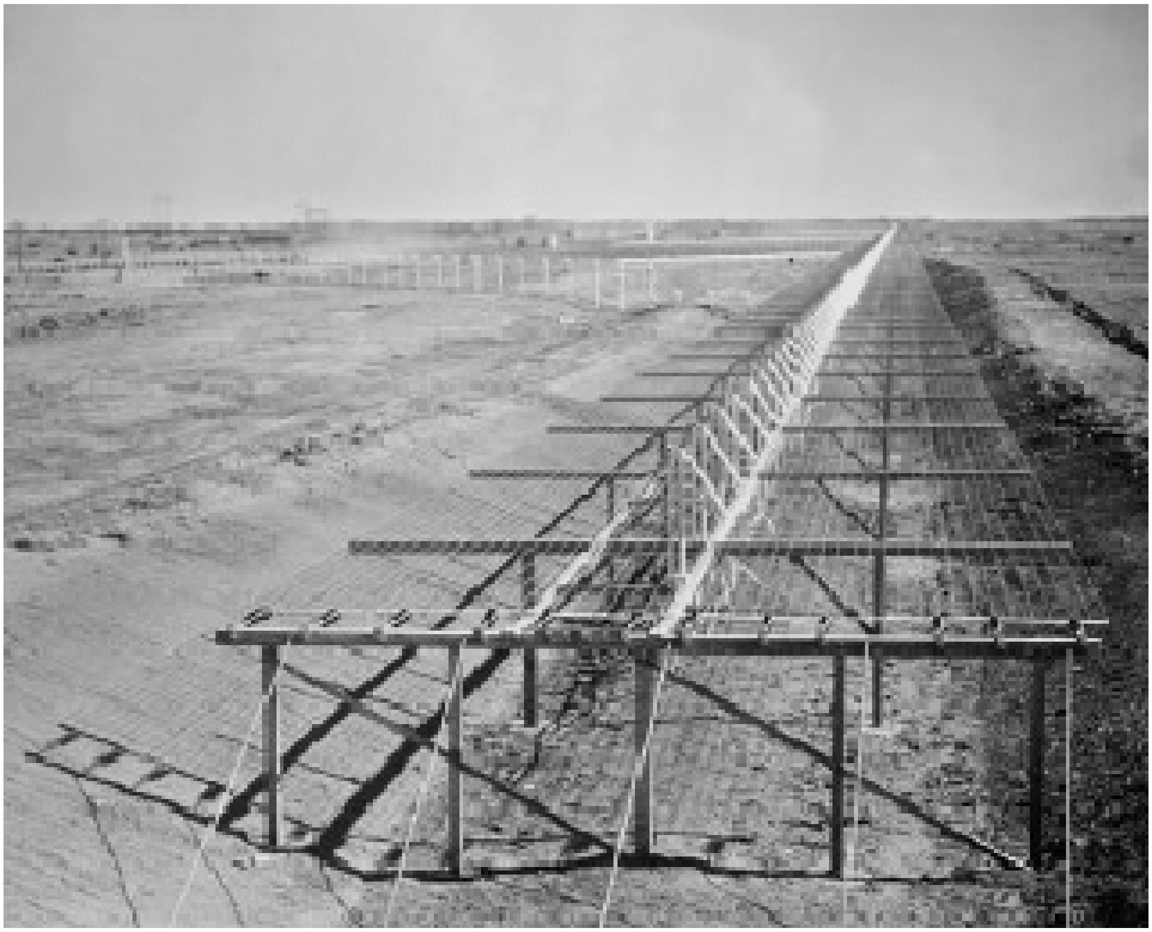


Figure 4. Photo of Lake Kickapoo Transmitting Antenna[6]

The NSSS RADAR Experiment

The transponder on the RAFT1 satellite will provide a receiver and a transmitter on the Lake Kickapoo frequency of 216.980 MHz. The receiver will be a direct-conversion (synchrodyne) type so the recovered audio is actually the Doppler-shift of the Lake Kickapoo transmitter as seen at the satellite. When enabled, the receiver audio output will be fed into a 145 MHz ham radio transmitter so that ground stations can actually listen to the signal as the satellite flies through the RADAR fence. The satellite flies through the fence in about 1 - 2 seconds so the received signal will sound like a short “beep.” Ground stations can use this “beep” to determine the exact time that the satellite passes through the fence and the audio frequency (i.e. the Doppler-shift) can be used to calculate the longitude of the crossing.

The transponder transmitter is an un-modulated CW beacon that the RADAR ground stations will be able to detect along with the received echo of the RADAR transmitter. The idea is to correlate this beacon with the echo so as to positively identify the satellite.

Key Transponder Design Issues

Simultaneous Transmit and Receive

An interesting requirement of the transponder, dubbed the XP217 by the design team, is that it needs to transmit and receive *simultaneously* on 216.980 MHz. This is to allow both the receive and transmit experiments to be conducted at the same time. While the needed transmit level is only around 4 milli-watts, this is much more local oscillator leakage than any modern mixer circuit would provide. Even old-style, tube mixers with gimmick capacitor coupling right into the grid circuit would not have this much local oscillator leakage. The transponder circuit will need to provide a way to accommodate this requirement.

RAFT1 Antenna System

The antenna system of the RAFT1 satellite has not been finalized yet. The current plan calls for the 436 MHz antenna to be shared with the UHF receiver and the 217 MHz RADAR Transponder through a diplexor. For planning purposes, the 436 MHz antenna was assumed to be a simple ¼ wave whip sticking out of one side of the satellite. An EZNEC[7] model of this antenna was developed and it showed an impedance of around 50 ohms at 436 MHz and a complex impedance of around 10.5+ j293 ohms at 217 MHz.

A prototype diplexor and matching circuit was then designed to allow a characterization of the complete antenna system. While this may not be the final antenna configuration, the XP217 design team believes that any reasonable antenna system can be accommodated in the diplexor without requiring changes to the XP217 transponder.

Low Cost

The circuit was designed to keep costs low so that the completed transponder could be reasonably replicated for use in other satellite projects. The development team is also strictly adhering to the KISS[8] principle and has attempted to minimize complexity.

Expected Received Signal Level

The planned orbit of RAFT1 is approximately circular and will have an altitude of about 360 Km. The NSSS RADAR receiving antenna on RAFT1 is expected to have a maximum gain of about 0 dBi at 217 MHz and its diplexor is expected to add -1 dB of loss at 217 MHz.

The NSSS RADAR System transmits a continuous-wave (CW) signal, with a power density of -7.5dBm_0/m^2 at this altitude[9]. An isotropic antenna at this frequency has an effective aperture of .152 m^2 so the maximum received signal power level at the satellite is -15.7 dBm_0 for an overhead pass.

At the horizon, the path loss would increase by -15.6 dB and the NSSS transmitting antenna pattern is down by -13 dB. Also, there may be an additional polarization mismatch loss which would result in an additional -3dB or less loss roughly half the time. This means that at least half of the time, the minimum expected signal level would be greater than -49.3 dBm_0 so with the diplexor loss, on a typical *Fence* crossing, the signal levels at the XP217 Transponder Unit's RF port are expected to be in the range of about -17 $dBm_{\mathbf{0}}$ to -50 $dBm_{\mathbf{0}}$.

Note that the IARU[10] specification for an "S9" signal is -93 $dBm_{\mathbf{0}}$ so the maximum signal level is greater than 70 dB over "S9." It is clear that the receiver does not need to be terribly sensitive but it does need to be able to tolerate a high RF level.

Receiver Local Oscillator Frequency Tolerance

The XP217 receiver will use a direct-conversion, approach so the local-oscillator operates at the same 216.980 MHz frequency as the NSSS RADAR System transmitter. The recovered audio output of the XP217 receiver will be re-transmitted by RAFT1's 2 meter FM transmitter and this transmitter has a bandwidth of at least 3 KHz. Depending on the satellite pass geometry, the *Doppler-shift* on the received signal can be ±2 KHz. In order to guarantee that at least some passes will be audible, the XP217 local oscillator must be less than ±5 KHz from the 216.980 MHz center frequency. This represents a tolerance of 25 parts-per-million (ppm) or better including *all* sources of error.

Additionally, the XP217 local oscillator frequency must be predictable given the oscillator temperature to allow accurate Doppler-shift measurements. A temperature sensor will be provided on the XP217 board and the designers will provide the frequency versus temperature curve in order to allow the XP217 local oscillator frequency to be accurately determined while in orbit.

Transmitter Frequency Tolerance

The NSSS RADAR System receivers have a bandwidth of around 30 KHz centered at 216.980 MHz. This represents a much wider tolerance than the requirements on the XP217 receiver local oscillator. Since this oscillator will be shared between the receiver and the transmitter, no additional requirements are placed on the XP217 transmitter frequency tolerance.

145 MHz Transmitter Signal Rejection

The recovered audio signal from the XP217 receiver will be re-transmitted by a downlink transmitter operating in the amateur 2-meter band. This transmitter has an output power of 1 watt (+30 dBm_0) operating into a ¼λ whip.

An EZNEC model of the RAFT1 satellite antennas indicates that the worst case power transfer between the 145 MHz downlink antenna and the XP217 receive antenna should be no more than -30 dB.

The XP217 receiver will be coupled to its antenna through a diplexor and a circuit simulation of this diplexor showed a rejection of the 145 MHz transmit signal of -20 dB. Therefore, the 145 MHz transmitter signal will be injected into the XP217 Receiver input at a power level of up to:

P_{rx} = +30 dBm_0 -30 dB -20 dB = -20dBm_0

This means the downlink signal, at 145 MHz, may be nearly +30 dB higher at the receiver input than the desired 216.980 MHz RADAR signal and the XP217 receiver must operate normally under these conditions.

Transmitter Radiated Signal Characteristics

In order to provide sufficient link margin to the NSSS RADAR System receivers, the RAFT1 satellite will have an effective isotropic radiated power (EIRP) of around +6 dBm_0 (4 milli-watts.) The RAFT1 antenna is expected to have a gain of 0 dBi and with the diplexor loss, the XP217 transmitter must be able to provide +7 dBm_0 output.

The XP217 transmitter will be operated under authority of the Department of Defense (NTIA.) The typical specified limit on spurious and harmonic emissions under this authority would generally be -50 dB. The prototype electrical model of the diplexor showed greater than 20 dB suppression of frequencies above 400 MHz so the transmitter might be expected to provide 30 dB suppression of harmonics and spurious signals. Note however, that this transmitter is very low power and any spurious emissions would already be far below a more typical VHF transmitter.

XP217 Technical Specifications

General

Service	Radiolocation
Emission Mode	N0N (continuous wave)
Operating Frequency	216.980 MHz
RF input/output impedance	50 Ω
Frequency Tolerance	± 20 ppm
Operating Temperature	-20 to +40 °C
Power Supply Voltage	+7.0 to +9.6 VDC
Power Supply Current	< 50mA

Transmitter

Power Output	+7 dBm_0 (nominal)
Operating SWR	< 1.5:1
Mismatch tolerance	indefinite
Spurious/harmonics	> 30dB suppression

Receiver

Type	Synchrodyne (direct conversion)
Sensitivity	> 10 dB S/N at -50 dBm_0 input
Dynamic Range	-50 dBm_0 to -15.7 dBm_0
Out-of-band rejection	> 40 dB at 145 MHz
Audio output bandwidth	> 3 KHz (10KHz target)
Audio output impedance	1 KΩ minimum load
Audio output level	10mV to 100mV (adjustable)

Temperature Sensor

Resistance	10 KΩ (nominal)
Temperature coefficient	negative
Manufacturer	Vishay/BC Components
Manufacturer part#	2322 640 64103

The transponder temperature sensor will be located as close as possible to the local oscillator module, possibly attached to it with an adhesive. The temperature sensor signals will be isolated (i.e. floating) from the other XP217 signals including any common/ground signals. The specified component is available from *Digikey Corporation* as part# 2322 640 64103-ND.

Physical Construction

The project goal is to make the XP217 “matchbook” size. The XP217 will employ a double-sided, printed circuit board and use primarily surface-mount components.

I/O Connections

All XP217 input and output connections must be on a single edge of the printed circuit board. All connections shall be made with gold-plated, right-angle, dual-row, Molex-type, male header pins with .1” x .1” spacing. The signal leads are as follows:

Signal Name	Function
PWR-POS	+DC power
PWR-COM	-DC Supply (Common)
TEMP-A	Temperature Sensor Lead A
TEMP-B	Temperature Sensor Lead B
RF-IO	RF input/output
RF-GND	RF ground
RX-OUT	Received audio output
RX-GND	Received audio ground

XP217 Architecture

The problem of how to transmit and receive at the same time was solved with the architecture shown in Figure 5. The transmitter power amplifier not only provides the transmit signal but also provides the local oscillator injection for the mixer and provides the RF termination for the received signals. An "infinite-impedance" mixer, which provides a very high input impedance, is connected in parallel with the power amplifier and does not load down either the transmit or receive signals. The nominal signal levels are shown on the diagram. The receive signal levels, labeled *RX*, are shown for an overhead pass through the RADAR fence. The resulting XP217 circuit consists of six major sub-systems; a Voltage Regulator, a Local Oscillator, a Power Amplifier, an RF Filter, an Infinite-Z Mixer, and an Audio Amplifier.

The Voltage Regulator provides a steady +3.3 VDC at up to 30 mA for the Local Oscillator. It is a single integrated-circuit, switching regulator. Though slightly more complicated than a linear regulator would be, it significantly reduces the total current drain on the satellite's 8V battery supply line.

The Local Oscillator uses a FOX Electronics *Just-in-Time-Oscillator* module (JITO-2.) The module includes of a crystal oscillator and factory programmable, PLL-synthesizer. This combination allows FOX to provide custom frequency oscillators, in a 2-week time frame, at a very low cost. The specified module operates at 216.980 MHz over a temperature range of -20 to +70 °C with a frequency tolerance of ±20ppm including all sources of error (temperature, initial accuracy, aging etc.) The oscillator provides an output of 3V peak-to-peak at a maximum current of ±2 mA.

The Local Oscillator has a temperature sensor (U1) which will be fed into a satellite telemetry channel. The temperature versus frequency curve for the Local Oscillator will be determined and specified before launch. This will allow a ground station to correct for the temperature induced frequency variation of the oscillator module and allows an accurate determination of the Local Oscillator frequency without requiring an oven or other tight tolerance temperature compensation circuits.

The Local Oscillator drives the Power Amplifier. This is a single transistor operated in a grounded-source configuration. It brings the Local Oscillator signal up to +8dBm_0. The output level can be adjusted by setting the value of resistor *Rbias*. The Power Amplifier has an input impedance of approximately 2K ohms and an output impedance of 50 ohms which also provides the termination for receive signals that pass through the RF Filter.

The RF Filter is bi-directional and provides significant rejection at 145 MHz to keep the downlink transmit signal from interfering with the transponder receiver. The RF Filter has 50 ohm input and output impedances and provides over 40 dB of rejection at 145 MHz. The insertion loss is about 1 dB.

The Infinite-Z Mixer provides a very high input impedance and works in a manner similar to the "infinite impedance detector" circuits that were commonly used in old vacuum tube TRF[11] receivers. It is connected to the Power Amplifier output. It's high input impedance does not load down the transmit or receive signals and it mixes the received signal with the transmitter output signal and produces an audio difference tone equal to the RADAR signal Doppler-shift seen by the satellite. The sum frequency is filtered out with a low-pass filter.

The Audio Amplifier stage is a low noise amplifier that provides an adjustable amount of gain and an adjustable output level. The voltage gain can be increased, if necessary, by changing the value of *Rgain*. With *Rgain* open, the Audio Amplifier voltage gain is about 4.2 providing about 100 mV RMS output into a 1.5 K-ohm load at the maximum receive signal level. The output voltage divider, *Rout1* and *Rout2*, provides an adjustable attenuator to set the output level to as required by the downlink transmitter.

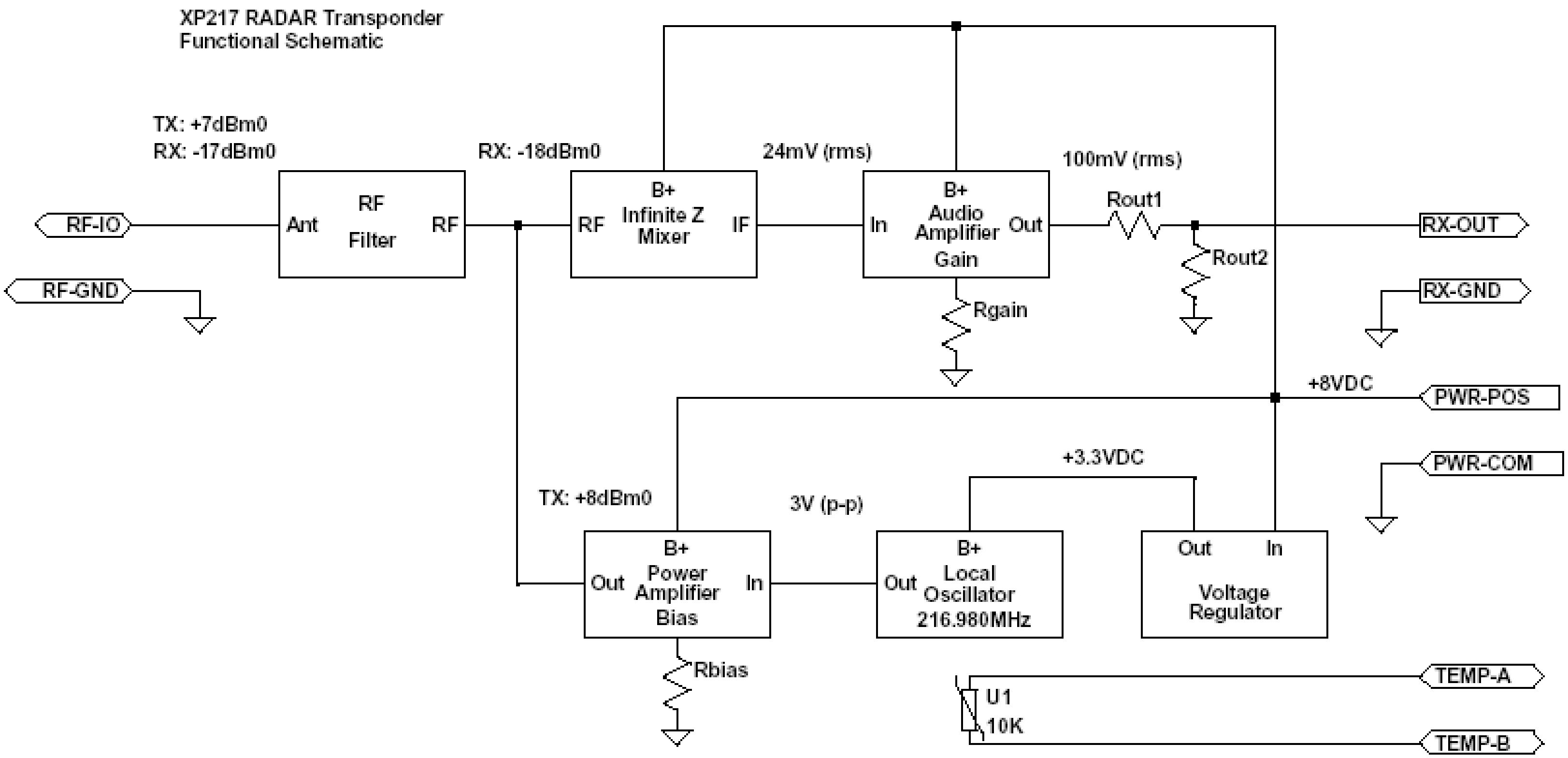


Figure 5. XP217 Architecture

XP217 Antenna Diplexor Circuit

The current plan is to use the 436 MHz antenna for operation on 217 MHz through a diplexor. The circuit shown in Figure 6 is a preliminary version of this diplexor since the 436 MHz antenna system has not been finalized at the time this article was written. The circuit is representative of what would be expected and it would be easy to tailor it to the final antenna design.

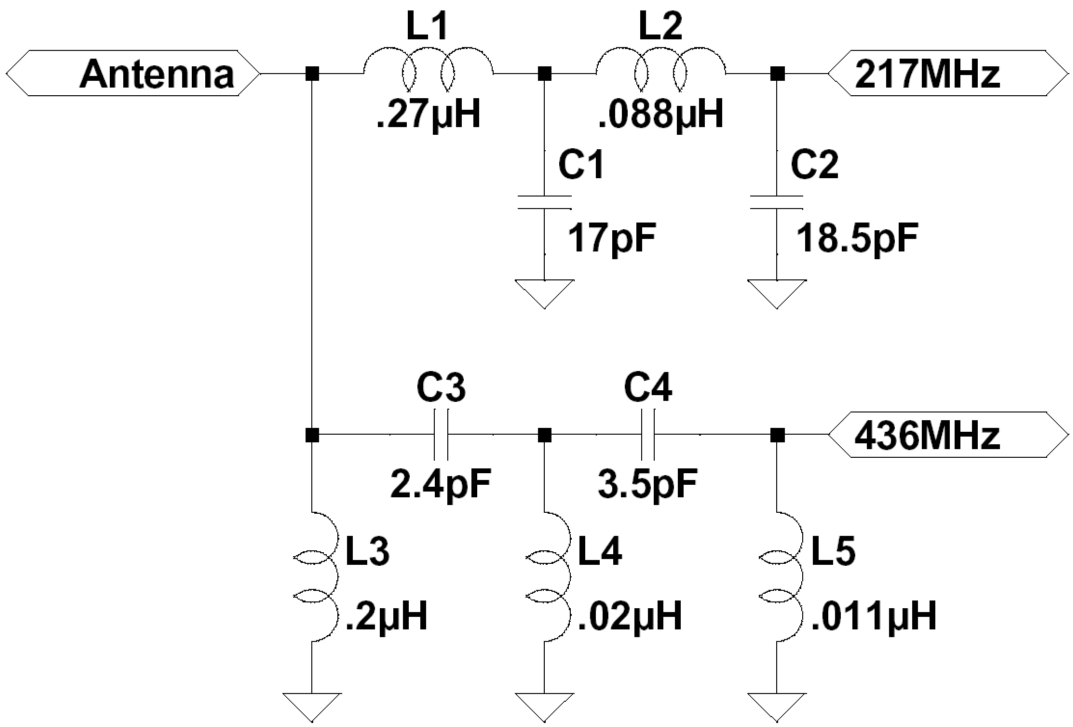


Figure 6. Antenna Diplexor Circuit

For this circuit, the antenna is assumed to be a single ¼-wave whip (at 436 MHz) coming off of one side of the satellite. This antenna would have an impedance of about 50 ohms at 436 MHz and a complex impedance of about 10.5+j293 ohms at 217 MHz. Both ports provide 50 ohms impedance as the 217 MHz port provides an impedance match to 50 ohms. The circuit shown provides sufficient isolation between the 217 MHz and 436 MHz ports that a short or open on either port has no significant effect on the other port.

XP217 Transponder Circuit

The XP217 Transponder circuit is shown in Figure 7. The MAX887 is a single-IC switching voltage regulator and provides +3.3VDC to the oscillator module. The oscillator module feeds a power amplifier consisting of Q2, a J309 type transistor, operating in a grounded source configuration. This power amplifier is both the transmitter output and the receiver local oscillator. The resistor, R10 (*Rbias*, on the Functional Schematic,) can be adjusted to set the output level. Capacitor C22 and inductor L6 form a matching network to allow the oscillator module to drive the power amplifier. Similarly, capacitor C19 and inductor L7 form another matching network to transform the output impedance of the J309 to 50 ohms. The Power amplifier signal is fed into the antenna diplexor through the RF-filter made up of capacitors C1-C3 and inductors L2-L5.

The RF-Filter provides rejection of the 145 MHz downlink signal but allows the received 217 MHz RADAR signal to pass through. The received RADAR and the local oscillator signals appear at the gate of Q1, another J309 type transistor, which operates as a high-impedance mixer. This transistor is biased almost to cut-off by the source resistor R1. When the input signal on the gate goes negative, the transistor remains nearly cut-off so and there is very little change in the current through the transistor. When the input signal goes positive, the transistor turns on and conducts a current from source to drain creating an output voltage across R1 which follows the envelope of the combined RADAR signal and local oscillator injection. The output signal is low-pass filtered by R2, C4, and C5 to remove the high-frequency components leaving just the audio signal.

The audio output of the mixer is coupled to Q3, a low-noise, 2N5088 type, bipolar transistor. This transistor amplifies the received signal with a voltage gain of about 4.5. The resistor, R17, (*Rgain* on the Functional Schematic) controls the degree of negative feedback which sets the overall voltage gain. Transistor Q3 is directly coupled to Q4, another 2N5088 type transistor, operating as an emitter-follower buffer. The audio output can drive a 1K ohm load. The output voltage divider consisting of R8 and R9 (*Rout1* and *Rout2*, on the Functional Schematic) allows the output level to be adjusted to that needed by the downlink transmitter.

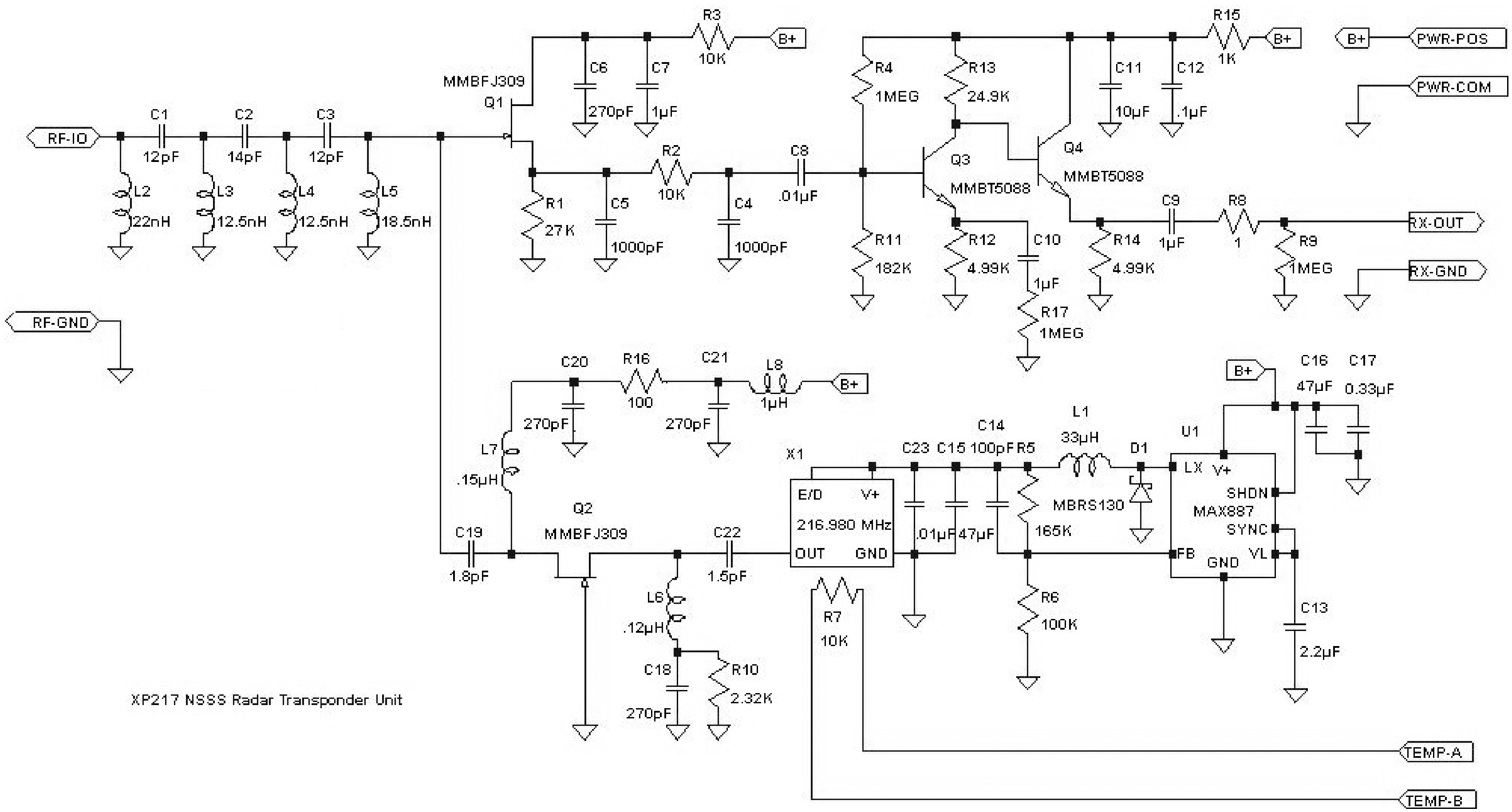


Figure 7. XP217 Circuit Schematic

Project Status as of 8/1/2004

At the time this article was written, the initial circuit design was completed, as shown in Figure 7, and the circuit was simulated and verified using LTspice/SwitcherCAD III[12] a SPICE-III based circuit simulator[13].

The complete Bill of Materials had also been generated and some testing had been completed on the oscillator module to characterize its operation although more testing remains to be done. The printed circuit layout, manufacturing of printed circuit boards and construction of prototypes was still under way.

The XP217 development team maintains a web site[14] with the current documents and status as well as interesting links. For the latest status please visit the web site.

Summary

The XP217 NSSS RADAR Transponder for the RAFT1 satellite is being designed and constructed by a team of AMSAT volunteers. The complete transponder uses only four transistors, an off-the-shelf oscillator module, and a single-IC voltage regulator keeping the circuit simple and inexpensive. As of the time of this writing, the circuit had been designed and simulated using SPICE-III analysis, a bill of materials had been generated, and some testing had been done to characterize the oscillator module. The current RAFT1 schedule calls for engineering models to be available in December of 2004 for testing with final flight hardware to be integrated in May 2005. The launch is scheduled for September 2005 via the Space Shuttle.

The development team would especially like to thank Tom Kneisel for his assistance in understanding the operation of the NSSS RADAR system.

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[1] For information about the AMSAT Bulletin-Board, please see www.amsat.org
[2] RAFT Satellite web site: http://web.usna.navy.mil/%7Ebruninga/raft.html
[3] NSSS Fence Image from National Space Security Road Map (NSSRM) unclassified photo list, http://www.wslfweb.org/docs/roadmap/irm/photo.htm
[4] Tom Kneisel 's NAVSPASUR web site at http://www.gate.net/~tomk/navspasur/index.html
[5] P.A. Crossley's NAVSPASUR web site at http://www.jump.net/~crossley/NAVSPASUR/
[6] Lake Kickapoo Antenna photo from "The Naval Space Surveillance System *Fact Sheet*," United States Navy Space and Naval Warfare Systems Command, Public Affairs and Corporate Communications. http://enterprise.spawar.navy.mil/UploadedFiles/nsss_fs_2002-09_093002.pdf
[7] EZNEC Antenna Modeling Software, Version 2.0, by Roy Lewallen, available at www.eznec.com
[8] KISS Principle: "*Keep it Simple…*"
[9] "Theoretical Radiation Patterns of NAVSPASUR Transmitter Antennas," by Dr. Steven L. Berg, Interferometrics, Inc. November 30, 1988.
[10] IARU: *International Amateur Radio Union*
[11] TRF: *Tuned Radio Frequency*, a type of receiver circuit using an RF amplifier, a detector, and audio amplifier.
[12] LTspice by Linear Technology is available for free from http://www.linear.com/software/
[13] The original SPICE circuit simulator was developed by the EECS Department of the University of California at Berkeley and is available at http://bwrc.eecs.berkeley.edu/Classes/IcBook/SPICE/
[14] The RAFT Tracking Device Development website is at http://www1.coe.neu.edu/~dpg/rx217.html

The CanX-2 Nanosatellite: Expanding The Science Abilities of Nanosatellites

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***Abstract*— As the second Canadian Advanced Nanospace eXperiment (CanX) satellite, CanX-2 aims to support Canadian researchers while expanding the capabilities of nanosatellites. Designed and built at the University of Toronto Institute for Aerospace Studies' Space Flight Laboratory (UTIAS/SFL), CanX-2 will include experiments in GPS technologies, earth observation, advanced materials, and space communications protocols. In addition to the science payloads, CanX-2 will also fly engineering payloads such as a momentum-bias attitude control system, an experimental S-band communications system, a custom on-board computer, and a miniature propulsion system. With such an ambitious science platform, CanX-2 hopes to demonstrate the use of a nanosatellite as a valuable scientific tool that is cost- and schedule-effective for today's researchers. With a target launch in late 2005 into a highly-inclined orbit, the experiments and satellite subsystems described in this paper will help pave the way for future nanosatellite science missions both at UTIAS/SFL and other institutions.**

***Résumé*—Étant le deuxième satellite dans le programme Canadian Advanced Nanospace eXperiment (CanX), CanX-2 a pour but d'appuyer les scientifiques canadiens et d'améliorer les capacités des nanosatellites. Conçu et construit au Laboratoire du vol spatiale à l'Université de Toronto institut pour études aerospatiales (UTIAS/SFL), CanX-2 comprendera des expériences dans les domaines de technologies de Système mondial de localisation (GPS), d'observation terrestre, de matériaux avancés, et de protocole de communication spatiale. En plus des expériences scientifiques, CanX-2 volera avec des charges utiles de génie, dont un système de contrôle d'orientation basé sur le momentum, une expérience de système de communication à bande S, un ordinateur spécialisé, et un système de propulsion miniaturisé. La plate-forme d'expériences scientifiques de CanX-2 étant tellement ambitieux, nous espérons que CanX-2 démontrera qu'un nanosatellite peut être un outil scientifique à la fois efficace et rentable. CanX-2 sera lancé vers la fin de 2005 vers une orbite ayant une haute inclinaison. Les expériences et les sous-systèmes de satellite décrits dans cette publication serviront à faciliter les missions scientifiques de nanosatellite de l'avenir au UTIAS/SFL et aux autres institutions.**

I. Introduction

The Canadian Advanced Nanospace eXperiment (CanX) series of satellites was started in September of 2001 at the University of Toronto Institute for Aerospace Studies' Space Flight Laboratory (UTIAS/SFL). The CanX program began with the intention of providing an opportunity for Canadian graduate engineering students to learn about the field of microsatellite engineering, while at the same time providing a low-cost orbital platform for Canadian scientists. CanX missions use the CubeSat standard developed by Stanford and CalPoly universities, with the aim of lowering satellite launch costs through standardization that allows small cube shaped satellites to be launched inside a compatible deployment system [1]. A single CubeSat has a mass of less than 1 kg, a side length of 10 cm, and is cube shaped as the name suggests. The CanX program also takes advantage of the latest advances in technologies that are applicable to space, by using a relatively short design cycle.

Student participation is essential for the success of the

Fig. 1. Master's students get hands-on training by assembling CanX-1 on the lab bench.

Fig. 2. Class 10,000 Clean Room Facility at UTIAS/SFL.

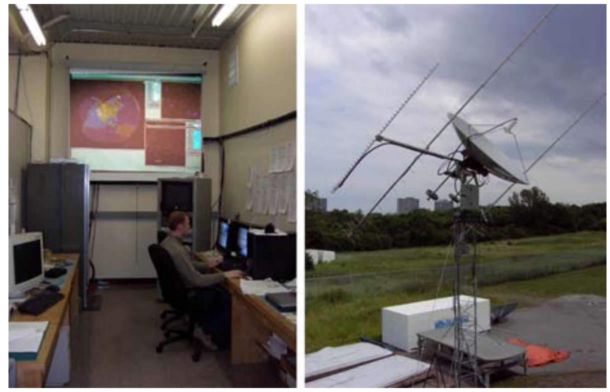

Fig. 3. Left: Mission Control at UTIAS/SFL. Right: Antenna tower supporting communications with the MOST microsatellite.

CanX program. The expected design cycle of a CanX satellite, lasting approximately 18-24 months, nicely coincides with the length of time typically required for students to complete a Master's degree. In this way, the students are able to experience a complete satellite development cycle and leave the CanX program with training in all phases of satellite design, construction, testing, and operations. See Figure 1.

In addition to the student team responsible for much of the work on a CanX satellite, there is also a team of UTIAS/SFL staff members who may design some subsystems of the satellite. The range of fields covered by the staff members includes computer engineering, power systems engineering, radio frequency communications, systems engineering, mission design, propulsion design, satellite testing, and mission operations. The engineering staff have previous experience in microsatellite design and are able to mentor the students and share the lessons learned through previous UTIAS/SFL satellite experiences to help ensure the success of the current CanX mission.

II. Facilities

The Space Flight Laboratory at UTIAS is a modern satellite engineering facility built within the confines of a world-recognized centre for aerospace research. The laboratory has incorporated significant facilities to allow most of the design, assembly, and testing of UTIAS/SFL satellites to be accomplished in-house. For satellite design, there are significant computing resources along with many of the latest software packages for aiding the development mechanical, electrical, and software designs. There are also facilities for constructing basic mechanical and electrical prototypes of flight systems.

Prototype systems can be tested in-house. UTIAS/SFL has two thermal cycling chambers, which can test items within a temperature range of -70°C to +180°C. The laboratory also possesses equipment to operate a small vacuum chamber which can be used within a thermal chamber, thus allowing thermal-vacuum testing of spacecraft components, or, in the case of CanX series satellites, the entire spacecraft. For radio testing, UTIAS/SFL possesses a small anechoic chamber. There are also instruments available for spacecraft testing, such as oscilloscopes, spectrum analyzers, and signal generators. For vibration testing and EMI/EMC testing, UTIAS/SFL has relationships with other departments at the University of Toronto, some Canadian government agencies, and industry partners to provide support for testing that cannot be conducted at UTIAS/SFL. For final spacecraft integration and assembly, there is a Class 10,000 clean room located on-site. The clean room facility allows for integrated functional testing in-house, saving the cost of having to move the established test support equipment to an off-site clean room facility. See Figure 2.

UTIAS/SFL also contains ground station facilities for communicating with and tracking satellites. There are two separate ground stations at the present time: the MOST ground station, and the CanX ground station. The MOST ground station has fully-automated facilities for VHF/UHF/S-band satellite communications using Yagi antennas, as well as S-band downlink capability with a 2.1 m parabolic dish antenna [2]. The S-band communications are currently dedicated to the MOST microsatellite mission that operates in the Space Research band. At present, the CanX ground station works in half-duplex in the 70 cm Amateur Satellite band with UHF uplink and downlink using a dual Yagi antenna array. The ground station control area at UTIAS/SFL also has a large screen projection system (shown in Figure 3), so that major spacecraft events can be watched easily by larger groups.

III. Program Legacy

The CanX-2 nanosatellite builds upon the legacy of the first CanX series satellite: CanX-1. The CanX-1 project commenced in September 2001 as the first in a series of CanX satellites to be designed and built at UTIAS/SFL. The program goals of CanX-1 were to provide education for students and to set up laboratory infrastructure for future CanX use. CanX-1 was a nanosatellite (satellite $<$ 10kg). At 1 kg and in the shape of a 10 cm cube (Figure 4), the mission goals for CanX-1 were to demonstrate systems for use in future CanX missions, as well as to demonstrate several technologies in space. [3]

Among the technologies that CanX-1 hoped to demonstrate in space were as follows:

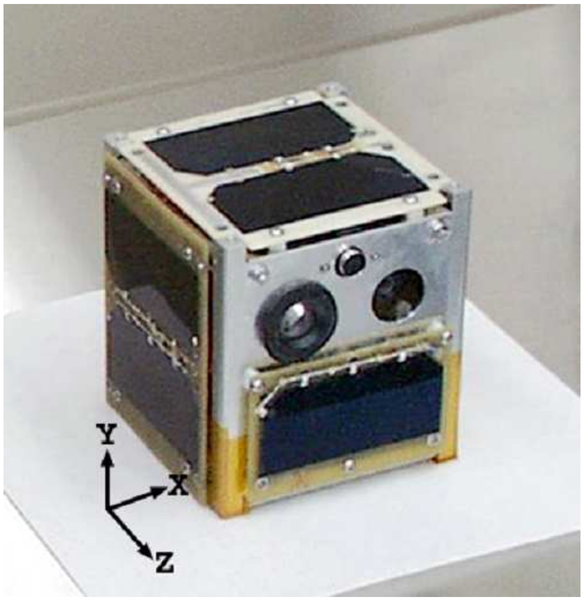

Fig. 4. CanX-1. (Note: Antennae are stowed and not visible.)

- A custom designed on-board computer (OBC) using an ARM7 processor.
- A custom designed UHF radio operating in the 70 cm Amateur Satellite band.
- A magnetic B-dot attitude control system, including an on-board magnetometer.
- Two CMOS imagers (colour and monochrome) on a custom designed board for Earth imaging and ground-based star tracking.
- A CMC Electronics GPS receiver.
- A Xiphos Q4 board.

CanX-1 was launched on June 30th, 2003 on a Eurockot vehicle along with several other payloads including the UTIAS/SFL-developed MOST microsatellite. CanX-1 was launched in a deployment tube along with two Danish CubeSats. Although one one of the Danish CubeSat teams managed to receive a small amount of data from their satellite AAU-CubeSat [4], contact was never achieved with CanX-1 and the Danish satellite DTUsat [5].

Although CanX-1 did not return data from orbit, the program met 90% of its objectives. It successfully allowed the development of many in-house capabilities and provided a valuable learning experience for the CanX team to build upon when designing future CanX satellites.

IV. CanX-2

Initiated in September 2003, CanX-2 is the second in the series of CanX satellites. At present, CanX-2 is in the detailed design phase, with prototypes of key satellite subsystems built or expected soon. CanX-2 is planned to be one of the first operational science nanosatellites for Canadian researchers. The size of the satellite is triple that of CanX-1, measuring $10\times10\times30$ cm and is approximately 3 kg in mass. This allows for a greater available volume for payloads and a larger surface area, permitting more solar panels for power generation. This configuration is shown in Figure 5.

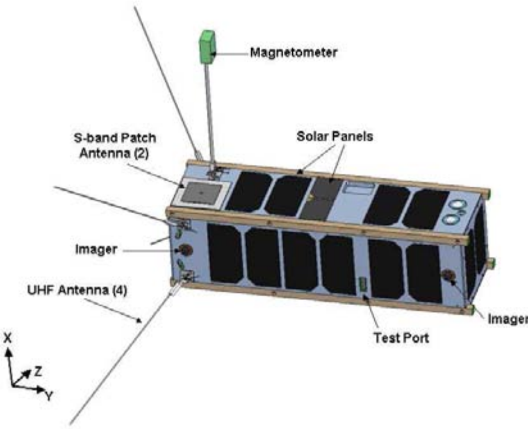

Fig. 5. Solid Model of CanX-2.

CanX-2 features a UTIAS/SFL-developed on-board computer (OBC) that it more versatile and consumes less power than the CanX-1 OBC. It utilizes an ARM7-based processor with 3 MB of SRAM memory with error detection and correction (EDAC) protection for running spacecraft software. The prototype OBC is shown in Figure 6. The design includes 32 MB of flash memory to increase the capacity for storage of pre-positioned software, science data, and archived telemetry data. Serial (USART) and SPI buses link the OBC to the payloads, the power switches, and the telemetry systems. There are 65 hardware and software telemetry points; these sensors monitor key temperatures, currents, voltages, and software outputs and are used to evaluate the health and performance of the satellite.

Power is provided by triple junction GaAs solar cells, and, with more surface area that CanX-1, the maximum power generation is increased to 4 W. Electrical energy is stored for peak usage periods and eclipse conditions using a 3.6 Ah lithium-ion battery connected to an unregulated satellite power bus operating nominally at 3.6 V. The power system uses direct energy transfer to convert the power generated by the solar cells for use by the power system. Currently the power system has been prototyped and is being used to conduct testing of both it and the CanX-2 prototype OBC.

Primary radio communications is accomplished using a custom half-duplex radio operating in the 70 cm Amateur Satellite band. The radio design is similar to that used on CanX-1 [3] but includes an improved power amplifier providing a final transmitter power of 30 dBm (1 W). This downlink provides engineering and telemetry data with an information rate of 4000 bit/s using a GFSK modulation scheme. The receiver consists of a low-noise amplifier followed by a single-conversion heterodyne receiver. After down-conversion to the intermediate frequency (IF), the signal is demodulated using a phase-coincidence demodulator, filtered by a baseband filter and coupled to a GFSK modem. The uplink is used for command and control purposes only, and all operators are

Fig. 6. CanX-2 Prototype On-Board Computer. Note that smaller connectors will be used on the flight-ready OBC.

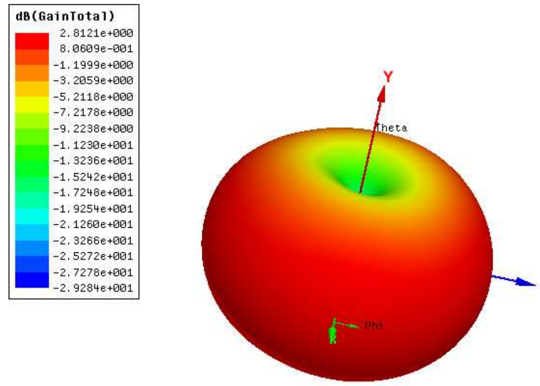

Fig. 7. Ansoft HFSS 3D plot of the UHF turnstile antenna pattern. The pattern is near-omnidirectional with minimum gain along the Y-axis of the satellite.

students and licensed radio amateurs.

A quad-canted turnstile antenna arrangement has been selected for CanX-2; the array is made up of four quarter-wave whip antennas, fed in phase, and mounted near the corners, canted outwards at an angle of 45°. The arrangement provides the near omni-directional coverage that is required during commissioning, before the satellite's orientation is stabilized by the attitude control system. A simulation of the antenna pattern is shown in Figure 7.

A custom Nanosatellite Protocol (NSP) is employed for all communications. This protocol is a simplified form of HDLC that allows for efficient communication with low overhead. After launch, the protocol and downlink frequencies will be published.

CanX-2 will also be equipped with a VHF beacon transmitting an identification and several telemetry parameters in Morse Code at 15 WPM. The beacon transmitter antenna length is constrained by the orbital deployer; thus, it will be less efficient than a quarter-wave radiator. The design calls for the beacon antenna to be a 30 cm whip antenna oriented perpendicular to one long face of the satellite. It is planned that the beacon will operate early in the mission to facilitate tracking and signal acquisition during the satellite commissioning phase. The beacon can be permanently deactivated on command from the ground station; this causes a fuse to blow, disabling the beacon's power connection.

V. CanX-2 Payloads

CanX-2 includes an extensive suite of engineering and science payloads. These payloads consist of the following:

- A three-axis momentum-bias coarse pointing attitude control system.
- A Nanosatellite Propulsion experiment.
- A high-data-rate S-band transmitter.
- Two CMOS imagers (colour and monochrome).
- A GPS receiver for radio occultation studies.
- An Atmospheric Spectrometer.
- A Surface Materials experiment.

A. Engineering Payloads

1) Attitude Control System: Like CanX-1, the CanX-2 Attitude Control System (ACS) utilizes three magnetorquer coils. These vacuum core coils are manufactured at UTIAS/SFL using 32 AWG magnet wire to produce a maximum magnetic dipole of 0.13 $A{\cdot}m^2$. In addition, CanX-2 will include a momentum wheel provided by Dynacon Inc. in order to implement a momentum-bias three-axis control system. The momentum wheel will produce a maximum torque of 0.3 mN·m and can store a maximum angular momentum of 10 mN·m·s.

For attitude determination, the ACS will use a suite of Sun sensors and a three-axis magnetometer. The Sun sensor is currently being developed at UTIAS/SFL and aims to achieve an accuracy of better than 1.5° with a resolution of 0.3°. The UTIAS/SFL-designed magnetometer board uses Honeywell solid-state analog sensing ICs to detect the local magnetic field. The goal for the system is to achieve both attitude determination and pointing to within one degree of accuracy. The ACS is included to both test the momentum wheel technology, and to support the other science and engineering payloads. Currently the ACS sensors and actuators have been prototyped and are undergoing performance testing. The custom ACS software has also been prototyped and is being evaluated using a MATLAB-based simulator package.

2) Propulsion Experiment: A important engineering payload is the nanosatellite propulsion system developed at UTIAS/SFL. It consists of a liquid-fueled, cold-gas thruster system. Weighing under 500 g, the system is designed to have a total thrust of 50 mN and a specific impulse (I_{sp}) of at least 50 s. Such a system has never been flown before on such a small satellite and the CanX-2 mission will characterize its performance.

The nanosatellite propulsion system will be evaluated on CanX-2, along with the dual frequency GPS receiver for position determination. If successful, future CanX missions are planned to demonstrate the capability of nanosatellites to perform formation flying. In this configuration, multiple spacecraft act as a single mission spacecraft for coordinated observations, in situ measurements, or virtual instrumentation (e.g. interferometry, distributed sensing). The potential then exists for evaluating formation flying algorithms (including relative distance measurement accuracy) and applying them in novel experiments.

3) S-Band Transmitter: The S-band transmitter is an UTIAS/SFL-designed unit. In the CanX-2 mission, it is a payload that evaluates the performance performance of miniaturized S-band technology for nanosatellites, while also increasing the amount of science data that can be received by the ground. The transmitter has a maximum output power of 27 dBm (0.5 W) and is designed for high-speed data downlink. The data rate and modulation scheme can be dynamically adjusted as the link conditions change and the satellite approaches its minimum distance at higher elevations in the sky. By selecting interchangeable components during assembly, the S-band transmitter can operate in either the Amateur Satellite S-band or in the Space Research S-band allocations. The S-band transmitter is connected to two RHCP patch antennas mounted on either side of the satellite.

If the S-band transmitter is successful, the baseline communication mode for CanX-2 will be a UHF uplink and an S-band downlink. This would permit full-duplex communication and increase the data return rate by an order of magnitude.

4) Imagers: The two CMOS imagers that are being planned for CanX-2 are very similar to the CanX-1 imagers. These imagers, manufactured by National Semiconductor, are slightly larger than the CanX-1 imagers and both have a field of view of about 30° with a resolution of 1200×1024. The monochrome imager provides the option of doing ground-based star tracking experiments, while the colour imager will be used mainly to take pictures of interesting targets like the Earth and its moon. Both cameras may be used for on orbit calibration of the ACS performance.

B. Science Payloads

1) GPS Occultation Experiment: The primary science payload on CanX-2 is the GPS Occultation Experiment, designed by Dr. Susan Skone of the University of Calgary [6]. Through the use of a dual-frequency GPS receiver and a directional antenna mounted on the outer surface of the satellite, measurements are made of GPS radio signals as the GPS satellites are occulted by the Earth's atmosphere. These signals refract during occultation, introducing a delay in the signal. Data from ground-based GPS stations are used in conjunction with the space-borne data, and differential GPS processing methods are employed, to recover atmospheric properties such as total electron content and tropospheric water vapour as a function of altitude.

These properties can be used to model the atmosphere and generate 4-D electron density profiles. These models can be used to help mitigate GPS positioning errors during periods of enhanced ionospheric activity, to monitor the development of auroral activity, magnetic substorms, and associated ionospheric disturbances that have an adverse impact on navigation and communications systems.

2) Imaging Spectrometer Experiment: The Atmospheric Spectrometer, developed by Dr. Brendan Quine of York University [7], is an earth imaging spectrometer. It provides measurements of airborne greenhouse gases to support the goals of the Kyoto protocol. The payload operates in the near infrared band using Earthshine spectra. It features a surface resolution of 1 km, which will enable the identification of local variation and sources of pollution emission.

This experiment will be used to test and validate the low-mass spectrometer hardware and electronics system. The data collected will be used initially to detect pollution plumes from large-scale industrial and other processes, and subsequently to develop a calibrated system to record surface emission fluxes of greenhouse gases and to estimate surface horizontal fluxes from particular geographic areas.

3) Materials Science Experiment: The surface materials experiment for CanX-2 is provided by Dr. Jacob Kleiman of the University of Toronto. This experiment uses a photon detector to measure the degradation of a material sample exposed to the space environment. The sample is divided into two parts: one having been given a special surface treatment and another without surface treatment. The plan is to monitor the changes in sample thickness as a result of atomic oxygen erosion to evaluate the effectiveness of the special surface treatment.

4) Satellite Communication Protocol Experiment: A network communications experiment involving an innovative LEO satellite communication protocol developed by Dr. Michel Barbeau of Carleton University is included in CanX-2 [8]. The protocols include a network layer and a transport layer. The network layer protocol comprises an algorithm using dynamic source routing. The satellite remains silent by default, and dynamically reacts when it perceives traffic. In a self-organizing network approach, a satellite can automatically make use of ground stations or other satellites, when they are available, to reach a given target. The transport layer protocol is called eXtended Satellite Transport Protocol (XSTP) and addresses data transport errors that occur specifically in LEO satellite links.

This experiment will run the networking protocol under the open-source operating system eCos [9] and evaluate it in the LEO environment. During the experiment, XSTP will be used instead of the NSP that is used for command and control functions and all other experiments.

VI. Present Status

CanX-2 is aiming for a launch date in late 2005, and negotiations with prospective launch vendors are ongoing. As a secondary or tertiary payload, the orbit for CanX-2 has not been finalized. Several potential high-inclination orbits are being used in the design analyzes.

The design of CanX-2 is well underway: prototype hardware has been built, flight software development is progressing, and the design analyzes are being refined. The flight hardware is planned for completion in early 2005.

Fig. 8. The successful assembly and integration of CanX-1 in the UTIAS/SFL clean room.

VII. Conclusion

The CanX program serves Canadian and international partners by providing exceptional hands-on training to graduate students in the area of space systems engineering. At present, this program is unique in Canada. University researchers, industry and government have opportunities to fly science and technology experiments in space cheaply and rapidly. The CanX program is intended for aggressive experimentation in space. In combination with the training aspect of the program, missions are completed in less than two years for a few hundred thousand dollars. In keeping with the nano/microspace philosophy, redundancy in the satellite is traded for simple, good design, with mission risk distributed over multiple low-cost missions rather than over multiple components in a single mission. The CanX program is pioneering the low-cost exploitation of space and intends to revolutionize Canadian space activity in the 21st century. The UTIAS Space Flight Laboratory encourages companies, university groups and government agencies across the world to collaborate on these low-cost missions.

For more information please visit www.utias-sfl.net.

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GPS, Distributed Communications, and Thruster Experiments on the University of Texas FASTRAC Mission

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Abstract. Enabling technologies for nanosatellite formations will be demonstrated under the Formation Autonomy Spacecraft with Thrust, Relnav, Attitude, and Crosslink (FASTRAC) program. Two flight-ready nanosatellites will be designed, fabricated, integrated, and tested during the two year design period. Three specific new and innovative technologies which will be demonstrated during the mission are GPS Relative Navigation, Distributed Communications, and Microdischarge Plasma Thrusters.

A sensor set consisting of Global Positioning System (GPS) receiver and magnetometer will be used to determine position and coarse attitude. Using a UHF crosslink, the two satellites will exchange state vector information and perform sub-meter level accuracy relative navigation. Each satellite will also contain a Microdischarge Plasma Thruster (MPT) developed at UT-Austin. This innovative device is capable of generating low-thrust, high-efficiency propulsion at low power levels using microdischarge plasmas. The ability of the MPT to extend the life of the orbit will be determined by monitoring the orbit decay rates of the two vehicles as well as the MEMS IMU.

A distributed tracking network with multiple university partners will be utilized to track the low Earth orbit satellites. Amateur radio experimenters, high schools, universities, and other interested parties will be encouraged to record telemetry from the satellites and report their data to a project web site for processing. In addition, amateur operators will have the opportunity to utilize many of the satellites communication systems once the science experiments have been completed.

INTRODUCTION

SPACECRAFT formations will play an important role in the future utilization of space. The National Aeronautics and Space Adminstration (NASA) and the United States Air Force (USAF) have several missions planned to perform experiments with distributed space systems.[1] In these cases, multiple satellites work together in a coordinated manner to perform tasks that would be impossible or cost prohibitive using a single satellite. These missions will become progressively more challenging in terms of the number of satellites in the formation and the complexity of the tasks that must be performed. In order to prepare for these advanced mission concepts, new technologies must be developed and demonstrated that enable these tasks to be completed. Nanosatellites are well suited for missions that utilize spacecraft formations. There is always a premium on the mass and cost of an individual satellite, but these metrics are more significant when many satellites are required to perform the mission. There are obvious savings to be obtained by using nanosatellites (<30 kg and 45 cm linear dimensions per satellite) over conventionally larger satellites in these situations. Employing nanosatellite formations requires technologies and capabilities that are in relatively early stages of development. Many of the challenges associated with nanosatellites are related to the miniaturization and integration of suitable sensors and actuators that allow the vehicles to determine and control their position and orientation. Electrical interference and heat transfer are two of the integration challenges that must be addressed. These devices must be individually small and operate within centimeters of other devices. The supply of consumables, such as propellant, is also extremely limited. This requires the development of highly efficient microthrusters capable of delivering high specific impulses to minimize propellant mass. Navigation and control of the formation is also a challenge. Control of a large formation manually by ground operations is cumbersome and expensive. Formations will benefit from the ability to perform autonomous relative navigation via communications crosslinks so that on-orbit control may be performed. While control is performed on-orbit, the formation will also be monitored from the ground. New operations concepts using the internet to control ground station networks in remote locations can simplify formation management. These techniques need to be demonstrated experimentally before they are incorporated into mainstream satellite design. Many of these nanosatellite formation concepts can be demonstrated with a two vehicle nanosatellite mission. The demonstration of these enabling technologies is the goal of the Formation Autonomy Spacecraft with Thrust, Relnav, Attitude, and Crosslink (FASTRAC) mission.

OBJECTIVES

The objective of this proposal is to design, fabricate, and test two flight-ready nanosatellites under the University Nanosat Program Broad Agency Announcement (AFOSR BAA 2003-2). The two satellites will be built within the mass, size, and cost constraints listed in the BAA for a single satellite. That is, each satellite will have mass $<$15 kilograms, and dimension less than 20×40×40 centimeters, so that when stacked on a launch vehicle, they fit within the total mass and volume budget of a single launch opportunity (total mass $<$30 kg and linear dimensions $<$45 cm). The entire project will be accomplished within the period of performance of 2 years and under a budget of less than $50k per year ($100k total cost). The satellites will be built and tested at the University of Texas at Austin's Satellite Design Laboratory (SDL). UT-Austin will receive assistance in satellite and ground systems design from Santa Clara University's Robotic Systems Laboratory (RSL) in the form of a subcontracting arrangement. The technical objectives of the mission are to use the two satellites to demonstrate enabling technologies for nanosatellites and satellite formations. The two satellites will be deployed from a single launch vehicle with an initially small separation. Each satellite will contain a sensor set capable of determining its position and coarse attitude. The sensor set is defined as follows: Global Positioning System (GPS) receiver, magnetometer, and MEMS Inertial Measurement Unit (IMU). Using a radio crosslink, the two satellites will exchange state vector information and perform sub-meter level accuracy relative navigation. The relative navigation solutions will be reported to the ground station for monitoring, but the entire navigation system will reside on each vehicle. Autonomous on-orbit relative navigation will therefore be demonstrated. Each satellite will also contain a Microdischarge Plasma Thruster (MPT) developed at UT-Austin. This innovative device is capable of generating low-thrust, high-efficiency propulsion at low power levels using microdischarge plasmas. The plan is to operate the MPT on one vehicle when the satellite's attitude is favorably aligned to reduce the rate of orbit decay. Using the MPT aboard the second satellite to accelerate decay, it will be possible to demonstrate the use of the MPT to extend the life of the orbit by monitoring the orbit decay rates of the two vehicles. The MEMS IMU will be used as a sensor to detect the acceleration produced by the MPT and determine its on-orbit efficiency. Innovative ground tracking and satellite operations concepts will also be demonstrated. A distributed tracking network with multiple university partners will be utilized to track the low Earth orbit satellites. Amateur radio experimenters, high schools, universities, and other interested parties will be encouraged to record telemetry from the satellites and report their data to a project web site for processing. In this manner, global public participation is possible in the FASTRAC mission. Although the main purpose of the mission is technology demonstration, science goals will also be pursued. These include post-processing sensor measurements to determine satellite drag, as well as Earth atmospheric and magnetospheric studies.

RESEARCH EFFORT

The FASTRAC mission is composed of several key mission elements. The mission elements are independent in the sense that the success or failure of one element is not directly related to the success or failure of the other elements. In this manner, the probability of overall mission success is maximized even if one element does not work as planned.

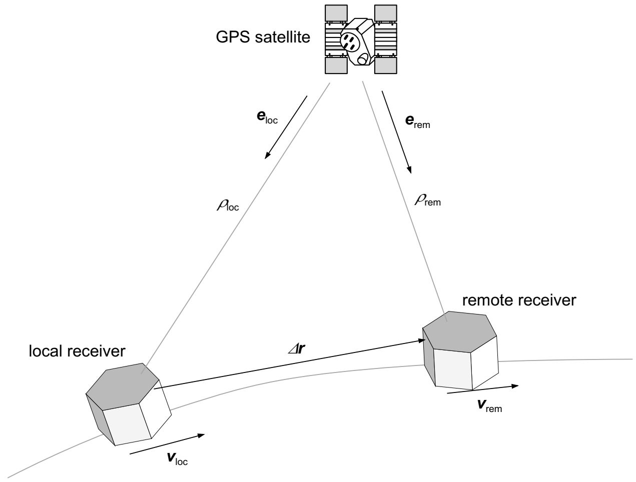
Mission Elements

On-orbit Relative Navigation

In order to determine the relative position and velocity of two or more satellites in space, the state vector information must be collected and exchanged between the vehicles. For Earth orbiting satellites, this information is efficiently obtained using GPS receivers. Although position and velocity may be exchanged directly, it is usually more accurate to transmit raw observables directly (pseudorange, carrier phase, and Doppler shift measurements) and process these measurements collectively on each vehicle.[2]

A proposed relative navigation sensor, shown in Figure 1(a), is based on two 12-channel L1 single frequency GPS receivers. It employs two individual receivers exchanging raw pseudorange, carrier phase, and Doppler measurements via a radio link. Subsequent to computing its own position and velocity, each receiver processes the single-differenced pseudorange and carrier phase after obtaining the partner's data set to obtain kinematic relative navigation solutions. The differential process allows for a high degree of common error cancellation over baselines of less than 10 km, which effectively eliminates the impact of broadcast ephemeris errors, ionospheric delay errors, and GPS satellite clock errors. In addition, a pronounced reduction of the measurement noise level is achieved through carrier smoothing techniques. Over longer baselines, the absolute and relative motion is modeled in a dynamical Kalman filter with a high-dimensional state vector.[3,4] A prototype implementation of this relative navigation system has recently been developed and demonstrated at UT-Austin. The GPS receivers used in this test are the same design that will fly on the FAS-

TRAC mission and they are described separately in the satellite design section of this proposal. Extensive hardware-in-the-loop simulations were conducted to qualify the relative navigation system using a Spirent STR4760 GPS signal simulator capable of simulating L1 signals for 2 vehicles on up to 16 channels each, as shown in Figure 1(b). For the relative navigation application, the auxiliary data port was employed as a dedicated interface for the exchange of raw measurements between a pair of receivers remotely connected via two UHF modems. Hardware-in-the-loop tests conducted with the GPS signal simulator show that overall accuracies of better than 0.5 m and 5 mm/s for the relative position and velocity can be achieved when the separation distances are within 10 km.[5] In the FASTRAC mission, each satellite will carry a GPS receiver and transmit its raw measurements over a wide beamwidth antenna. To keep the satellite design relatively simple, the orientation of each satellite will not be actively controlled, but the wide beamwidth antenna will guarantee that some of the time one satellite will receive the other satellite's measurement information when the satellites are within a range of several hundred kilometers (a detailed link budget has not yet been established). This minimum separation is guaranteed to occur at the beginning of mission life (at satellite deployment) and may reoccur at later times as the satellite positions continue to drift. During these times, relative navigation will be performed on the vehicle using the received measurements and stored for the next telemetry opportunity. Receipt of these relative solutions on the ground will demonstrate autonomous on-orbit relative navigation between the two vehicles. Limited closed loop control will be implemented with the MPT to demonstrate the capability and technologies for formation-keeping control. The raw measurements will also be stored and telemetered to the ground so that relative solutions may be post-processed to determine the on-orbit relative solution accuracy. The GPS receiver solutions will also be used to enhance the return of the other experiments.



a) On-Orbit Relative Navigation

b) Hardware in the Loop Simulation

Fig. 1 FASTRAC GPS Relative Navigation

Microdischarge Plasma Thruster Experiment

In a significant recent development, a number of researchers have demonstrated the ability to generate and sustain a new class of plasmas in micron-sized geometries.[6] These are called microdischarges. Microdischarge plasmas are highly non-equilibrium plasmas that can be generated at reasonably low voltages and are stable in geometric dimensions of ∼10-100 m in length. An important aspect of microdischarge phenomena is the efficient thermal heating of the flowing gas stream to combustion-like temperatures of ∼1000 K. Importantly, the proposers are unaware of any other physical phenomena that can be used to heat a gas stream to combustion-like temperatures in micron length-scale geometries. The resultant thrust force, which is obtained from expansion of an inert gas such as helium or xenon, is in the range of 0.1 10 N. The simplicity of the microdischarge design, the compatibility of the microdischarge operation with that of micron-sized thruster devices (microthrusters), and the ability to batch fabricate these devices in large arrays, leads the proposers to believe that microdischarges are a critical enabling technology for nanosatellite station-keeping propulsion.

Figure 5(a) shows a schematic of a microthruster concept for nanosatellite station-keeping propulsion. The microthruster comprises two relatively distinct sections, one the microdischarge itself which is located ahead of an appropriately designed nozzle. The microdischarge can use the hollow-electrode configuration or the parallel-plate configuration to heat a gas stream to combustion-like temperature of ∼1000 K. The hot gases are then expanded through a De Laval-type converging-diverging nozzle to the high-vacuum conditions of outer space, thereby producing thrust. The gas heating in the discharge is accomplished at an upstream location from the nozzle where the pressure can be regulated to high enough values in order to sustain the microplasma. There is little heat transfer to the chamber as the gases are expanded. The actual microthruster propulsion device might comprise an array of individual microthrusters that are monolithically fabricated on a single substrate/panel. Furthermore, each microthruster could be addressed individually to control the overall propulsive performance of the system.

FASTRAC will fabricate and fly two experimental Argon Microdischarge Plasma Thrusters (MPTs). Each satellite will contain two MPTs, one on each of opposite sides of the vehicle, which will fire when favorably aligned with the spacecraft velocity vector. Having microthrusters on both satellites provides an important mission contingency, since the satellites can switch roles on-orbit if needed. The effectiveness of the MPT will be measured using two different methods. A MEMS IMU will provide a direct measurement of non-gravity vehicle accelerations. When the MPT is off, the IMU will sense the drag acceleration. When the MPT is on, the change in the sensed acceleration will provide a measurement of the MPT performance. The second measure of the MPT's effectiveness will be through observation of the different orbit decay rates of the satellites. Coarse attitude determination will be performed using the GPS receiver. The MPT will be commanded to fire when the vehicle is favorably aligned so as to extend or shorten the life of the vehicle's orbit. Over time, this will cause the forward thrusting satellite's orbit to decay at a slower rate than the backward thrusting satellite's orbit. The observed difference in decay rates, as reported in the GPS position solutions, will provide a measurement of the MPT's effectiveness. This research leverages on-going activity in low pressure plasma research at UT-Austin. The UT-Austin Co-Investigator, Dr. Laxminarayan Raja, has received a National Science Foundation CAREER award for basic research in this subject area. The FASTRAC proposal builds on the current research to incorporate this work into a nanosatellite.

Distributed Communications System

The monitoring and management of a large satellite formation can be a formidable operations challenge. Low Earth Orbiting (LEO) satellites are typically visible over individual ground stations for only a few minutes per pass with perhaps 2 passes per day. In the case of formations, the entire formation will not generally be visible from a single ground station at the same time. In this case, it is advantageous to have multiple stations available for satellite tracking and communications. This will lead to more ground contacts overall and increase the number of satellites that can be tracked simultaneously. Multiple ground stations can lead to high operations cost and complexity, however, if each tracking site has to be locally scheduled and managed. Santa Clara University (SCU) has developed a tool to address these issues, known Remote Accessible Communications Environment (RACE). RACE is a general communications tool that can support operating several tracking stations simultaneously from a single location over an internet interface.[7] The graphical user interface is windows driven and appears as a web site. Data and commands are relayed over the internet to the bi-directional tracking stations and the results are displayed to the user in near real-time (subject to internet latency). Scheduling and mission planning are also possible so that multiple projects can use the same tracking network. Unattended operation of the remote stations is also possible. Application of the RACE system to formation tracking greatly lowers costs and simplifies operations while at the same time providing greater data return. RACE has already been demonstrated using amateur radio satellites on existing tracking stations in Pearl City, Hawaii, and Santa Clara, California.[7] As part of the FASTRAC project, the UT-Austin Satelite Design Lab tracking station will be linked with these stations to provide a University-level tracking network. Other universities may also join the tracking network over time, further increasing the range of the system by the time that FASTRAC flies.

Science

Although the primary mission elements of FASTRAC are focused on technology demonstration, science will also be performed based on the return of data from the satellites. For example, the reported positions of the satellites and the IMU measurements will be used to make studies of the drag forces that are acting on the vehicles. Atmospheric properties can be estimated as a function of altitude by studying the orbital decay rates of the satellites. The satellite crosslink will be used as an instrument to determine the inter-vehicle communication range as a function of altitude. Since the position of each vehicle is known, the Earth's magnetosphere will be measured and mapped. In a public outreach activity, schools and radio hobbyists in other parts of the world will be invited to track the satellites using amateur radio equipment. Any information that is recorded by the public and provided to the project web site will be used to improve the science return of the mission. In this manner, the public may monitor and participate in the FASTRAC mission. Prior to launch of the FASTRAC satellites, at least two American high schools will be specifically recruited and mentored by students at UT-Austin to guarantee a minimum level of public involvement in the project.

Table 1 FASTRAC Mass Budget

Top Satellite			Bottom Satellite	
Subsystem	Mass (kg)		Subsystem	Mass (kg)
GPS/ADCS	1.284		GPS/ADCS	1.284
Communications	0.607		Communications	0.607
C&DH	0.4		C&DH	0.4
Thruster	1.191		Thruster	1.191
Structure	5		Structure	5
Thermal	0.5		Thermal	0.5
Separation	2.88822		Power	3.5937
Power	3.5937			
Top Satellite Total	15.46392		Bottom Satellite Total	12.5757

FASTRAC TOTAL MASS	
28.04 kg	

MARGIN
1.96 kg
6.54%

SATELLITE DESIGN

The two FASTRAC satellites are identically designed for simplicity and redundancy, even though they will perform slightly different roles on-orbit. If needed, the roles of the satellites can be switched on-orbit to account for unplanned events. The major components of the satellite design are described below in more detail.

Mass Budget

The Preliminary Mass Budget is shown in Table 1. This is the fourth draft of the mass budget, and will continue to change as we do further analysis and design. Currently, our budget is above the allowable margin; however, many of the estimates are considered conservative and once closely analyzed will be fitted to the constraint of 14.5 kg per satellite (Which totals 29 kg, leaving 1kg for the UNP-supplied Lightband.)

Sensors

GPS Receiver

The GPS receiver used for FASTRAC has already had its algorithms modified and tested for space use by students at UT-Austin. Ten of these receiver boards were recently fabricated at UT-Austin, and two of them will be used on each FASTRAC satellite. The other boards will be available as spares if replacements are needed prior to integration. The availability of these receivers, their suitability for installation on a nanosatellite, and the fact that their design has been previously modified for space and demonstrated in simulation and on-orbit, is a key advantage to this mission. The GPS receiver board is based on the GPS Orion receiver, which is a reference design of a terrestrial GPS receiver built around the Zarlink (formally Mitel) GP2000 chipset.[8] The original receiver provides C/A code tracking on 12 channels at the L1 frequency. The receiver main board is roughly 5 cm × 10 cm in size and requires a power of 2 W for normal operation. An additional 1 W of power is needed for 2 antennas and preamplifiers. To support user specific software adaptations for the GPS Orion receiver, the GPS Architect Development Kit was made available by Mitel Semiconductor.[9] Numerous software modifications and enhancements have already been made to the original firmware of the Orion receiver and tested on the GSSI STR 4760 simulator at UT-Austin.[10] These modifications substantially improve the on-orbit performance of the receiver and its suitability for use in a relative navigation application.[11] Raw measurement accuracies obtained in signal simulator tests are better than 1 m for C/A code pseudorange, 1 mm for L1 carrier phase, and 10 cm/s for L1 Doppler measurements in the absence of environmental error sources such as multipath.[12] While the GP2000 chipset has not specifically been designed for space applications, Surrey Satellite Technology has demonstrated a sufficient radiation tolerance to allow its use in many low Earth orbit missions.[13] The Orion receiver design itself was successfully flown on the PCsat radio amateur satellite.[14] Two patch hemispherical GPS antennas will be placed on opposite sides of the satellite to allow for reception of GPS signals regardless of vehicle attitude, which will not be controlled. The signals from the two antennas will be cross-strapped so that the receiver may switch to the antenna with the best view of the GPS constellation. Although there is not a requirement for continuous GPS position fixing, it is believed that the receiver will see the minimum 4 GPS satellites necessary to obtain a solution most of the time. The exact antenna design has not yet been chosen, but standard designs (e.g. from Micropulse) should be suitable. These designs have a footprint of about 5 cm × 5 cm on the surface of the vehicle.

Magnetometer

A simple magnetometer provides information as an additional sensor. This will provide a separate directional measurement which may be combined with GPS measurements to coarsely determine the attitude vehicle. The magnetometer will also be used as a science instrument to make magnetic field measurements. The Honeywell HMC2003 will be used in this role aboard FASTRAC. Although desirable as a source of extra measurements, the magnetometer is not required for mission success.

Inertial Measurement Unit

A MEMS IMU demonstration is also planned for FASTRAC. A unit from MicroSatellite Systems is under investigation. This IMU can resolve measurements of linear acceleration as small as +/- 10 g with a low mass suitable for nanosatellite applications . A more substantial market survey, along with solicitation of donated or discounted equipment, will be attempted during the first year of the program. The IMU will be used to provide drag acceleration measurements and to evaluate the performance of the MPT. Since the MPT's effectiveness may also be assessed by observing the change in orbit decay, the IMU is not strictly required for mission success.

Command and Data Handling/Telemetry (C&DH)

Radio Design

The radio design is composed of individual Kantronics and Hamtronics components. This design was chosen over an integrated wireless modem because the individual electrical components are simpler than an integrated modem and the overall design is cheaper. The design includes: a UHF downlink (435-438 MHz), a VHF uplink (144-146 MHz), a VHF APRS Automatic Position Reporting System beacon, and a UHF crosslink for intersatellite communication. The UHF crosslink receiver acts as a secondary uplink. Figure 2 shows the radio system schematic with its associated components. The primary uplink will operate at 1200 baud in order to minimize communication errors, while the telemetry downlink operates at 9600 baud.

Data Budget

Currently, the estimated telemetry sample is 1000 bytes, as shown in Table 2 . The data sample contains processed and raw GPS data, battery/solar panel status, magnetometer measurements, command echoes, check sums, and encryption.

Data Rate and Sampling Modes

Each satellite will be sampling data and storing it in onboard memory. When the satellite is within view of an authorized ground station, it will downlink its stored data upon proper request. It is planned to have two data sampling modes: high and low. The low rate mode of 1 sample per minute is the normal operating mode. During the initial separation of the satellites however, it is preferred to have more frequent data.

Table 2 FASTRAC Data Budget

GPS Measurements	600 bytes
Housekeeping Measurements	100 bytes
Magnetometer Measurements	50 bytes
Battery/Solar Panel Status	50 bytes
Command Echoes/Check Sums	50 bytes
Encryption	50 bytes
Telemetry Re-Sends (10%)	100 bytes
Total	1000 bytes

The high rate mode will sample at 30 samples per minute, and is intended for use over short intervals. Several ground passes may be required to downlink the data sampled at this rate. The low and high rate modes will require 60 and 1800 Kbytes of data storage per hour of sampling. It has been determined that the average ground pass will last only 6 minutes. At the data rate of 9600 bps, this allows access to 72 Kbytes of data per ground pass. For this reason, there will be 15 Mbytes of onboard memory storage to allow for ~10 hours of continuous high rate sampling during the initial separation.

Command and Data Handling

There will be two separate buses used for data and power distribution respectively. The power bus will provide 5 and 12 volts to each subsystem. An I^2C protocol will be used for intersystem communication over a distributed data bus architecture. This will be used to control the operational mode of the satellite (automatically and manually) as well as monitor the temperature and power consumption of each subsystem.

Power

The objective of the power subsystem is to supply sufficient power to subsystems to support successful completion of the mission. The power is supplied to the electrical system, which distributes the power to all other subsystems and provides all switching requirements. The power system must meet average requirements as well as all peak requirements, as well as supply a continuous, regulated power supply regardless of illumination state.

All power production will be from the spacecraft solar panels. A 5V and 12V regulated output will be supplied to the electrical subsystem. In addition, there will be sufficient power storage to enable uninterrupted operation during eclipses. The power subsystem will consist of solar arrays, batteries, voltage regulators, battery chargers, and extra circuitry.

Solar Array

A Power-Available analysis is an important part of solar array selection and design. For FASTRAC, a hexagonal satellite of diameter 46 cm and height 22 cm is assumed. Also, 90% cell coverage is assumed

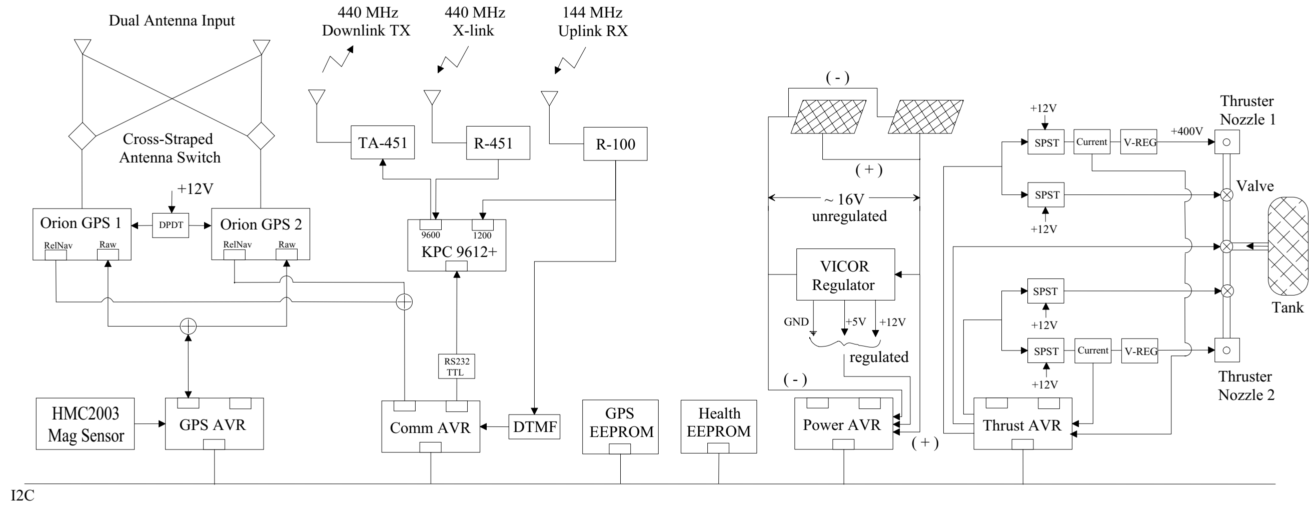
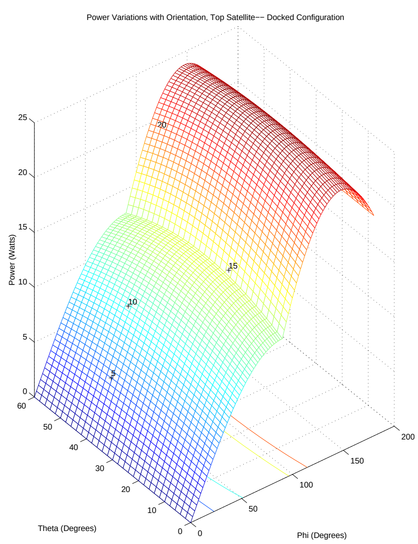
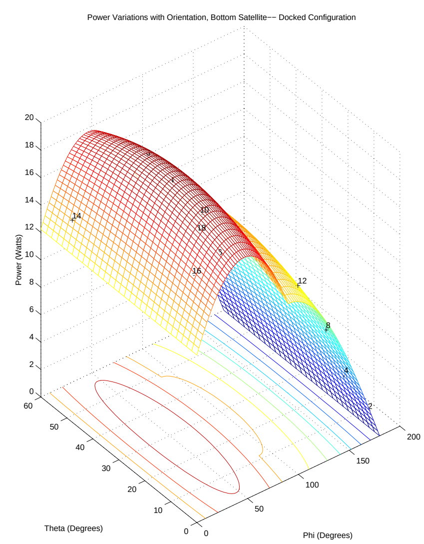


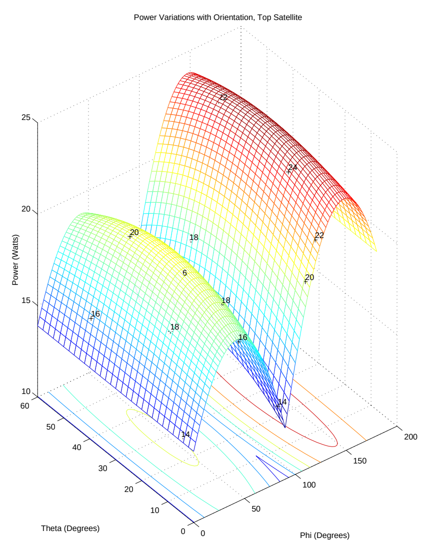
Fig. 2 FASTRAC Communications System



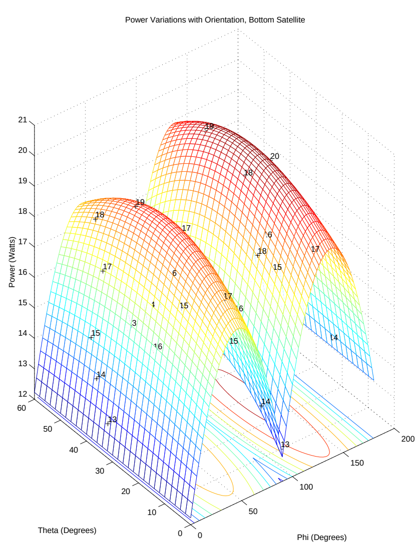
a) Top Satellite- Docked



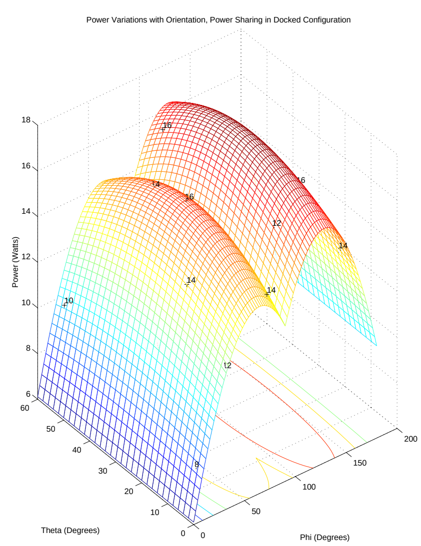
b) Bottom Satellite- Docked



c) Top Satellite- Undocked



d) Bottom Satellite- Undocked



e) Stacked Power Sharing

Fig. 3 Average Orbit Power by Satellite Orientation

Table 3 Average Illuminated Power

		Top Satellite	Bottom Satellite	Average
Undocked	Charge Pwr (W)	11.41	9.01	10.21
	Orbit -DOD%	18.19	14.36	13.28
	Eclipse -DOD%	-12.72	-12.72	-12.72
Docked	Charge Pwr (W)	14.38	11.98	13.18
	Orbit -DOD%	26.96	22.46	24.71
	Eclipse -DOD%	-6.01	-6.01	-6.01

-DOD%: Negative Depth of Discharge (Battery Charging)

on the sides. On the bottom of the satellites, there are Keep-Out areas for the separation system and the NSS. The remaining cell coverage in these areas is 90% and 80%, respectively. Assuming a solar constant of 1353 W/m^2, this gives the Average Illuminated Power levels shown in Figure 3. Obviously, the satellite will not spend its entire time illuminated, but will spend a portion of each orbit eclipsed by the sun. Preliminary analysis of eclipse times based on the FASTRAC orbit shows an Average Eclipse Schedule of 36.2% and Maximum Eclipse Percentage of 40%. Since the satellite spends significant times near maximum eclipse, that value will be used for the normal power budget. Multiplying the illuminated power by the percentage of time illuminated yielded the eclipse results in Table 3. This is the actual power delivered to the satellite's electrical distribution system, accounting for 85% efficiency in the batteries and voltage regulators. It is also important to compare this to the estimated Power Required Budget shown in Table 4. The values show that the satellite can operate normally during a majority of its mission life. It is of interest to know how the power generated varies with orientation of each satellite. The orientation plots are found in Figure 3, and all power values are the orbit average values for each individual orientation. If the satellite had a particular inertial orientation for an entire orbit, this would be the average power. The plot represents this power for all orientations. Phi represents "latitude" with 0 being the "South Pole" and Theta, which is periodic in 60 degrees, represents "longitude." The bottom satellite always generates at least 12W of power when illuminated in any orientation. This worst case orientation occurs when the Nanosat Separation System (NSS) is pointed towards the Sun. In the docked configurations, both satellites have orientations in which they are eclipsed by the other and generate almost no power. Fortunately, the Lightband Separation System has the electrical connections necessary to share power between satellites. The average power produced by both satellites combined can be shared. The power each satellite receives is the average power shown in Table 3. Figure 3 shows the power each satellite will receive as a function of the orientation of the stack. Some power sharing system will be necessary, but even with the power sharing, an orientation exists in which each satellite receives only 6W of power, and this orientation must be avoided.

Table 4 Power Required Budget

	Satellite Downlink	
Subsystem	Current at 5V	Current at 12V
GPS/ADCS	400	20
Comm	0	380
C&DH	250	50
Thruster	0	0
Totals	650	450

	Thruster Operation	
Subsystem	Current at 5V	Current at 12V
GPS/ADCS	400	20
Comm	0	235
C&DH	250	50
Thruster	20	100
Totals	670	405

	Worst Case Mode	
Subsystem	Current at 5V	Current at 12V
GPS/ADCS	800	20
Comm	0	380
C&DH	250	50
Thruster	20	100
Totals	1070	550

All Currents in Milliamps

The FASTRAC satellites will use Single-Junction Ga-As cells from Spectrolab, Inc. These cells are rated at 19% efficiency and will be arranged in strings of 18 cells each providing 15.5 V. This configuration allows for an average 2.4 W per string over an entire orbit. For a voltage regulator requiring a nominal 12V[15] and a battery charger requiring a nominal 14.5 V,[16] a string of 18 cells with diodes on the end provides the needed voltage to the power subsystem.

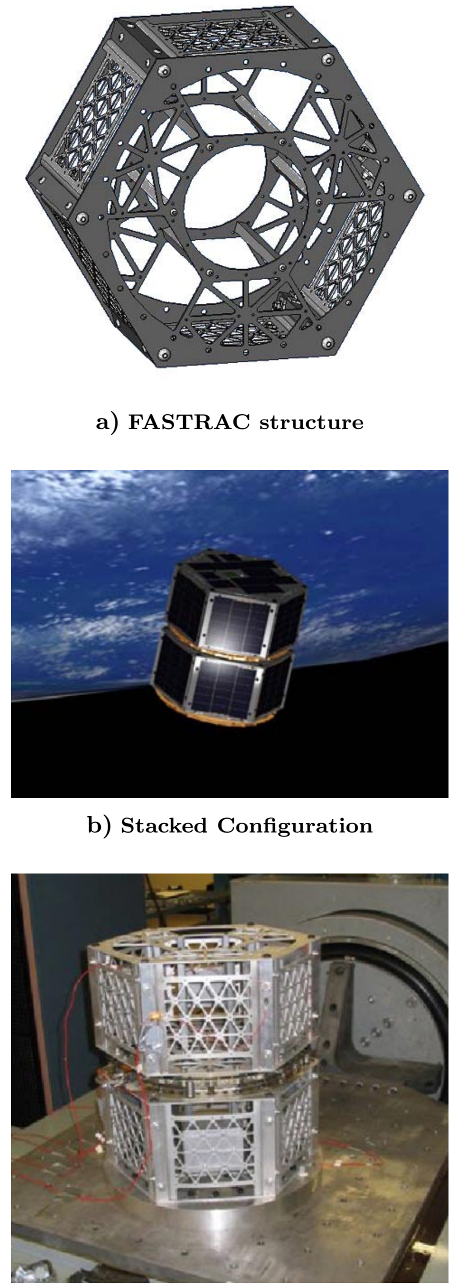
Batteries

The FASTRAC mission will use Nickel-Cadmium (NiCd) batteries for power storage. These are an excellent choice as NiCd batteries meet all the requirements of space operation, have been extensively space-qualified, and meet NASA safety requirements. NiCd batteries also have an extensive database of past performance in space, allowing more accurate estimates for sizing and lifetime. NiCd batteries have an energy density of ∼25Wh/kg. Over six months of operation, the FASTRAC satellites will orbit the Earth almost 3,000 times, and the batteries experience one charge/discharge cycle per orbit. To have a 3,000 cycle lifetime, extensive experience with NiCd batteries in space states that the depth of discharge must be less than 45%.[17] The $<$35% depth of discharge allows a cycle life of almost 10,000 orbits, or about 20 months. This 10% margin is to allow for adjustments to depth of discharge, if the thruster runs extensively during one orbit, using power that would have charged batteries, or excessively drains batteries.

Structure

The structure subsystem houses all the major subsystems. It is designed to withstand the harsh space environment (i.e. temperature fluctuations) and the difficult launch phase (vibration and high gravity loads). Material selection is an important factor that must be considered when designing a structure for a particular satellite. The specific material must provide a stable environment for the structure and the components inside. Material selection was based on the following criterion: density, stiffness, cost, availability, workability, thermal, vacuum, fracture, fatigue, and magnetic properties. For example, temperature fluctuates dramatically in space (-160°C - 180°C). One side of the structure may be hot and the other side may be cold. Cold environment increases the yield strength, tensile strength and Young's Modulus of the material. The material must have low thermal expansion coefficients to avoid scenarios that affect the stability of the structure. Since the use of composite structure is discouraged low expansion coefficiency can still be achieved by selecting the appropriate material. Aluminum Alloys are non-magnetic, easy to work, have high stiffness to density ratio, high corrosion-resistance and high thermal conductivity. Therefore, the FASTRAC satellites utilize Aluminum 6061-T6 for the structure. The structure is a simple hexagonal isogrid with each side having a dimension of 22 $\times$ 23 $\times$ 0.5 cm, as shown in Figure 4. All the panels are attached with NASA approved fasteners and brackets. The internal subsystems attach to the side panels that connect the top and bottom plates of the structure. A thin, segmented aluminum skin provides a substrate for mounting the solar cells. Currently, the mass of the entire structure is about 5 kg.

The structure was modeled using SolidWorks and initial Finite Element Analysis (FEA) was performed using COSMOSWorks. A structural test vehicle was fabricated and subjected to sine-sweep vibration testing with representative component mass loads, as shown in Figure 4. This test shows that the stacked satellites have a better than 75 Hz natural frequency response in all axes of vibration. A complete thermal/vacuum test is anticipated in November 2004.



a) FASTRAC structure

b) Stacked Configuration

c) Structural Vibration Test Setup

Fig. 4 FASTRAC Structure

Thermal Control

The thermal subsystem must help decide the location of components to guarantee that the satellites stay within thermal operational limits. Three stages guide the work in this subsystem. The critical temperatures and component properties have been defined for all satellite components. Concurrently, a model to determine the most efficient locations is under construction in SINDA. Finally, thermal/vacuum testing of the satellite will ensure the temperatures remain inside the critical regions.

There are 4 critical temperatures defined for each component as shown in Table 5. These temperatures along with the thermal properties of the components are being compiled by the other subsystems and will determine the design criterion. The anticipated range inside the satellite is around -10°C-50°C. The thermal properties include the emmisivity of the surfaces of the components and the thermal capacitance. These properties combined with the heat generation and physical geometry will determine the model in SINDA. The

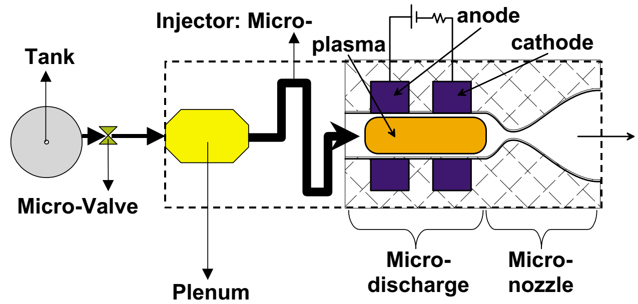
Table 5 Critical Temperature Levels

Critical Temperature	Description
Operation	the temperature range at which the unit will function successfully
Non-Operation	the range which the unit can endure while turned off and when returned to the operation temperature will function successfully
Survival	the temperature(s) at which the unit will suffer permanent damage.
Safety	the temperature(s) at which the unit could cause damage to the orbiter or injure crewmembers

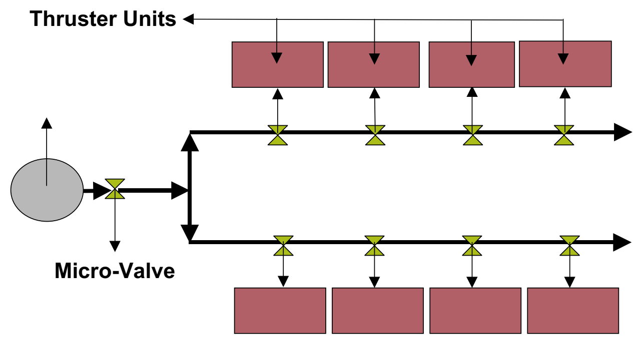
modeling process in SINDA is complex and requires a lot of education for our team. SINDA uses the conductor-capacitor network representation of thermal systems. The procedure is generally as follows: The geometry of the structure is first created in the sub-program SINDA/ATM (Advanced Thermal Modeler). Nodes are added that correspond to the different components and a mesh is made of the structure. Nodes represent either heat flux or thermal capacitance. The model is then passed to the SINDA program where transient and steady state analysis takes place. The SINDA program calls NEVADA to compute the radiation view factors and then performs the analysis needed. Once this model is run, the placement of various devices will be revised to better allow heat exchange out to space. Since the only mode of cooling is radiation to space thermal material will be used to help create channels of expulsion as well as insulation. FASTRAC has no active thermal control and relies exclusively on passive heat transfer. Multi-Layer Insulation (MLI) will be used on the majority of the satellite's interior. Various optimizations will be run in the model to help re-design the locations of the sensitive components. Once a model yields results that satisfy our design criterion the satellite will be tested in a thermal/vacuum. This test will be designed to measure the temperature at critical locations. Other information including thermal stresses will be measured and incorporated into the test. Final design will be determined once the tests are completed.

Propulsion

The propulsion subsystem will employ a Microdischarge Plasma Thruster (MPT). The primary purpose of the MPT will be to provide station keeping propulsion for UT nanosatellites. The thrust produced by this kind of propulsion system is expected to be in the range of 100-200μN. Several individual thruster units could be used in tandem to provide the required thrust for a nanosatellite, although a single unit will be used on FASTRAC. The basic layout of the propulsion system is shown in Figure 5(a) and is comprised of individual thruster unit (enclosed in dashed box) connected to a pressure tank. The unit is comprised of a plenum, an injector, a discharge chamber, and a two-dimensional converging-diverging micro-nozzle. Figure 5(b) shows the configuration of the subsystem using multiple thrusters.



a) Individual Thruster Unit



b) Multiple Thruster Units

Fig. 5 Microdischarge Plasma Thruster

Structure

The estimated weight of the propellant subsystem is 2 kg, mostly due to the propellant tank and electrical components. The size of the individual thruster unit will be about 1 cm^3. The components of the propulsion subsystem will have the following function and approximate specifications. The gas tank will be used for storing the propellant and will be made of space rated aluminum alloy. The pressure inside the tank will be 100 PSI, with slightly lower pressures in the plenum, the injector, and the discharge chamber. The plenum will act as a reservoir for the individual thruster unit. The micro-channel, 1500 μm long, with a rectangular cross-section, 29 x 50 μm, and 90$^{\mathrm{O}}$ bends, will act as an injector that will supply the discharge chamber with propellant regulated for both the pressure and the mass flow rate. The injector will provide the regulated propellant flow to the discharge chamber by decoupling the pressure fluctuations, by preventing the back flow, and by reducing the propellant pressure through viscous losses. The discharge chamber will be 1000 x 200 x 200 μm. Lastly, the two-dimensional converging-diverging nozzle will have a throat area of 9000 μm^2, an exit area of 72000 μm^2, and a length of 500 μm. The nozzle will exhaust in a vacuum at a Mach number of 4.5.

Advantages and Disadvantages

The microdischarge plasma thruster offers many advantages. Once designed, MPT is expected be a simple system with high thrust density and high efficiency. In addition, a variety of propellants can be used. There are, however, some disadvantages. A pressure tank is required and a high voltage impulse of about 200 V is initially required to initiate the microdischarge.

Propellant

Early studies suggest the following properties of the microdischarge plasma were found through tests using Helium gas. The voltage, current and pressure at which a continuous discharge was created were of the order of 200 V, 30 mA, and 0.75 atm, respectively. In order to produce a stable discharge, the electrodes were separated by a distance ranging between 10 and 100 m apart. The propellent gas will be Argon, chosen due to the fact that it is non-hazardous, non-contaminating, offers high thrust density and the possibility of higher specific impulse on the order of 700 s. As a propellant, it offers more mass for a given pressure. The propellant flow rate will be about 15 g/s in order to produce the required thrust of 150 N.

Power Supply

The design of the power supply is a challenge mainly because of the high voltage needed to initiate the discharge. An ultra-miniature DC to High Voltage DC converters is connected to capacitors and controlled by microcontrollers when the nanosatallites are in a favorable attitude. To reduce the risk of satellite damage, provisions are made to isolate the MPT power supply from the rest of the power system. These consist of blocking diodes and shielded cabling.

Separation System

The separation system for the FASTRAC nanosatellites will involve the use of two Planetary Systems Corporation (PSC) Lightband clamp-release separation mechanisms. The first will be used following the complex launch mode necessary for all University nanosatellites. This sequence is described in detail in the proceedings of the University Nanosatellite-3 Program kickoff meeting held on 2 February 2003. Generally, the nanosatellites are launched from the Space Shuttle Canister-for-All-Payload-Ejections (CAPE) while it is contained within the Internal Cargo Unit (ICU). Shortly thereafter, the ICU opens and releases the nanosatellites while they are in their stacked configuration using an AFRL-supplied round 15-inch PSC Lightband release mechanism. Following a two-week checkout period during which the two nanosatellites will remain attached, a second Lightband mechanism will be used to separate the two spacecraft and initiate the primary mission phase. Planetary Systems Corporation has generously committed to providing the FASTRAC team with a Motorized Lightband (MLB) separation mechanism as shown in Figure 6 to separate the two nanosatellites for this phase of the mission. PSC has provided the necessary training in the operation of the system and has certified necessary persons from the FASTRAC team to work on the mechanism.

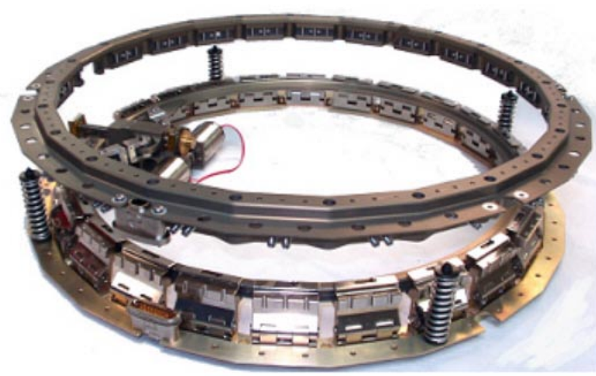


Fig. 6 PSC Motorized Lightband Separation System

PSC Lightband separation mechanisms are non-pyrotechnic and low shock systems that are easily re-settable for testing. They consist of two rings connected by a leaf-groove interface held together by a pre-stressed inner hoop. To initiate separation, a 24V, redundant linear motor relaxes the stress on the inner hoop and allows the springs to detach the upper ring from the leaves. It is important to note that separation will still occur, just slower, if the motor is supplied with a lower voltage. Once the leaf-groove interface disengages the four springs impart the required delta-v to the nanosatellites. Several inhibits are incorporated into the design of the separation system to guarantee that premature separation cannot occur.

An aggressive series of performance tests on the separation sequence were developed by the FASTRAC separation subsystem team and were carried out in the spring of 2004. Many tests were done in the UT Austin Satellite Design Laboratory, however, the separation team was approved in October 2004 by NASA Johnson Space Center to test the Lightband system on the KC-135 Microgravity research aircraft in March 2004. These tests were done to examine the separation velocity and tip-off rates of the nanosatellites in deployment. Understanding of this performance was critical to ensure that the nanosatellites will remain in the required range for crosslink and to provide accurate a priori knowledge for relative navigation.

Software

Operational modes were developed for every possible phase of the mission. These different modes are designed to ensure the safest, fail-proof operation of the satellites. The modes designed for the satellites are the following:

- Ground Diagnostic
- Ground Fueling
- Launch

- Preseparation–charge
- Presep–checkout
- Presep-Baseline GPS
- Presep–Downlink
- Separation
- Downlink APRS
- Ground Init Downlink
- Continuous Downlink
- Single Sat Digipeating
- Crosslink/GPS–Ping
- Relnav–close
- Relnav– far apart
- Safe Mode
- Thruster Operation
- Min Power Mode
- Reset Mode
- Leviathan (Power Drain)

During almost all modes of operation, the communication subsystem will be powered in order to maintain communication with the ground in case of a satellite malfunction. Once the satellites have been attached to the launch vehicle, the satellites will hibernate in Launch Mode. NASA requirements prevent the satellites from using any power during the launch of the satellites. Because of this requirement no subsystems will be powered up until the connection between the lower satellite and the launch vehicle has been severed. After the connection has been severed, the satellites will initiate the Automatic Satellite Self-Verification Mode. The purpose of this mode is for the satellites to verify startup and begin checking each subsystem to verify that no damage was incurred during launch. During this mode, the satellites will initiate communication with the ground and satellite power will be delivered by the solar cells. After the satellites have verified proper startup and experiment initiation from the ground, the Stacked Mode begins. The ADCS will begin attitude determination for both satellites and the relative navigation experiment will begin. After several orbital periods, the satellites will initiate the Separation Mode. The lightband connecting the two satellites will begin to sever causing the two satellites to disconnect and begin tumbling independent of each other. A Thrust Firing Operational Mode will be used to manage the large power consumption required by the propulsion system. All nonessential subsystems will be turned off to conserve power. After separation, the thrusting satellite will alternate between Normal Mode and Thrusting Mode. During the Normal Mode, the relative navigation experiment will be operating along with the ADCS. Data and telemetry will be transmitted to the ground during this mode. Another operational mode that will be employed during the initial phase of the mission is the Variable Power Crosslink Mode. If necessary, all nonessential systems will be shut down except for the relative navigation system. The available power going to the crosslink will be increased or decreased as a function of the distance between the two satellites. This mode is important because the relative amount of time that the two satellites are within range of the crosslink is small compared with the life of the mission. A worst case Safe Mode will be developed in case of a malfunction within the satellites. All nonessential systems will be shut down and the power subsystem will be charging the batteries. A ground station command or an automatic timer will reset and restart the satellite back to Normal operation.

Currently, the flight software is in a moderate stage of development. The main satellite data bus is operational, however. After the individual subsystem programs have been compiled and tested, they are integrated into the data bus. As errors are found and the programs become updated, revision control software is utilized to create a history of the software development.

Attitude Determination

The GPS receiver signal to noise ratio measurements will be used for coarse pointing information. This technique, which has been developed and demonstrated at UT-Austin, can be used to determine the antenna's direction to within approximately 15 degrees.[18] FASTRAC's only on-board attitude determination requirement is to know when the MPT is favorably aligned for thrusting to extend the orbit lifetime. 15 degrees of direction knowledge is considered sufficient for this requirement. In post-processing, the magnetometer and GPS receiver measurements may be combined to determine three-axis attitude to within a few degrees.[19] It is anticipated that this technique will be employed to enhance science data return and improve situational awareness.

MISSION SUPPORT

Orbit Analysis

In order to provide accurate space environment conditions for the FASTRAC design team, satellite orbit analysis, and access visualization, a simulation of the mission was built using Satellite Tool Kit (STK). STK is a commercial, off the shelf, product created by Analytical Graphics. Sample orbit plots are shown in Figure 7.

The FASTRAC orbit was modeled using both a two-body and high precision orbit propagator. An arbitrary circular orbit of 350 km altitude, inclined 51.6, was chosen for the simulation because of it's similarity to a typical Space Shuttle orbit. STK's high precision orbit propagator uses lunar and Earth oblateness effects as well as atmosphere, gravity, and solar flux models to accurately depict orbit decay. The two-body model does not incorporate any drag effects, allowing the satellite to remain in orbit indefinitely. The two-body model was used to observe trends, such as eclipse times, for a given orbit over an arbitrary length of time. The high precision model was used to analyze environmental effects on the spacecraft during the mission life, and even the mission lifetime itself.

The mission lifetime was determined using the high precision model and STK lifetime determination tools. The lifetime was determined to be approximately 100 days; variations depend on the solar flux and atmospheric density conditions. This lifetime value was determined using no thrust contributions from the vehicle. The mission lifetime is projected to increase with the use of the micodischarge plasma thruster. An orbit model that includes the thrust contribution of the vehicle is being finalized. This new model should show the expected benefit of the thruster through improved mission lifetime results.

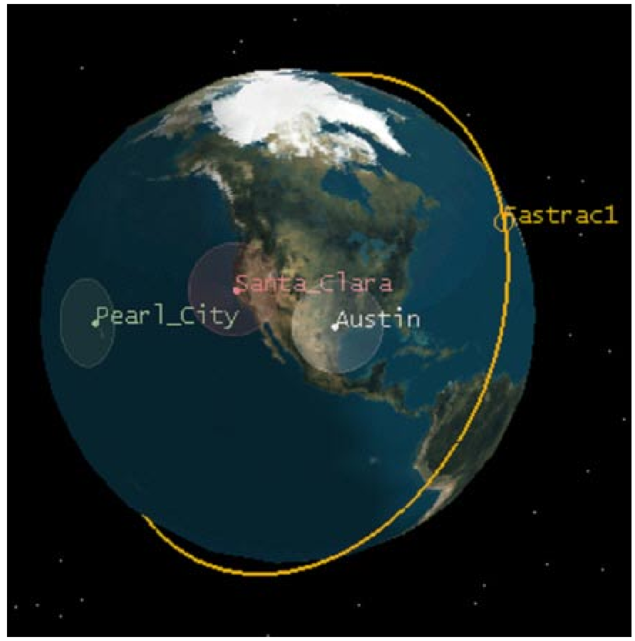
The high precision model was also used in analyzing the drag on the vehicle. This analysis is ongoing, and includes the use of atmospheric and solar pressure drag in determining a total drag value over the lifetime of the orbit. The drag magnitude is used in determining the size of thrust that is needed to produce noticeable improvement in mission lifetime. The drag analysis will be completed using minimum, maximum, and mean solar flux variations, and a Harris-Priester atmosphere model.

Both the high precision and two-body orbit models were used to determine groundstation access opportunities. Access to the satellite was determined for the University of Texas (UT) groundstation, as well as the entire UT-Santa Clara University network. These results will be used to schedule groundstation usage for data retrieval.

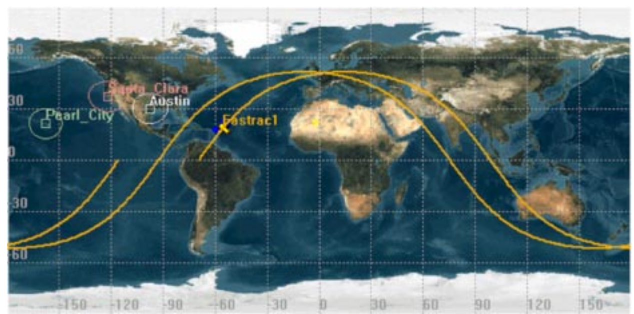
Ground Station

The ground station is being configured to serve both the specific task of supporting the FASTRAC mission and more generally to allow communication with a wide range of amateur radio and research satellites. Design and construction of the ground station is currently under way atop W.R.Woolrich Laboratories located at The University of Texas Austin campus.

The equipment used directly to support the FASTRAC mission includes V-band (144-146 MHz) and U-band (435-438 MHz) transmit and receive hardware for the primary command and data handling functions.



a) FASTRAC 3-Dimensional Orbit Track



b) FASTRAC Groundtrack

Fig. 7 FASTRAC Orbit

Antenna positioning and Doppler correction is accomplished using Yeasu rotors controlled through Nova for Windows.

The V-band equipment consists of a 12.25dB gain, circularly polarized Yagi antenna connected directly to a low noise-figure pre-amp mounted at the antenna. The signal is fed to an Icom IC910H transceiver connected to a Kantronics KPC-9612 packet communicator. Appropriate transmit/receive switches and filters are used to protect the system from damage. The Icom radio will be computer controlled to facilitate Doppler correction. The U-band equipment is similar to the V-band equipment. A 16.8dB circularly polarized Yagi antenna is used in conjunction with the appropriate pre-amp and associated hardware.

Both antennas are mounted on a fiberglass crossboom connected to a Yaesu G-5500 computer controlled antenna positioner. Position track files are generated and sent to the positioner using Nova for Windows software.

Currently it is planned to make the ground station compatible with the Remote Accessible Communica-

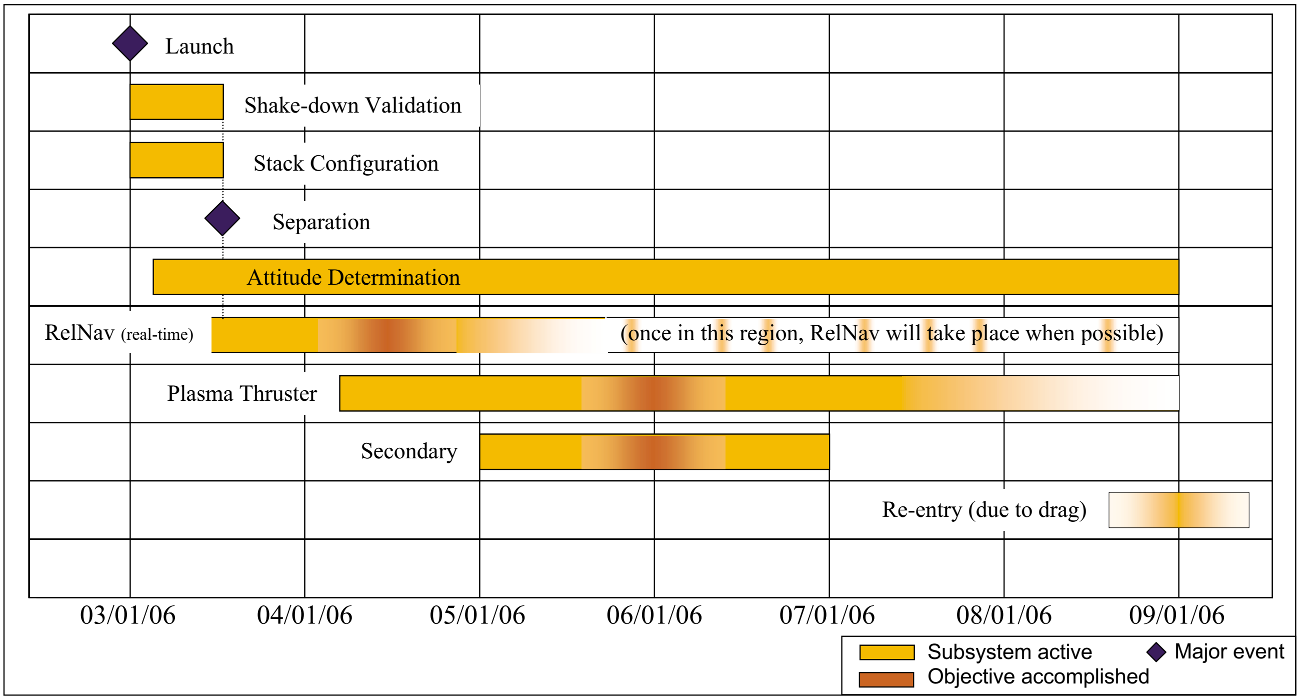


Fig. 8 FASTRAC Mission Timeline

tions Environment (RACE) ground station network pioneered by Santa Clara University. This will allow the ground station to be operated remotely via the Internet. Scheduling and control will be achieved using Labview software and an internet interface . Being a member of the RACE network will permit additional access to the FASTRAC satellites by using the ground stations in Santa Clara, California and in Pearl City, Hawaii. Prior to the launch of FASTRAC the ground station will be thoroughly tested by communicating with a multitude of satellites. Experience will be gained and signal strengths will be analyzed and compared to similar ground stations. This process will be used to bound the station's capabilities allowing for an accurate link budget to be calculated.

Safety

Standard mechanical and electrical safety procedures will be observed when working with satellite hardware. On-orbit, the main safety considerations are the NiCd batteries and the Argon sealed containers. The NiCd batteries being considered have been previously approved for Space Shuttle flights. It is anticipated that the Argon sealed container can be approved with appropriate NASA certifications. The tank volume is small (10 cm^3) and the pressure level is relatively low (<100 psi). The project team will contact safety engineers at NASA to ensure that all proper certifications are obtained.

SCHEDULE AND BUDGET

FASTRAC is a two year (24 month) program to design, fabricate, integrate, and test two flight-ready nanosatellites. The second year is listed as an option, but it is needed to finish the program. The first six months of the first year consisted of a detailed satellite design, review, and preliminary parts selection. UT-Austin employed its consulting arrangement with SCU to receive advice on successful nanosatellite design practices and suggested parts selection. After a design review, the second six months were used to finish parts selection, close action items, and purchase components for the first nanosatellite. The cost for FASTRAC-1 (satellite number 1) was therefore mostly encumbered in the first year. The first six months of year two consisted of integration and testing of FASTRAC-1 and purchasing of components for FASTRAC-2. The costs for FASTRAC-2 are therefore mostly encumbered in the second year. The second six months of year two will be used to integrate and test FASTRAC-2 and resolve any known problems with FASTRAC-1. A flight readiness review will be held at the conclusion of the second year with members of the University Nanosat Program from AFRL and NASA invited to participate. FASTRAC program expenses are broken down by year in the following categories: (1) management oversight and overhead, (2) travel, and (3) fabrication and testing. The majority of expenses occur in the fabrication and testing category by design. In all cases, donated and/or discounted hardware are sought whenever possible. The C&DH subsystem is delivered by SCU as part of their subcontract to UT-Austin, and the GPS subsystem is donated by UT-Austin. These subsystems are not included in the fabrication cost. Costs may be shifted between categories as appropriate. If it was not possible to obtain a suitable sensor with the funds available, it was eliminated from the budget and the funds were reprogrammed into other categories as appropriate. The fabrication costs include testing and incidental expenses. When possible, existing equipment was used rather than purchasing test equipment specifically for this program. The existing labs contain most of the necessary equipment for testing and other equipment can be borrowed if needed.

MISSION TIMELINE

For the FASTRAC Mission, a timeline of the mission is important in visualizing the duration of the mission, and mapping out the lifetime of each subsystem onboard, as well as understanding a reasonable range of time for each of the mission objectives to be accomplished. Attached below is the mission timeline for FASTRAC once the mission has been certified and prepared for launch. The launch date estimated as being March of 2006, and has been chosen on the timeline arbitrarily as March 1, 2006. Our team was advised based on previous Nanosat missions to successfully achieve our mission goals within a time span of three months after launch. After analysis, our team concluded a lifetime of six months based on drag calculations. Therefore, we will accomplish our goals in the three months as recommended, but anticipate additional time afterward to further collect and analyze data. Since one of our mission objectives is to prolong the lifespan of the satellite, an aspect of determining success will be in defying the three month supposed limitation.

As can been seen in the timeline below, the RelNav will be turned on throughout the duration of the mission. However, since the satellites will drift apart relatively early after separation, RelNav will only be applicable when the satellites come back in range (based on Crosslink range of 45 km). In addition, the Microdischarge Plasma Thruster will be fired until no more fuel is available.

FACILITIES

FASTRAC draws upon the resources of a major research university (UT-Austin) and a university with experience in small satellite and mechatronics fabrication (SCU). Each of these organizations contributes state of the art facilities and expertise to the program.

UT-Austin Satellite Design Lab

The design, fabrication, and testing of the FASTRAC satellites will take place in the Satellite Design Lab (SDL) at UT-Austin. The UT SDL was created in 2001 to provide hands-on fabrication and test experience for undergraduates and graduates in aerospace engineering. The lab emphasizes cross-disciplinary projects with a high diversity in subject matter (aero, electrical, mechanical, etc.) and student seniority (graduate, high seniority undergraduate, and low seniority undergraduate). The lab received an industry grant and successfully designed, built, and launched a sounding rocket payload in 2002. The UT SDL contains 2 marble tables for satellite integration and 4 electronics bench areas for component fabrication and testing. In addition, the lab contains a clean-room contamination control area for satellite fabrication. All tables and floor tiles are electrically grounded, and electrostatic discharge (ESD) procedures are followed when working with flight hardware. A satellite tracking station is operational on UHF and VHF bands, and a 3m S-band dish is under installation.

UT-Austin GPS Lab

UT-Austin has a world-class GPS lab for testing spaceborne GPS receivers. The lab contains a GPS Formation Flying Testbed, which allows multiple vehicles to be simulated with real-time GPS hardware-in-the-loop closed-loop formation testing.[3] Additional resources include more than 20 GPS receivers, including 10 recently fabricated flight-ready GPS Orion receiver boards. At least two of these boards will be donated to the FASTRAC project. The availability of the GPS lab will ensure a low-risk delivery of the GPS receiver to the FASTRAC project.

UT-Austin Plasma Research Lab

UT-Austin has a Plasma Research Lab located in the same building as the Satellite Design Lab. The Plasma Research Lab was set up under a recent NSF CAREER award by Dr. L. L. Raja to perform basic research on low pressure plasmas. The lab already contains equipment to test microdischarge plasma propulsion nozzles, including a small vacuum chamber. It is anticipated that the final combustion chamber and nozzle design will be contracted out to a local mechanical fabrication facility and this cost has been incorporated into the MPT budget.

Santa Clara University Robotic Systems Lab

SCU's RSL conducts an aggressive, integrative research and education program in intelligent robotic systems. Initiated in 1998, the centerpiece of this program is a set of yearly undergraduate design projects in which teams of senior students completely design, fabricate, test, operate, and manage high-quality robotic systems for performing a variety of scientific investigations. Past and ongoing projects include spacecraft, underwater vehicles, terrestrial rovers, airships, telescopes, and industrial robots. For FASTRAC, the RSL will be subcontracted to deliver the CPU/C&DH subsystem. FASTRAC benefits from the experience that the RSL has obtained in developing a similar distributed communications system for the Emerald project. The RSL will also provide the resources of the Satellite Tracking Network with ground stations in Hawaii and California as well as Austin, Texas. Additionally, the RSL has agreed to provide valuable experience gained in previous University Nanosat projects to UT-Austin. The RSL will offer consulting advice on design, hardware, parts selection, integration, and testing. This will enable the UT-Austin team to benefit from the lessons learned by the RSL in previous efforts.

PARTICIPATION

Student Participation

The education of new engineers is one of the most important goals of the University Nanosat program. Student participation provides the manpower that enables the FASTRAC mission to be completed under the proposed budget in two years. At UT-Austin, two senior project and hardware design courses were used in 2002 by the Satellite Design Lab to guide a team of 8 undergraduates to successfully design, build, and launch a sounding rocket payload. A similar mechanism will be employed for FASTRAC, with students being asked up front to commit to a two year work plan. Design team members will be solicited based on academic performance, expertise, and seniority diversity, ranging from sophomores to (potentially) graduate students. A selection process will be used where students may apply for FASTRAC by submitting applications with resumes and references. The students will not be paid but will instead receive design course credit for their time. This approach enables the majority of the budget to be used for satellite fabrication and testing costs. Based on the comments of current students, there should be many outstanding students who will volunteer their time for the opportunity to work on a real flight program.

Outreach

FASTRAC provides opportunities to increase public awareness and participation in space flight research, and to encourage individuals to pursue careers in science and engineering. The Texas Space Grant Consortium will be asked to help promote awareness of the FASTRAC program. The FASTRAC satellite signal is designed so that anyone with access to amateur radio equipment will be able to receive the signal and relay the data they record to the project web site. Because of the internet-enabled communications system, a satellite web page will be available for the public to use to display live or the most recent data coming from the satellites. In addition to the general promotion of the FASTRAC program through press releases and a project web site, at least two high schools will be selected to participate in the program. These schools will receive mentoring from university students to assist them in receiving signals from the satellites and to encourage their participation in amateur radio.

Throughout the next two years, the members of the FASTRAC team will be engaging in several forms of outreach activities. The primary avenue of outreach will be through presentations that the team will give to primary, middle, and high school students from the Austin Independent School District. The Aerospace Engineering Department has participated in many successful presentations to various audiences in the past several years including heavy participation in the annual EXPLORE UT event that consistently hosts thousands of visitors from several counties surrounding Austin. Our team has also developed a relationship with the UT Austin College of Engineering Women in Engineering Program (WEP) that organizes outreach programs meant to introduce engineering and the sciences to visiting students from all over Texas. In addition to WEP, FASTRAC will also be organizing several tours and presentations with the Texas Space Grant Consortium that will be focused on middle and high school students. Finally, FASTRAC is also involved with the Student Engineers Educating Kids (SEEK) program in the College of Engineering that organizes tour groups and mentoring between engineering teams and students from local middle schools. This program is very comprehensive and is a wonderful way to educate children in the sciences.

In addition to presentations and tours, the FASTRAC team will be featured in several publications around the University and Austin-area communities. The team will be featured in departmental and college-wide newsletters as well as the University newspaper, the Daily Texan, reaching over fifty thousand students, faculty, and staff. Lastly, the team will maintain an interactive and detailed team website that will track the team's progress, post pictures, and video files, and include data from the spacecraft after launch.

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University of Louisiana at Lafayette Starts a Satellite Program

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Abstract

The Electrical Engineering Department, under the leadership of Dr. Bob Henry, decided in the spring that the engineering school would undertake to build and place a small satellite into orbit. This paper will illustrate the reason why the university should under take this project. It will describe the satellite they will build, discuss the contributions that Dr. Bob Twiggs and Cal Poly made in getting the satellite launched, detail the contributions the AMSAT community has made, and make suggestions how AMSAT could add more value to the education community in the future.

Mission

The mission of the satellite program is to transform students into professional engineers by placing functional hardware into orbit. In accomplishing this mission, the students will master the following skills:

- Managing a large program for 18 months
- Design of mechanical structures
- Design of power supplies in constrained spaces & driven by solar power
- Design of communications systems including:
    - Transceivers suitable for space craft environment
    - Antenna systems
    - Link budgets
    - Transmission protocols
    - Ground stations
- Marketing and money acquisition
- Interface with news media

Satellite

The satellite will be a cubesat with the following characteristics:

- 4 inches by 4 inches by 4 inches cube (see figure 1)
- Weight - Less than 2.1 pounds
- Peak Power - Approximately 2 watts
- Orbit - Sun synchronous with apogee of 800 Km
- Communications - UHF Transceiver approximately 2 watts
- Protocol - 1200 baud AX.25
- Beacon - UHF CW with telemetry
- Solar cell - Dual junction 19% efficiency
- Batteries - Lithium ion
- Attitude control - Passive magnetic

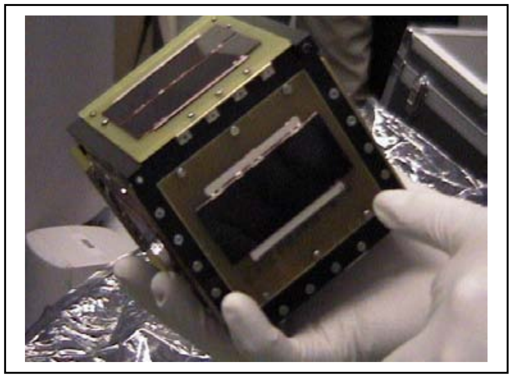

Figure 1

Payload

At this time, the payload is yet to be finalized. However, the students are investigating the possibility of placing small radio transmitters on large sea turtles found in the Gulf of Mexico to track their travels. In addition to sea turtles, they are also investigating the possibility of placing transmitters on other marine life in the waters off Louisiana.

Contributions to Date.

In order for rank novices to "piggyback" hardware into orbit requires huge obstacles to be overcome. Not the least is to convince the launch authority and the primary satellite payload owner that you will not blow up the rocket nor destroy the satellite. These obstacles were, to a large degree, solved by the very innovative ideas of Dr. Bob Twiggs and his colleges at Cal Poly State University. They developed a satellite carrier and launch device call a P-Pod (see figure 2). This device just about guarantees that your device will do no harm to the launcher or the adjacent satellite. Their program makes it easy for a group of universities to come together with a sufficient mass to attract interest from launch authorities. In this case they have contracts with Russian companies to launch our satellite on the DNEPR rocket which in a former life was a Russian SS 18 ICBM. Cal Poly had a successful launch in the Fall of 2003 and scheduled a Fall 2004 launch where 15 satellites will be launched. It is the plan of our university to be manifested for a Fall 2005 launch.

AMSAT, and its successor organizations within the amateur community, has also made huge contributions to the state of the art. They informed the education community how voluntary organizations can build and place a satellite into orbit; especially small satellites. Below is a list of some of AMSAT's contributions.

- AMSAT organizations are the frequency coordinators for the IARU
- Lead the way with the microsats program of the early 90's
- Developed the AX.25 protocol
- Developed the market for Icom, Yaesu and Kenwood radios used in ground stations
- Developed several tracking programs used in ground stationed antenna systems
- Developed low cost terminal note controllers
- Developed low cost modems like the G3RUH and various sound card modems
- Developed the market for low cost antennas, rotators and rotator controllers used in ground stations

AMSAT FUTURE CONTRIBUTIONS

AMSAT has an opportunity to play an ever-increasing role in space. In doing this, they should embrace the education community and serve as mentors, as visionaries, as fund raisers and provide leadership by leveraging our past experiences. AMSAT as a organization is graying. As our members retire, we will have the time to invest in the education community.

The amateur radio community also has an opportunity to help build and man a network of ground stations placed around the globe. These stations could be connected via the Internet and make it easier for universities to retrieve data form the satellites. If we are clever at how we interconnect these stations, it is possible to combine the capture area of several antennas to improve the link margin and save satellite power for payloads. There is some work being done in this area by the students at the University of Toronto. If there is to be a network of ground stations, then there should be a universal protocol for communicating with the satellites. Industry has several protocols for supervisory control and data acquisition and should be web based. There is a need to port error correction algorithms like Phil Karn's that was demonstrated on AO-40. This implementation should be constrained in size and power consumption.

In general AMSAT should help generate ideas concerning what payload could be flown given the size and power constraints. AMSAT should develop detailed descriptions of several payloads they would like to fly. They should also move forward the state of the art of radio projects such as robust error correction algorithms, innovative modulation methods or satellite access schemes. Let's not forget that single side band was largely developed by the amateur community. That was many decades ago. It is time we start leading the technical innovations and not adopting them behind the curve.

PAY OFF

The question is; “why should the amateur community embrace the education community?” The answer is simple. We are mandated by the FCC in exchange for the use of the frequencies. The following is an excerpt directly from the rules part 97.1.

(b) Continuation and extension of the amateur's proven ability to contribute to the advancement of the radio art.
(c) Encouragement and improvement of the amateur service through rules which provide for advancing skills in both the communication and technical phases of the art.
(d) Expansion of the existing reservoir within the amateur radio service of trained operators, technicians, and electronics experts.
(e) Continuation and extension of the amateur's unique ability to enhance international goodwill.

However the most compelling reason is that “as tinkerers”, playing with satellites is fun.

Peter Gülzow, DB2OS, Translated by John J. Bubbers, W1GYD

P3E-Status

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On April 4 another meeting took place in Marburg to clarify the transponder situation and the antennas on P3E. On the previous day there was a meeting of the Board and the Project management to discuss the status of the modules and components of the P3E satellite and to deal with measures to take at the critical points.

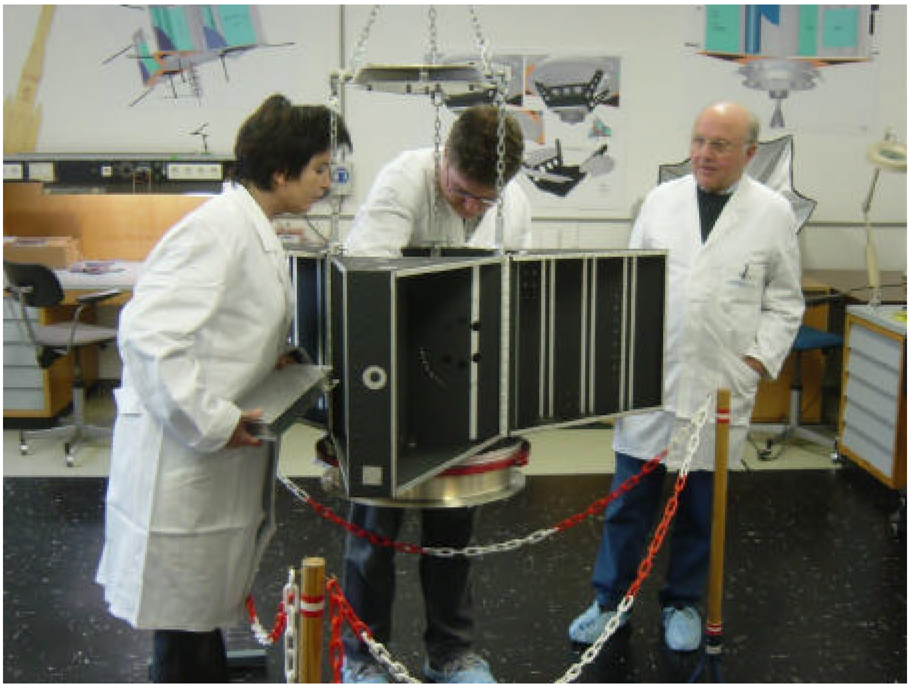

Fig 1: The mechanical integration of P3E makes progress in the integration of P3E in the AMSAT-DL laboratory in Marburg. (l. to r.: Heike Straube, Peter Osswald and Karl Meinzer)

The participants at the transponder meeting on April 4, 2004: Frank Sperber, Heike Straube, Ralph Lampenscherf, Karl Meinzer, Peter Gülzow, Henning Rech, Freddy de Guchteneire, Helmut Neidel, Ulrich Müller

Currently the U/V transponder and the S-band transponder are especially critical, however, a solution was found, to hopefully finish these projects in a timely fashion. Unfortunately, several HF specialists have left amateur radio completely, so we are experiencing these results. At earlier projects the module makers practically over-ran us, it now becomes more difficult to find competent people with suitable motivation. The general shortage of HF engineers as well as the economic conditions of many candidates is also felt here.

To help remedy this, there will be a cooperative work program with the technical college in Coburg. Project assignments for seventh semester students majoring in information and communication technology will be offered under the direction of Jochen Jirmann, DB1NT. A HF transponder that will fly on a satellite is certainly an interesting subject. At the meeting many questions presented by the module builders were clarified, especially in regard to space-qualified hardware requirements.

Battery Problem Solutions

Many members will certainly ask what after-effects followed from the failure of the batteries on AO-40. In the first instance it was planned to use only one main battery for P3E and to forgo a back-up battery based on space and weight considerations. This subject has to be viewed from a different aspect based on

Figure 2: The participants of the transponder meeting on April 4.: From left to right: Frank Sperber, Heike Straube, Peter Gülzow, Freddy de Guchteneire, Henning Rech, Helmut Neidel, Karl Meinzer, not in the picture Ulrich Müller, Ralph Lampescherf

the actual events on AO-40. The basic cause for the failure of the main battery on AO-40 is to be found in a short circuit in one of the three distributed battery banks with great probability, relative to the cabling, as a possible result of the propulsion system damage shortly after the launch. There is an apparent sudden voltage loss with that kind of a short circuit. In a normal 'death' of a battery in which several cells probably short circuit, there would be sufficient time to switch over to the back-up battery and to charge it up. The bi-state (latching) relays on AO-40 are fed from the bus voltage of 24 V, and still operate at 14 Volts according to brief experiments done at the previous P3D integration laboratory in Orlando, Florida, but not if the voltage is lower. The on-board computer receives its own 10 Volts, and obviously still operates, but this is not sufficient to switch over the batteries.

On the Mars rovers, Spirit and Opportunity, the temperature is the determining factor for the life expectancy of the batteries and therefor a switch-over was provided, in which the battery is completely cut off from the supply bus if the battery voltage is too low because of a defect, for example. Only once the energy cells deliver energy again on the Mars day, Mars Rover and the on-board computer wake up. At night all systems are dead, but at least in the daytime experiments can be undertaken.

On our satellite it isn't quite as simple, because the linear transponder needs the battery as a buffer to filter out performance peaks for optimum energy supply from the solar cells. Very limited operation would be possible without the battery. An auxiliary logic system had been provided on AO-40 in which one or both of the batteries was always in operation but operation is never possible without a battery. A electronic switch with power MOSFETs is being developed that will still operate at low voltages after a battery defect, for example, to disconnect the defective battery so that the AO-40 problem is not repeated on P3E or P5A. If the switching needs to operate reliably and actually increase the redundancy, then P3E will also get a supplementary back-up battery. This AUX battery will be smaller, however, so that certain limitations must be made.

France Telecom and AMSAT-DL Sign a License Agreement for the Use of Turbo-Codes

Shortly a license agreement for the use of Turbo-Codes could be signed between the intermediary license holder "France Telecom" and AMSAT-DL. Thereafter the non-commercial use of the so-called Turbo-Codes will be permitted by AMSAT-DL for its missions P3E (earth orbit, launch 2005/2006) and P5A (Mars mission, launch window 2007 or 2009) as well as the AO-40 satellite currently in orbit. The earth segments of satellite users are included as long as the use is limited to the designated space travel missions. Distribution of sub-licenses through AMSAT-DL is therefor not anticipated. AMSAT-DL has sole control for the use in conjunction with Turbo-Codes is special, rearward looking method to make radio signals robust against noise incursions and a very low signal/nose ratio. In comparison to the forward error correcting code (FEC) combined with a convoluted code (Viterbi) the use of the patent protected Turbo-Codes for the Mars mission promise a 3 –4 dB improvement in the signal paths over the on-going methods. The signal paths between earth and the AMSAT-DL Mars probe P5A will either transfer more data in the same length of time or the earth antenna requirements can be reduced by approximately one third, depending on which requirement is in place.

The first prototypes for encoding and decoding using Turbo-Codes signals by the AMSAT-DL team were developed immediately after the signing of the agreement, and have already demonstrated their usefulness for the Mars mission of AMSAT-DL

IHU-3 News

Meanwhile, Lyle Johnson, KK7P, has been able to make some progress in the implementation of the new IHU-3 prototype. Although there is a smaller number of building blocks, the design and implementation are quite complex. Many functions are buried in the FPGA's, the programmable building blocks.

A new IHU was necessary because the complete satellite bus of P3E is controlled through the CAN-bus and new paths are laid out in the communications techniques. The demands of Turbo-Code signals also require additional hardware and increased demands on the performance capabilities of the processor. The new IHU-3 will also be installed on the Mars mission. There will be at least two on P3E, maybe even three new IHU-3 computers that will fly, in which each IHU can be used as primary on-board computer. Compared to previous systems, this first became possible with the introduction of the CAN-bus on the satellite. The third IHU-3 will possibly function as a RUDAK system and transmit pictures from different cameras to ground, for example.

Naturally IPS will be introduced as the operating system again, in which several basic modifications in the structure will become necessary, since the modem is based completely on software and this part must consequently operate from a flash memory. The previous IHU-2 and IHU-3 could be fully reset and loaded with software, while the IHU-3 is dependent on the software in the flash memory. However, a combination of several software and hardware watchdogs and other mechanisms are provided, so that it cannot end up in a catastrophe, so the new IHU-3 offers the at least same reliability as the good, old IHU-1.

Karl Meinzer, DJ4ZC, will concern himself personally mostly with the adaptation of the hardware related parts of the IPS, supported by James Miller, G3RUH, and Stefan Eckart, DL2MDL, who has especially taken on the translation of the Turbo-Codes.

WINNING THE SETI OLYMPIAD: THE ROLE OF THE DEDICATED AMATEUR

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n6tx@setileague.org

ABSTRACT

Since its emergence as a respectable scientific discipline nearly a half century ago, the electromagnetic Search for Extra-Terrestrial Intelligence (SETI) has been dominated by three classes of practitioners: government agencies, academic institutions, and nonprofit organizations surviving on a combination of private contributions and research grants. Recent technological advances have brought a new group of players into the SETI game – dedicated amateurs with a personal passion for achieving interstellar contact. This paper explores the contributions such non-professionals are making to SETI science, in the realms of experimental design, equipment construction, software development, direct observation, sky coverage, signal analysis, and message interpretation. Like the amateur athlete competing in an Olympiad, the amateur SETIzen can expect to struggle for survival, absent commercial or institutional sponsorship. We will show how grass-roots amateur efforts can nevertheless supplement the accomplishments of the professional SETI community, bringing us all closer to the day of contact.

INTRODUCTION

Just fifty years ago, the last true amateur sports hero left his mark on history. Roger Bannister was in has final year at St. Mary's Hospital Medical School. He had finished fourth in the 1500-meter run at the 1952 Olympics in Helsinki. Undaunted, he set his sights on the elusive four-minute mile. Bannister sensed that this was his last chance; once he completed his studies, he knew, his medical career would prevent him from continuing as an amateur athlete. (In fact, he went on to distinguish himself as a prominent neurologist, but it is for his athletic accomplishment that Bannister will always be remembered.)

Working alone, without the benefit of trainer, coach, sponsorship, or steroids (the fight against the latter which he went on to lead in the 1970s), Bannister rode by rail on 6 May 1954 to Iffley Road in Oxford, where he paid his own 3-pence admission. Arriving at the minor amateur track meet after a morning of hospital rounds and a heavy English luncheon with friends, he noticed St. George's flag dipping above a nearby church, realized that the winds were shifting in his favor, and decided the time was right to go for his goal. His success is a tribute to the spirit of amateurism, in sports as well as in science.

THE SETI OLYMPIAD

The challenge of interstellar contact, no less elusive than the four-minute mile, is equally demanding of human skill and perseverance. Unfortunately, success in this particular arena is also a function of one significant factor beyond human control: the very existence, in the proper timeframe, of technologically advanced extraterrestrial beings. Given that no human effort can im-

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pact this particular factor, what can we do to maximize our chances for SETI success?

For a brief time (admittedly a mere eyeblink in human history), the governments of planet Earth threw their prestige and fiscal resources at the SETI problem, sponsoring any number of scientific searches. But it is amateurs who have made, and continue to make, the most significant strides toward contact.

An amateur, as defined by science and the Olympics Committee alike, is one who strives to excel without financial compensation. The motivation of the amateur is revealed by the Latin root of the word: an amateur works for love.

Ask any contemporary SETI scientist or technologist why he or she strives against incredible odds. The answer is always the same. What modest salary he or she may draw is almost incidental. Any skilled SETI-zen could always make more money by diverting the requisite effort in a different direction. It is indeed for the love of the game that the best and the brightest choose to compete in the SETI Olympiad.

THE ATHLETES

Not all SETI pioneers are licensed radio amateurs (though those I will discuss here are, or were). Not all of the work described here was pursued as a strictly amateur endeavor (though some of it was). What these SETI players share is the spirit of amateurism which marks their science as being of truly Olympian stature. These representative examples, by no means inclusive, show how the world's dedicated radio amateurs competed, and continue to compete, for SETI glory.

Grote Reber, W9GFZ

When the Father of the Radio Telescope (SK, 20 December 2002) built in 1937 the world's first modern radio telescope, a ten-meter diameter parabolic reflector in the back yard of his mother's house in Wheaton IL, he was working strictly as an amateur, and under the authority of his ham radio license. Grote produced the first radio map of the Milky Way Galaxy, though it took years for his amateur accomplishments to gain acceptance from the world's astrophysics professionals. His subsequent low-frequency radio astronomy research from Tasmania continued in the amateur tradition of independent research for its own sake. Never one to shy away from controversy, Reber's last published paper was titled "The Big Bang is Bunk!"

Phil Morrison, W8FIS

Undeniably one of the patriarchs of SETI, Prof. Morrison had long since gone inactive on the ham bands when in 1959 he co-authored the first serious scientific SETI paper. His boyhood interest in amateur radio had motivated his interest in exploring the feasibility of microwaves for interstellar communication. During SETI's Golden Age he has inspired a whole generation of engineers and scientists. On a personal note, my own SETI interests were motivated by following in Phil Morrison's footsteps (albeit from a distance of thirty years). As an EE undergraduate at the Carnegie Institute of Technology, I had the privilege of operating W3NKI, the campus ham radio station he founded three decades prior.

John Kraus, W8JK

Arguably the most creative antenna designer of his generation, Kraus (SK, 18 July 2004) is best remembered for the late Big Ear radio telescope which he designed and built at Ohio State University. Big Ear conducted the longest running continuous SETI sky survey in history. John Kraus' grad student Bob Dixon, W8ERD, succeeded him as Director of the OSU Radio Observatory. Dixon is now leading a team of dedicated amateurs in the design of the omni-directional Argus radio telescope.

Paul Horowitz, W1HFA

Still active on the amateur radio bands, a passion he has pursued since childhood, Horowitz heads Harvard University's SETI efforts, and designed the Project META and BETA searches funded in part by the Planetary Society. He is the author of the world's most popular Electronics Engineering undergraduate textbook. Lately he has been turning his interests and expertise toward Optical SETI.

Kent Cullers, WA6TWX

A world-class leader in Digital Signal Processing, Cullers is better known to the public as Kent Clark, the character based upon him in the popular film "Contact." The first (and probably still the only) blind individual to earn a Ph.D. in the highly visual discipline of astronomy, Kent developed the signal detection algorithms for the late NASA SETI program, and later for The SETI Institute's Project Phoenix targeted search. If he has seen farther than other men, it is because Kent Cullers stands on the shoulders of some very clever code.

Seth Shostak, N6UDK

Seth's face is familiar on television, and his voice a fixture on broadcast radio, in his professional role as public programs scientist for the SETI Institute. That voice is less often heard on the ham radio bands, but it is there that Shostak first gained exposure to the technologies he routinely exploits as a senior SETI scientist. He encouraged The SETI League in the construction and testing of its W2ETI Microwave Moonbounce Calibration Beacon, and was the first radio amateur to detect its weak signals reflected off the lunar surface (albeit with the 305 meter diameter Arecibo Radio Telescope).

Richard Factor, WA2IKL

If SETI is truly the science that refuses to die, that is due in large part to this New Jersey industrialist. An active radio ham since boyhood, Factor was dismayed at Congressional cancellation in 1993 of the NASA SETI program. Then, putting his money where his mouth is, he founded the nonprofit SETI League, to involve the world's radio amateurs in privatizing the search. Though not as active as he would like to be in amateur radio astronomy, Factor's greatest contribution has been his leadership role as SETI League president and primary source of financial support. He can claim much of the credit for the 122 amateur radio telescopes which SETI League members operate all over the world.

THE ORGANIZING COMMITTEE

Founded by Richard Factor (see above) in 1994 as a response to the demise of the NASA SETI program, The SETI League, Inc. is a grass-roots amateur radio club of global scope and galactic span. It coordinates the SETI activities of 1400 experimenters in 65 countries on six continents. Its members design hardware and software for a coordinated all-sky survey, publish articles, conduct conferences, construct and operate equipment, and collectively control more SETI radio telescopes than exist in the rest of the world, combined. Funded entirely by membership dues and individual contributions, The SETI League currently has no paid employees, with all its functions being performed by volunteers.

The SETI League's main medium of communications is it extensive Web presence, along with half a dozen specialized email discussion lists, whereby members can pursue a variety of collaborative projects. The organization also publishes Contact In Context, an online peer-reviewed scientific journal, and provides webmaster services for the SETI Permanent Study Group of the International Academy of Astronautics -- all on an operating budget of just a few thousand US Dollars per year. In addition to their scientific and engineering activities, SETI League members are involved in publicizing and popularizing SETI, having conducted hundreds of media interviews, and appeared in dozens of television documentaries.

The backbone of The SETI League is its Field Organization, a cadre of 65 volunteer Regional Coordinators around the world, who offer their expertise and assistance to SETI enthusiasts, whether they themselves are SETI League members or not.

THE EVENTS

SETI amateurs are challenged by and involved in a number of technological pursuits. A brief sampling:

The Discus

The antenna of choice for amateur back-yard radio astronomy is the discarded C-band home satellite TV dish. These three to five-meter diameter parabolic reflectors exhibit in excess of +30 dBi of gain in the Waterhole spectrum between 1.4 and 1.7 GHz, provide modest resolution with their 2 to 4 degree beamwidths, and can generally be had for the asking, in communities where TVRO technology has been replaced digital by Direct Broadcast Satellite television distribution. Several hundred amateur radio telescopes are already online or under construction around the world, using just such antennas as their basis. A suitable L-band feedhorn can be readily fabricated out of hardware store materials and tin snips, by any experimenter reasonably skilled in sheetmetal working techniques.

The 21 cm Closed Circuit

Once those L-band photons falling from the sky have been captured by a suitable antenna, it remains for the dedicated amateur to amplify, filter and process them in a suitable microwave receiver. Amateur radio astronomers have modified military and government surplus equipment, employed commercial receivers produced for the ham radio and telecommunications markets, and, more recently, designed their own dedicated SETI receivers from scratch. Every year at its SETICon Technical Symposium, The SETI League hosts a microwave circuit construction workshop, to train its members in the skills necessary to produce a workable hydrogen line receiver.

The Binathalon

The output of the typical microwave receiver is analog baseband, generally in the audio range. This signal is converted to a string of binary digits for signal analysis, often in a personal computer sound card. More advanced analog to digital conversion at a receivers Intermediate Frequency stages is recently becoming a preferred method of preparing the receiver's analog output for Digital Signal Processing (DSP). Amateur radio astronomers are working on the next generation of DSP hardware, software, and algorithms, to ferret out the hallmarks of artificiality buried in receiver and cosmic noise.

Synchronized Scanning

With over one hundred amateur radio telescopes now engaged in a coordinated all-sky survey, it is necessary to efficiently allocate the search space among participants, in terms of sky coverage, frequency spectrum, and time. A major challenge for The SETI League has been to develop means of ensuring maximum spectral and sky coverage, with minimal overlap, constrained by the equipment capability and location of each individual participating station. Real-time coordination via the Internet turns a hundred individual instruments into a zeroth-order interferometer of impressive capabilities. Still, the challenge remains to automate the coordination process, especially as more stations are added, growing the Project Argus sky survey toward its eventual goal of 5,000 participating amateur radio telescopes and real-time all-sky coverage.

The Broadband Jump

The typical commercial communications receiver has an instantaneous bandwidth on the order of a few kilohertz. Given the enormity of the spectral space across which valid ETI signals are likely to be dispersed, the time factor to analyze a reasonable portion of spectrum is inordinate. New receiver designs are needed, which ca process and digitize hundreds of kilohertz, or preferably many MegaHertz, of bandwidth in real time. SETI League members are recently applying new components designed for the wireless telecommunications industry, to the challenge of seeking out narrowband emissions across broad chunks of the electromagnetic spectrum.

The High-Frequency Hurdles

Although there is a certain romance associated with searching for ETI across the traditional Waterhole frequencies spanning the spectral emission lines of neutral hydrogen and hydroxyl (the disassociation products of water), four decades of SETI in this portion of L-band have thus far failed to produce positive results. The higher frequency reaches of the electromagnetic spectrum are a ripe area for SETI exploration, and a number of amateur radio astronomers are now equipping themselves to monitor across S, C, X, and Ku bands, and in some cases clear into the millimeter waves. It is axiomatic that, whereas there are interesting magic frequencies to be explored, there are no *wrong* frequencies for SETI research. The current push toward ever higher frequency coverage can be expected to continue, with amateur radio astronomers "searching where no man has searched before."

The 500 nm Dash

Optical SETI, though proposed as early as the 1960s, is only now beginning to be regarded as a serious and potentially productive branch of SETI science. Amateurs have pioneered the search for high-energy pulses in the visible and infrared spectra, helping that pursuit to gain legitimacy among SETI professionals. As academic institutions and governments begin to invest resources in Optical SETI, they can turn to the more experienced and numerous amateur optical astronomers for guidance.

The Pole Vault

With hundreds of amateur radio telescopes at work around the world, a commonly available calibration and validation means became a necessity. Three years ago The SETI League constructed its Lunar Reflective Calibration Beacon, a continuously operated transmitter, locked to an atomic frequency standard, and driving antennas which track the moon under computer control. Microwave signals reflected off the Moon can be received by amateur and professional radio telescopes alike, any time the Moon is above the horizon at the transmit and the receive location simultaneously. These weak but stable moonbounce signals, at a frequency adjacent to those for which most amateur radio telescopes normally operate, enable the experimenter to verify the proper operation of his or her equipment. To date the W2ETI beacon (identified by the assigned callsign of The SETI League's amateur radio club station) has been used as a test source by the Arecibo Radio Observatory, at the Bernard Lovel Telescope in Jodrell Bank, UK, and by a handful of Project Argus stations around the world. We hope it will become the calibration standard for all amateur radio astronomers observing in L-band.

The Five Million CPU Relay

The SETI@home project run by the University of California, Berkeley, is undoubtedly the world's most successful distributed computing experiment, though arguably its most dubious SETI experiment. The strength of this well-known project lies in its five million participants, all crunching data from the SERENDIP receiver at Arecibo, the world's most sensitive radio telescope. The weakness is that all five million users are crunching data from the *same* sensitive radio telescope. Where is the weak link in this chain?

Nevertheless, SETI@home has done more to raise public consciousness about SETI than any other project, and SETI League members are eager and active participants. The project has demonstrated how a large-scale task can be broken down into manageable tasks, and parsed out to a cadre of participants. What remains now is to marry the distributed processing aspects of SETI@home to the distributed observing network of The SETI League's Project Argus all-sky survey. The result will be the most powerful SETI project ever, a net stretched wide to capture that elusive fish in the cosmic pond.

The Uneven Parallel Bars

In 2001 the SETI Institute started the design of the One Hectare Telescope (1HT), a dedicated SETI array of unprecedented sensitivity. Later renamed the Allen Telescope Array (ATA) in honor of a major contributor, this instrument is now under construction at the University of California's Hat Creek Observatory facility, at a projected cost in the tens of millions of dollars.

At around the same time, The SETI League Inc. began work on its Very Small Array (VSA), a significantly more modest SETI array of much more limited performance, but budgeted at mere tens of thousands of dollars. The ironic parallel between these two disparate projects is that, at present, each is funded at a level of about a third of its ultimate cost. Thus, the leading professional and the leading amateur SETI organization both find themselves in the position of having to expend a significant fraction of their scarce resources on fundraising, to complete the construction of their respective next-generation SETI instruments.

THE FUTURE OF THE SPORT

As public and private funding for SETI science continue to wane, its greatest untapped resource is the dedicated amateur. Thousands of amateur radio enthusiasts, and millions of personal computer users around the world, promise to the SETI enterprise more observing and analytical power than had ever been imagined in the days of Government-sponsored SETI. The challenge facing us is to focus their energies and coordinate their activities in the most efficient way. This is the charter of The SETI League, Inc., and the direction which other organizations will likely take to ensure the survival of SETI as a respectable science.

CONCLUSIONS

In his biography The First Four Minutes, Sir Roger Bannister writes that, upon completing his famous run, "pain overtook me. I felt like an exploded flashlight with no will to live." One can only speculate as to whether SETI success will be as draining. I expect elation to dominate the mood of those detecting the first valid signal, but only after the weeks or months of follow-up verification activities which responsible science demands. In the athletic Olympiad, success is immediately evident at the finish line. In the scientific arena, definitive results take a little longer.

A mere 46 days after his momentous accomplishment, Bannister's record was beaten by another distinguished amateur, his Australian rival John Landy (later the governor-general of Victoria). Since then, nearly a thousand runners have turned sub-four-minute miles. Similarly, once the first substantiated evidence of ETI is presented, we expect others to strive for still more news of our cosmic companions. Just as aviation activities did not cease once Lindbergh had flown the Atlantic, we expect that first SETI success to be only a beginning. Whether that first detection is made by an amateur or a professional, one can expect numerous amateurs to contribute to the efforts that follow.

On the eve of his famous fiftieth anniversary, Bannister told an interviewer, "the race taught us we could do most things we turned our minds to in later life. And it made us friends."

One can ask no more of SETI success.

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Demonstration and Development of Amateur Radio Applications of Natural Vacuum Electronics

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Natural vacuum electronics is the utilization of the natural vacuum of space for the operation of robust electronic components and circuits. In natural vacuum electronics specially constructed vacuum “tubes”, without the tubular enclosure, are operated to provide the basic services of rectification, oscillation, and amplification using the thermionic emission of electrons from a heated cathode.

At the lunar surface, there is a very high quality vacuum that can be used as the basis for the operation of a natural vacuum multi-grid vacuum valve. Since the valve is an open structure, the internal components of the valve can be modified at will for experimental and operational reasons.

A main goal of the natural vacuum electronics project is starting work using the vacuum of space as a valuable resource for electronic circuits.

Advantages of Natural Vacuum Electronics

Natural vacuum electronics allows the construction of electronic circuits in space that are highly resistant to ambient ionizing radiation and to solar radiation storm events. Natural vacuum electronics has none of the semiconducting materials that are vulnerable to ionizing radiation.

Also, natural vacuum electronics provides an open environment for electronics development where large volumes are available for the flow of electrons and the modification and control of that flow of electrons. This provides a flexible control of streams of electrons that has not been previously available.

Phase 1 – A Natural Vacuum Electronics Beacon Station

The first application of natural vacuum electronics should be an amateur radio beacon station installed in an orbital or lunar location. The beacon signal itself should be generated by natural vacuum electronics consisting of several experimental electron valves open to the natural vacuum of space.

A basic CW beacon can consist of a simple three-stage transmitter with an oscillator stage, buffer stage, and final amplifier stage. Each of these stages is a natural vacuum electron valve providing a similar function to a traditional vacuum tube.

These experimental stages would probably be fairly large electron valves to allow for easier construction and modification as the transmitter is developed and tested. However, it is also possible to consider smaller and lighter electron valves. In theory, highly miniaturized electron valves such as those developed by the Naval Research Laboratory (NRL) could be designed and built. However, larger scale electron valves are preferable in this prototype system where many of the components are being designed and built from scratch.

This beacon station would be delivered to a high Earth orbit or to the lunar surface. It would be powered by a solar cell array. A few Watts of output radio frequency power would be sufficient.

Phase 2 – A Natural Vacuum Electronics Amateur Radio Repeater

The second phase of this project, is an amateur radio repeater station that would be installed on the Earth-facing side of the Moon. The natural vacuum repeater will initially be operated only during the lunar daylight using a solar electric power source and directly solar-heated cathodes (electron emitters). The solar-heated cathodes would reduce the total electric power demand for the repeater station.

The repeater station would relay amateur radio signals that are transmitted from the Earth to the Moon back to the Earth. This repeater would provide experimental international communications as well as a useful capability for emergency situations. Amateur radio stations with a view of the Moon would be able to directly communicate through the repeater. At any one time, about half the World would be able to use this repeater station.

Later versions of the repeater can operate continuously using radioactively heated cathodes and nuclear battery electric power sources.

The success of an amateur radio lunar repeater would probably lead to numerous commercial and governmental radio repeaters on the Moon. These repeaters would serve terrestrial maritime and aeronautical traffic providing new capacity in addition to synchronous orbit satellites. Repeaters installed on the Earth could provide similar over the horizon relay service for different stations and exploration groups on the Moon.

Phase 3 – A Natural Vacuum Ham Radio Station at the Manned Lunar Base

The third stage of this technology development would be a full-scale high-power amateur radio station at the manned lunar base. Operational experience with variable geometry electron valves would be provided. Such valves would change their electrode spacing, resonant cavity structures, and grid mesh sizes as the frequency or power of the station is changed. This will provide an unusual electronics design opportunity on amateur radio VHF, UHF, and microwave allocations.

The amateur radio station would be installed in the ambient lunar vacuum. This station would be operated from within a manned habitat by a remote control interface. Routine controls of frequency, mode, power, and antenna pointing would be supplemented with additional controls to vary the vacuum valve parameters such as grid spacing and mesh sizes used.

Numerous experiments with natural vacuum electron valves would be conducted. This would lead to improved designs for valves that could operate over wide frequency ranges and power levels. Prototypes can be constructed to evaluate the relative advantages and disadvantages of using electric or magnetic fields to control electron flows.

Phase 4 – Large-Volume Natural Vacuum Electron Valves

As this amateur radio project evolves to more sophisticated applications of natural vacuum electronics, it will develop the capability to operate large-volume natural vacuum electron valves. In these circuits very large electron valves will be used including volumes of many cubic meters. These very large valves will be capable of running very high power levels and including numerous valve functions in a single volume.

The first steps at this large scale will be scaled up versions of conventional devices such as travelling wave tubes (TWTs). Then multiple valves will be incorporated in a single large vacuum such as including oscillator and amplifier valves in a continuous vacuum structure. Special attention will be applied to providing a return path (complete circuit) for electron flows.

Very large and robust devices could be potentially operated at power levels of millions of Watts for microwave power broadcasting services. Cooling of very high power components using radiation of heat or active Peltier effect solid-state coolers will be a special challenge. Natural vacuum power transfer devices can be integrated into stages of a lunar magnetic levitation railroad or lunar mass-driver launching systems.

Eventually, this technology can be used for high power interstellar signaling transmitters in an active program of search for extraterrestrial intelligence (SETI). Further in the future, even larger versions of this natural vacuum technology could be used for managing Dyson Sphere clouds of artificial structures in an entire solar system. In the long run, there is no need to be limited to thinking small about natural vacuum systems. Space is large, so we will find that large-scale electronics will often be valuable there. Of course if amateur radio operators are to build such high power devices, the amateur radio regulations will have to be changed to allow higher output powers.

Natural Vacuum Electronics in Low Earth Orbit

Natural vacuum electronics are well suited for the very hard vacuum at the lunar surface. However, natural vacuum electronics can operate in low Earth orbit (LEO). Orbiting a wake shield structure ahead of the natural vacuum equipment would enhance this operation. The wake shield would deflect ambient gas molecules away from the vicinity of the natural vacuum electronics equipment.

This type of natural vacuum electronics can be tested at the International Space Station (ISS) in small-scale applications such as amateur radio beacons and repeaters. In addition, amateur radio natural vacuum circuits can be flown into space in a space craft payload and exposed to space for test operation.

Required Skills for Natural Vacuum Electronics

The development of natural vacuum electronics is a difficult hardware development effort that requires several skills. In this development, radio amateurs will be developing individual components in addition to the circuits using these new components. This is a more demanding development project than the typical hardware development using commercially manufactured components.

The first step in the development of natural vacuum electronics should be bringing vacuum tube design engineers out of retirement. These engineers will have appropriate detailed experience in the development of vacuum state electronic components. Their insights into the analysis of electron flows in vacuum tubes and how that analysis can be applied to natural vacuum electronics should be preserved before their generation passes away.

In addition, physics experimenters who have worked on electron optics and particle accelerators should be brought into the development team. These experimenters have valuable experience in large vacuum systems and the use of electric and magnetic fields to control particle flows in a vacuum. The physics people can also address the interesting concept of using particles other than electrons in natural vacuum circuits.

Metal working technologists with hands-on experience in complex metalworking are needed. Most of the natural vacuum electronic components will be metal structures that provide and support electric and magnetic fields. The team needs people who are very comfortable with the engineering and the actual hands on construction of complex metal objects.

The insulators used in natural vacuum electronics will often be ceramic components. People capable of making these components are needed for the team.

Electronic engineers open-minded enough to deal with the natural vacuum electronics concept are needed. These engineers will design the interfaces between natural vacuum electronics systems and more conventional solid-state electronics systems.

All of the staff members on this project team will have to be especially patient and open minded. There will be some frustrating failures and set backs in the development process.

Costs of Natural Vacuum Electronics Development

If natural vacuum electronics were developed on a commercial basis, the development costs would be very high. This high cost is because you are inventing new components from scratch and incorporating them into new circuits. All of this diverse development has to be included in prototypes that actually work in a vacuum test environment.

A team of several highly skilled and diverse developers will have to work for several years to produce working natural vacuum electronics prototypes. Additional work will be required to make these prototypes space worthy.

This development is not appealing commercially because it does not offer the prospect of quick profits. However, it could be quite appealing in a university environment where innovative and interdisciplinary thinking is valued. In addition, a large university or set of universities could include this project in their educational program allowing the high staff costs to be covered.

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PROPOSAL FOR AN AMSAT SATELLITE WITH A ROBOT FOR REPAIR OF THE SATELLITE

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I have a deep interest in all things technological and I would like to participate with AMSAT with its future projects, in whatever way that I can.

Let me share an idea, and let me introduce the idea with a few comments.

Amateur radio has always been in the forefront of technology. Notable advances include short wave radio, single sideband, and of course AMSAT. But what have we done lately that has been a quantum leap past current technology?

Before I propose an answer to that question, let me remind everyone regarding last year's shuttle tragedy and the problems that arose in the aftermath. For example, needed maintenance to the Hubble telescope will be forgone. Less devastating but affecting amateurs are the AO-40 problems.

Therefore, let me propose this: that a future AMSAT (Phase 3-E?) will include its own little robot, intended to do repairs. The robot would be remotely controlled from the ground by AMSAT personnel, and alternatively, by any ham on Earth. This initial version would be a demonstration of concept. Can a robot be included on a satellite? Would it make sense to do so? What types of repairs can be done by a robot in space?

This robot would be included on the satellite. It would enable any ham to "take control" and perform "repairs" in space.

This simple concept would be a quantum leap in space faring technology. A successful mission could be viewed as a model for similar missions. A robot could be sent up to the Hubble to do the needed maintenance, replacing a whole shuttle flight. (How much does a shuttle flight cost, a half billion, not to mention the risk? How much is the Hubble worth?)

And, considering the problems with the current AO-40 AMSAT satellite - imagine if we had a combination of a camera, probe measuring ohms, volts and waveform, and arm to connect and disconnect units on the AO-40. And the package would be independent from the satellite. So when the satellite was inoperable, the robot package would be there to take a look, and make repairs.

I have word that this concept is being discussed at NASA, also. Perhaps there could be collaboration. The difference between the NASA effort and my idea, is that the NASA effort is intended to launch a robot from Earth, and have the robot rendezvous with the Hubble to repair Hubble. My idea is to construct and launch a working satellite that includes its own repair robot. No costly launch and rendezvous would be required for the robot to operate.

The truth is, that this robot repair satellite idea is not such a stretch as you might think. But I like the idea for a couple of reasons. It is something that has never been done before, by hams or pros. Sure, you've seen remote controlled robots, you even have seen autonomous robots on the surface of Mars. But you have never seen a robot repair a satellite. And, I say, why can't this be done? And, of course, it would be so much fun.

A successful project has a definite goal. The goal must be stated in definite and certain terms. Let me propose a goal, and if the group accepts it, then this is it. Let's not change the goal once it has been decided.

Goal: design, develop, build, test and launch a robot satellite that will be a "proof of concept" of the ability for robots to repair orbiting satellites. The robot will be remotely controlled from the ground. The robot will have "vision", in order for the ground controller to see the work done. The robot will have manipulators or hands, in order to open compartments and change components in the works of another satellite. The robot will have probes on moveable arms to measure voltage, current, resistance, and waveform. --- end of goal statement ---

These would be the objectives of this project.

One possible objective that I would reject, would be a capability to move in space away from the repeater satellite, and come back to the repeater satellite, and such. That would be a "blue sky" project that really may be beyond amateurs. Instead, I think that the "robot" and the target satellite would be joined on one craft, as a single piece. That one decision should make the project much easier. Sometimes a project depends on what is decided not to do, as much as what is to be done. If new features are constantly added, then the project is in jeopardy due to "scope creep".

The design of the target satellite and the robot should be done together. The target satellite should be designed so that it would be easy for the robot to open, manipulate, and test.

Systems to be designed:

1. Repeater
2. video downlink
3. video position control uplink
4. robot hand
5. probe
6. hand control uplink
7. probe control uplink
8. telemetry downlink
9. power supply
10. satellite communications repeater
11. “spare parts” to include on craft

Satellite Communications Repeater

The satellite repeater part of this project is something that the group has experience with. Other AMSAT satellite projects have become increasingly more complex; each project is more complex that the previous. But for this project, I would recommend that the repeater part of the project not to be so complex that it overwhelms the effort. I think that most of the effort should be invested in the robot. Therefore the actual working part of the satellite, the repeater, should be of simple nature. It should be only one uplink band and one downlink band, just to keep that part of the project relatively simple. The "wow" of this project is the robot.

Video Downlink

The purpose of the video camera is two fold. First, it provides feedback on the positioning of the probe and the robot arm. Second, the video camera may be positioned to other objects, such as the Earth, Moon and so on.
The video downlink need not be 30 fps full frame video, but should be faster than sstv. Something in-between. One extra attraction would be to make the video speed switchable, and make the camera pointable away from the satellite to, say, the Earth or Moon.

Video Position Control uplink
There is no reason that the video camera should be fixed, other than for the sake of simplicity of the effort. The camera may be panned and tilted using the same type of controllers that are used for the robot arm and the probe.

Robot Hand

I won't speculate on the hands, just to say that the components on the satellite and the hands on the robot need work together. For example, a couple of bolts that hold the compartment door close could be the type that remain on attached to the door when the bolts are loosened. That way, the bolts don't get lost in space.

Hand Control Uplink
Probe Control Uplink

The hand control uplink and the probe control uplink could be the same signal, with different commands for the hand and probe. An encryption scheme possibly would be introduced, depending on the command. For simple movements that do not touch the important electronics, perhaps no encryption would be necessary. This would allow any ham who could make contact with the satellite to control arm movements, and watch the arms move via the video downlink. A possibility would be for voice control.

Probe

The probe would be the positive end of a volt-ohm meter. The other end would be grounded. Probe pads would be designed into the repeater electronics, so an easy point of contact would exist for each probe measuring point.

Telemetry

Besides the normal telemetry readings from the repeater portion of the satellite, the probe would provide important telemetry information on the status of each point of the satellite repeater. Each function of the probe would be selectable from Earth. Possible functions would be volts (ac and dc), ohms, and waveform.

Telemetry Downlink

The telemetry information from the probe should be transmitted separately from the repeater signal. Perhaps the telemetry information could be duplexed on the video signal.

Power Supply
Power to the robot side of the spacecraft, that is the arm, probe, video, and radio control, should be separate from the power supply to the repeater side of the spacecraft. However, since robot equipment would not need to run continuously, it would have a lower power requirement. A separate battery for the robot could be charged slower than the battery for the repeater. For instance, the robot may be turned on for only an hour per day, while the repeater would be on continuously. An interesting situation would occur when both the repeater battery and the robot's battery would tend to fail at the same time in orbit. A technique may be used to disconnect the repeater battery from the repeater, connect it to the robot, disconnect the robot's battery, replace the robot's battery, and then reconnect the repeater's battery.

“Spare Parts” included on spacecraft

Some spare parts may be included with the spacecraft. For example, spare batteries. These parts could be installed by the robot arm after launch, in orbit. This is the “proof of concept” of the project. Any and all components of the working parts of the satellite may be included as spare parts. The design of the components and the satellite should provide for the robot arm to have the capability to install and remove different components.

Encryption and Control Commands

A decision would need to be made on if and how to encrypt commands to the robot, and how to format the commands. Possibilities include voice recognition on board the robot, to allow hams to perform some limited commands by voice. Other commands, especially commands that could cause the robot to change the configuration of the repeater or otherwise affect the repeater, would be limited to encrypted data transmission.

Outreach to Non-Hams

In keeping with this year's emphasis of AMSAT for educational outreach activities, I would make the control of the robot enabled over the web or directly by radio, and have this presented to schools, universities and even the ISS. College students would be interested in probing the satellite for voltage and waveforms. It would be an historic first if the ISS crew would take a control turn at the robot! For that matter, it would be an historic first for anyone to control from the ground, a satellite repair robot in orbit.

Et Cetera

I have a name for the robot in mind, but more on that later. I am thinking as a public relations stunt to name the robot after a well known and loved performer. Someone who's music I love and that I wish to honor. The name would raise interest by itself. It would be a fine outreach tool, especially as an outreach to minorities. Who would name a robot satellite "Ray Charles"? Not even Ray Bradbury would think of that.

A few considerations:

Energy budget - solar panels charging a battery. A big requirement is that the robot be absolutely separate mechanically and electronically from the target satellite. All systems should be separate - power, control, communications, because we want the robot to continue to operate even if the satellite fails. So, with this understanding, we decide for a small panel of solar cells charging a battery. If that means that the robot's battery would need to charge for 12 or 24 hours to operate for one hour, so be it. The robot need not be available 24/7, only on command or in case of emergency.

The Robot could be designed to rendezvous and dock with satellite. But I envisioned a one piece affair; robot and satellite connected together. I would hate it if, when launched and in orbit, we could not get the two docked. I am assuming that any docking maneuvers would be difficult. I am asking myself (and everyone) why make this first robot project harder than it needs to be? As one piece, connected physically, the project is simplified greatly. I go with "simple".

Solar panel accidents – or other accidents involving the robot and movement of the robot arm. One solution would be to make the reach of the robot arms inaccessible to the solar panels. However, that would limit the usefulness of the robot. Perhaps we could make the robot arms accessible to the panels, but limit the range of the arms in software. And provide a special override in software for the arm to reach a panel. Imagine that a panel refused to deploy - the robot arm could deploy it. Or - new idea - rely on the arm to deploy the panels.

(Here is a Science Fiction thought – we could build and launch a robot, with a communication satellite parts, and have the whole satellite constructed in space. Has anyone ever soldered in space? How does space vacuum affect soldering? On another mind-expanding note: has anyone ever considered vacuum tubes without the tube envelope? It could be done in space. What would be the advantages in relation to plate power dissipation?)

I am excited already. Aren't you?

As to the question about "who" would be available to perform the tasks involved in this project, I want to be central to this and do a lot of work on it. Of course, I can not do it all myself, and I look at this project as a definite team effort, no heroes or champions, but a team. I definitely hope that my idea can inspire the group to this. Everyone is welcome and invited to participate.

I am able to participate in at least one way; I have training and experience in project management. I could put some of that to use. I envision this to be a group project, and any project that has more than one person working on it needs management.

That said, one more thing to remember is that every project as a definite beginning and definite end, and a definite goal. This project begins now, and ends with the launch of the satellite/robot. Once the craft is space borne, it becomes a support effort, not a project. That is my view, and this is the view of the industry that I am in (software engineer).

There are many sources and manufacturers for equipment that would be suitable for the purposes of the robot. Let me offer some suggestions. This list is of course not exhaustive. But a review of the list may give one a better image of the concept that I have in mind.

Why Is Space Flight So Difficult?
A Look at Kinetic Energy Requirements for Orbital Flight

Daniel Schultz N8FGV

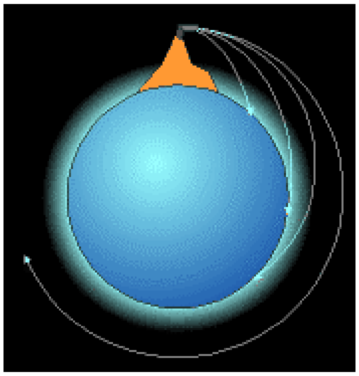
Thirty years after the Wright Brothers made their first airplane flight, reasonably well off persons could buy a ticket for a commercial airplane flight. It is now forty years after Yuri Gagarin made the first orbital flight but human space travel is still the exclusive province of government employees and a very small number of multimillionaires.

In 1961, a small group of radio amateurs were able to launch OSCAR 1 as a secondary payload on a US government satellite mission. The primary mission was cloaked in secrecy at the time but is now known to have been a Corona photographic imaging reconnaissance satellite. In the 1960’s amateurs were able to utilize, at no cost, the small nooks and crannies that were available inside the launch vehicle shrouds of larger satellites because the prevailing wisdom among space professionals was that small satellites were of no value in a serious space program. In the same way that our grandfathers were able to show that radio wavelengths shorter than 200 meters were not as useless as the professional experts had thought, the first generation of ham satellites proved that small satellites could perform a useful and valuable mission in spite of their low cost and diminutive size.

Amsat still manages to place small satellites into orbit at bargain-basement prices as piggyback payloads on multimillion dollar launch vehicles through the goodwill of several different launch agencies. If we had to pay the market price to launch our satellites we could not afford to do so. As it is, even the steeply discounted launch price is a heavy burden for an organization funded almost entirely from member’s out-of-pocket contributions. The competition from a small-satellite industry that hams helped to create is now driving up the cost of the piggy-back launches that we once got for free. Given the costs of putting our small satellites into orbit, it is natural for Amsat members to wonder if there is another way to place our satellites into orbit.

By the time you read this in October 2004, it is possible that some group will have claimed the X-Prize, a ten million dollar award for the first privately funded vehicle to reach 100 kilometers altitude with a pilot and the equivalent payload mass of two passengers. To satisfy the reusability requirement this spacecraft will be required to repeat the flight with the same vehicle within two weeks of the first flight. The news media has hailed the first flight of Spaceship-1 as the next generation of space vehicle and a possible replacement for NASA’s troubled Space Shuttle. Many otherwise well educated individuals do not seem to grasp the huge difference that exists between the suborbital space mission of the X-prize contestants and the much more difficult mission of placing a human crew in low Earth orbit. Even *The Washington Post* mistakenly reported that Spaceship-1 was to perform the first privately financed orbital manned space mission.

Given the frequent comparisons that space advocates make between commercial airline travel and the seemingly similar problem of launching the similar-sized Space Shuttle, and to understand why an orbital space mission is such a huge leap above a suborbital space mission, it is useful to examine the basic principles of orbital space flight.



Sir Isaac Newton explained how to place things in orbit in his book *Principia Mathematica*, published in 1687. Newton suggested finding a very high mountain and using a very powerful cannon. As you fire the cannon with more and more gunpowder, the projectile achieves higher velocity and greater range. Eventually the range exceeds the curvature of the Earth and the projectile never hits the ground. Newton also provided the mathematical basis to calculate the orbital velocity that such a projectile would have upon reaching its state of perpetual free fall.

$$V_{circ} = \sqrt{\frac{GM_e}{r}}$$

For an object in circular low Earth orbit, skimming just above the top of the atmosphere, the orbital velocity works out to about 18,000 miles per hour. Any satellite traveling more slowly than this will quickly fall back into the Earth's atmosphere. We can see that achieving a high altitude is a necessary but not by itself sufficient condition to put your satellite into orbit.

Since there are in fact no mountains taller than the Earth's atmosphere, we need to find another way to achieve the required altitude. The most common solution over the past 47 years has been the use of a rocket. We can sum up the requirements for launching an orbital space mission in two simple laws:

1. Get above the atmosphere as quickly as possible. (Climbing slowly in a rocket wastes energy.)

2. Once you are safely outside of the atmosphere, make a 90 degree turn and start accelerating until you acquire the magic velocity to stay in orbit.

In a real life space launch, these two actions are combined. At liftoff the vehicle travels straight up for a short time until it is above much of the Earth's atmosphere, then gradually starts to arch over and travel toward the east to build up velocity. In the first seconds of the flight the first law is the primary concern, then as the vehicle gains altitude the primary focus gradually shifts to satisfying the second law, acceleration to orbital velocity. Calculating the optimum fuel efficient trajectory is an interesting calculus problem.

As the vehicle climbs its velocity increases at the same time that the air density decreases. At liftoff the velocity is low and air density is high, in orbit the velocity is high but air density is extremely low. At some point during the climb to orbit, the product of velocity times air density reaches a maximum value. "MAX-Q" is the rocketman's term for the point of maximum aerodynamic pressure on the launch vehicle. The Space Shuttle is designed to throttle down its engines during the passage through MAX-Q to reduce structural loads on the shuttle stack. The "GO AT THROTTLE UP" call signals that MAX-Q has been passed and the engines can resume full thrust for maximum acceleration. As the shuttle burns off its fuel load its mass decreases dramatically and acceleration increases in such a manner that the shuttle acquires most of its orbital velocity in the final minutes of powered flight.

The Kinetic Energy of a moving body is $\frac{1}{2} M V^2$. If we calculate the kinetic energy of a 200 pound human engaged in various activities we can see some interesting numbers:

For a 200 pound person:

Riding in a car at 60 miles per hour: KE = 32,600 Joules

Flying on a commercial jet airplane, Mach 0.8 or 600 miles per hour:
KE = 3,260,00 Joules (factor of 100 increase over riding in a car)

Flying in suborbital X-prize entry, Mach 3 or 2150 miles per hour at engine cutoff:
KE = 41,859,300 Joules (factor of 13 increase over commercial jet aircraft)

Flying in low Earth orbit, Mach 25 or 18,000 miles per hour:
KE = 2,937,000,000 Joules (factor of 70 increase over X-prize Spaceship)
(factor of 900 increase over passenger jet)

Thus an astronaut flying in low Earth orbit possesses <u>900</u> times as much energy as he would have riding on a commercial passenger jet. We can also appreciate that energetically the suborbital X-prize spacecraft is much closer to a common passenger jet than it is to an orbital spacecraft. With present day rocket technology, the huge amount of kinetic energy required to place an object into orbit must be obtained by burning a large amount of chemical propellant at the start of the mission, and this energy must be dissipated by atmospheric friction at the end of the mission. Any vehicle capable of propelling itself into orbit is inherently dangerous no matter how well it is designed.

Several of the X-prize competitors have expressed a goal of offering passenger rides to 100 kilometers altitude for $40,000 per seat, or about $200 per pound to accelerate a person to Mach 3. If cost scales linearly with kinetic energy then an orbital flight requiring 70 times as much energy would cost $14,000 per pound. At that price a 40,000 pound Space Shuttle payload would cost $560 million, which is remarkably close to the current estimate of what it costs NASA to launch a Space Shuttle mission.

There are of course other ways that we might launch payloads into orbit. A commercial jet airplane is flying rather slowly but it is flying above most of the Earth's atmosphere. The Orbital Science's Pegasus rocket takes advantage of this to gain a head start over launching the same rocket from the ground. There have also been many designs for air breathing space planes that would obtain their combustion oxygen from the Earth's atmosphere instead of carrying it up from the ground in a tank, unfortunately such vehicles violate our first law by trying to achieve a high velocity while still inside the Earth's atmosphere. Atmospheric drag thus removes energy at the same time that the vehicle's engines are trying to add energy. Nevertheless, with continuing research the space plane may one day be a practical way to launch satellites and people into Earth orbit.

The most intriguing new possibility was just wild science fiction a few years ago. A Space Elevator could be built by dropping a 23,000 mile long cable from a geosynchronous satellite to the surface of the Earth on the equator. This concept is credited to Konstantin Tsiolkovsky and was the subject of a science fiction novel by Arthur C. Clarke. To launch a payload onto geosynchronous orbit one would simply carry it up the cable on some kind of elevator car for the cost of the electricity, a few dollars per pound. The only trouble with this idea so far is that no known material is strong enough to support its own weight for a 23,000 mile cable span. Recent work with carbon nanotubes suggests that this new material is in fact capable of supporting its own weight in such an application. If it should be possible in the next few years to turn this laboratory curiosity into a practical industrial level production process then it might be possible to contemplate the construction of a Space Elevator in a few decades. A recent conference was held in Washington DC to explore the concept in greater detail. A Space Elevator would open a highway between Earth's surface and geosynchronous orbit and would change the Earth's economy in ways we cannot imagine today.

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