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AMSAT
RADIO AMATEUR SATELLITE
CORPORATION

PROCEEDINGS OF THE AMSAT-NA

16th Space Symposium,
and **AMSAT-NA** Annual Meeting

October 16-18
1998
Vicksburg,
Mississippi

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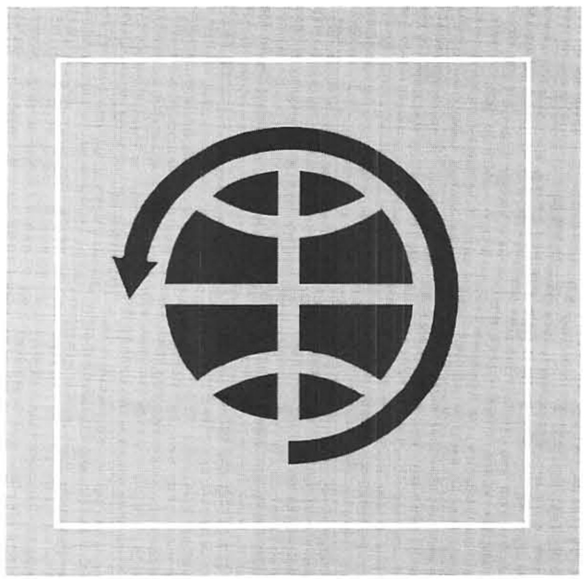

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STATE OF MISSISSIPPI
OFFICE OF THE GOVERNOR

KIRK FORDICE
GOVERNOR

August 19, 1998

Greetings:

As Governor of the State of Mississippi, I am honored to welcome the Board of Directors and members of AMSAT-North American to Vicksburg. The First Lady and I commend your achievements and 25 years of commitment to the future of Amateur Radio. We wish for you a successful Annual Meeting and 16th Space Symposium.

While in Vicksburg, we hope you will take advantage of the many tourist attractions, historical sites, and opportunities the "Red Carpet City" has to offer. You will find the citizens of Mississippi to be among the most hospitable folks in the world.

The word of our probusiness, anti-crime, and *Positive Mississippi* climate has spread, and the State of Mississippi can compete with any state in the nation in recruiting new business and industry. More than $14.9 billion in investments by business and industry in Mississippi since 1992 and a net gain of more than 167,000 new jobs provide ample evidence that the *Mississippi Miracle* proceeds vigorously.

Undoubtedly, your work will continue to have far-reaching, positive effects on the future of Amateur Radio, as well as other governmental, scientific and commercial activities. We hope yours will be an enjoyable stay and that you will choose to visit again. Best wishes for a successful and memorable event. May God bless you, the State of Mississippi and the United States of America.

Sincerely,

KIRK FORDICE
Governor

KF:tc

POST OFFICE BOX 139 • JACKSON, MISSISSIPPI 39205 • TEL: (601) 359-3150 • FAX: (601) 359-3741

The City of Vicksburg

"one city...one vision...one destiny"

Office of The Mayor
Robert Major Walker, Mayor
Phone: 601-631-3719
Fax: 601-631-3764

July 29, 1998

Dear Friends,

It is with great pleasure, that I welcome the Board of Directors and members of AMSAT-North America to Vicksburg. I trust that your Annual Meeting and 16th Space Symposium will be a success not only of terms of the presentation of technical papers and conducting the business of your organization, but in experiencing the history and hospitality of Vicksburg.

In addition to our industrial and tourist based economy, you will find that Vicksburg is at the fore front of technical innovation and development. Because of the significant presence of the U.S. Army Corps of Engineers, major research and development initiatives are continually underway at the Waterways Experiment Station in the areas of coastal and inland hydraulic and hydrologic processes as well as structural, geomechanical. and environmental studies. Also, the Mississippi Valley Division and Vicksburg District of the Corps manage the day-to-day traffic, planning, engineering, and maintenance operations on "Ole Man River," himself.

Although I am aware of your intense amateur radio satellite interests, please don't get so caught up in the technical aspects of your visit here in Vicksburg that you don't miss the opportunity to visit the Vicksburg Battlefield and fine museums in the area. You might also want to try your luck at one of our "high tech" games of chance, or just get to know some good people.

If there is anything I or the staff of the City of Vicksburg can do to make your stay more enjoyable, please don't hesitate to ask.

With Best Regards,

ROBERT MAJOR WALKER
Mayor

City Hall • 1401 Walnut Street • Room 300 • P.O. Box 150 • Vicksburg, Mississippi 39181-0150

Welcome

I am glad that so many amateur satellite enthusiasts are able to attend the 1998 AMSAT-NA Annual Meeting and Space Symposium. Since the early 80s, we have been holding our meetings in various parts of the U.S. in order to permit as many people as possible to attend at least one meeting every few years. We have held these meetings in Vail, Colorado, Los Angles, the Dallas area, Orlando, back in Washington, Tucson and last year in Toronto. This year, I am especially pleased to bring our gathering to the Deep South, an especially historic part of it, Vicksburg, Mississippi.

Other than the fine location and excellent program the Vicksburg folks have come up with, this year's AMSAT General Meeting and Space Symposium is not a particularly happy occasion. All of us had hoped that Phase 3D would be in orbit by this time, and we would enjoy its outstanding performance. Unfortunately, as you all know, this was not to be. Events beyond the control of any of us have conspired to prevent the new bird from riding into space aboard the Ariane 503 test flight. We are actively seeking an alternate launch, either on another Ariane, or on some other launcher. But, unfortunately, I cannot claim that anything is certain as of the time that this is being written.

Nevertheless, the Phase 3D spacecraft has been completed. That is a notable accomplishment in itself. It has represented over six years of intense work on the part of many dedicated individuals and groups, both in this country, Europe, Japan, as well as several other locations around the world. The completion of Phase 3D could not have happened without the dedication of all of those who have worked on hardware, software and the many who contributed money so generously. AMSAT-NA members alone have come up with nearly One Million Dollars, and the ARRL, and its members, have put in another approximately $530,000. Our European compatriots, with inputs from the Germans and the British, have come up with a amount similar to that raised by AMSAT-NA and ARRL combined. Our friends from JAMSAT, the Japanese AMSAT organization, in addition to providing the scope camera, have contributed Fifty Thousand Dollars in hard cash to help fund the completion of the spacecraft. Of course, expenditures have also been significant. To date over One and a Half Million Dollars have had to be expended by AMSAT-NA alone. The structural modifications, needed to meet the significantly increased launch environments specified early last year by ESA, have caused a significant increase in our total outlay.

Although Phase 3D's completion is an important event, it also means that AMSAT must finally face up to what it should so next. One obvious project, one which is already underway, is participating with a number of international partners in providing equipment to put Amateur Radio on the International Space Station. In addition, we have concluded an agreement with the University of Toronto to provide help on the MOST project. This is a very exciting opportunity to assist in putting a small telescope in orbit to measure variations in the intensity of certain stars. It may be possible to include an amateur package on board the MOST spacecraft as well, but that is not certain as of this time. In any case, our participation will enable us to share our expertise with young eager college students, as well as derive some much needed revenue with which to do future purely amateur projects.

We have also been working with John Hopkins University in connection with a proposal for the Triana project. This is the spacecraft that Vice President Gore has proposed to be placed at the L1 point about a million miles from Earth in the direction of the Sun. It is too early to know what our exact role in this project might be if, indeed, we will have any role. But we are exploring the questions of how Amateur Radio might participate in, and the benefit from, being included in a spacecraft in this unique type of orbit.

There are a number of other university-based projects in which we are rendering varying amounts of assistance. One of these is the ASUSAT project at Arizona State University. Another is the Citizen Explorer at the University of Colorado. Still another is PHOTON at the University of Central Florida. SEDSAT, from the Huntsville campus of the University of Alabama, in which AMSAT played a small role, is scheduled for launch about the time of this meeting.

In addition to the projects on which we have been assisting directly, several others have produced new Amateur Radio presence in space, with still more to come. Naturally, we applaud and congratulate these efforts and pledge to provide whatever support we can. In particular, we will be publishing orbits and schedules for these amateur spacecraft via our various electronic and print media.

So, there's lot's going on while we wait, not so patiently, for Phase 3D to go into space.

I hope you enjoy the 1998 AMSAT-NA Annual Meeting and Space Symposium, as I will; and that your attendance will prove to be productive to you, and to the amateur space community. I also hope that you will enjoy the various attractions that Vicksburg has to offer, but please don't loose too much in the casinos. If you're lucky and win, remember AMSAT can always use additional contributions.

This will be the final AMSAT Annual Meeting at which I will be presiding as President. After serving seven years in that office, I have decided that it's time to step aside. I won't be leaving active participation AMSAT affairs altogether. My term on the Board has another year to run. In any case, for the foreseeable future, I will continue my interest in AMSAT and its various projects.

The matter of my successor is up to the Board to decide. As one member, I will participate in that decision, but I cannot make it unilaterally, even if I wanted to.

It has been an interesting and challenging seven years, and I want to take this opportunity to thank all of those who have been of so much assistance to me and have contributed so much time, effort, and money to our various activities.

73 and thanks for coming to Vicksburg.

Bill Tynan, W3XO

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October 16, 1998

Dear Symposium Participants:

Welcome to Vicksburg! The Vicksburg Amateur Radio Club is honored to host the 16th AMSAT Annual Meeting and Space Symposium. We hope that you enjoy the genuine Southern hospitality and beautiful autumn weather that Vicksburg has to offer.

Lots of planning and hard work has gone into your symposium. Throughout the year leading up to the symposium, many persons have volunteered their time, efforts, and ideas to put on a good symposium. While hams, most of these volunteers were never associated with AMSAT prior to Vicksburg being selected as the symposium site. However like most hams, curiosity got the best of them and they eagerly volunteered for the many tasks necessary to put on the conference. During all of this, they learned a lot about AMSAT, its growing accomplishments, and diverse members; they also even had a lot fun doing their job! Certainly the following persons echo some of the true qualities and spirit of Amateur Radio - volunteerism and investigation:

Jerry Brown, KC5DNY – Tiger Team Support
Ron Brown, AB5WF - Jackson Amateur Radio Club Support
Lloyd Causey, K5IMT – Talk-in and Airport Communications
John Davis, N5ZJV – Jackson International Airport Welcome Table
Bill Ford, WB5SXK – Worldwide Web Page
Phillip Fortenberry, N5PF – Logistics
Sandra Fortenberry, KC5DNX – Logistics
Malcolm Keown, W5XX – Technical Sessions and Proceedings
Melinda Lamb, N5EZX - Registration
Ed Magruder, N5QDE – Special Events Station
Bill McLarty, KM5GE – Jackson Amateur Radio Club Support
Eddie Pettis, N5JGK - Marketing
Ed Schilling, KJ5XQ – Airport Shuttle Coordination

A special word of thanks is also in order for the Jackson Amateur Radio Club as their willingness to help out wherever needed was certainly welcomed and appreciated. Many thanks to last year's Symposium Chair Robin Haighton, VE3FRH for his encouragement and support. Also thanks to Martha Saragovitz, AMSAT Corporate Secretary for her constantly good (and free) sage advice.

73, enjoy the Symposium and Vicksburg,

RUSS TILLMAN, K5NRK
Symposium Chair

Working From Over 100 Grid Squares

By Chuck Duey, KI0AG
ki0ag@amsat.org

Abstract:
Working Satellites from over 100 Grid Squares.

In working from over 100 Maidenhead grid squares a great amount of knowledge about mobile and portable operations is amassed. AO-27 is the most popular among the grid square hoppers due to its ease of use. The RS birds can also be easily worked while in a number of locations with minimal equipment. The Fuji Oscar birds can also be worked, but require more equipment, time and practice. It does take care and planning to work a good grid square hopping dx-piditon. Even some quick hops across the border of your local square can be fun and get some rare squares.

Introduction:

The Maidenhead Grid Square Locator is a system used by amateur radio operators to indicate their location anywhere on Earth. A grid square is 2 degrees East to West and 1 degree North to South. That equates to about 67 miles North to South and 110 miles East to West at mid-latitudes. The Grid Square locator is given as 2 alpha and 2 numeric characters, with an optional 2 alpha sub-square designator. The first 2 alpha characters give the location in 20 by 10 degrees. The numeric characters give the 2 by 1 degree location within the 20 by 10 given in the first field. Denver, Colorado is located in Grid Square DM79. It takes 32,400 squares to cover the whole Earth.

Working only 100 squares out of the 32,400 does not seem like much, but at 67 miles by 110 miles it covers a large area in North America. In working from a variety of locations, experience in what works well and what does not is amassed. Knowing the right techniques on AO-27 can make the difference between 1 or 2 contacts from a rare grid to an average of 10 contacts per pass. The right equipment and antennas can make any vehicle a mobile satellite station. Knowing your system's limitations can make the difference between choosing a good pass or getting an ear full of static.

AO-27 is the most popular satellite to work from unique grid squares in North America. All it takes is a dual band radio, a good antenna and a set of headphones. The Russian Sputnik series of satellites can be worked out on the road with just a couple of mobile whips. The Fuji Oscar birds take a bit more radio and antenna, but can be worked just as well out in the middle of nowhere. The remaining high flying Amateur satellite, AO-10, can be worked away from the home station, but requires a bit more equipment and planning.

AO-27

AO-27 is a FM satellite, just perfect for HT use. There are two difficulties in working this satellite, hearing it and getting in. Hearing AO-27 is VERY important. A good set up should be able to work the pass from horizon to horizon, and hear every word. Some rare locations go by very quickly during the pass. Hearing the satellite as it rises can get some very nice locations like Inivik in the Northwest Territories or Barrow, Alaska. From Colorado, Hawaii can be worked on those waning moments of a low westerly pass. To get all of these locations, a 5 element or better Yagi is needed on the 70 cm side. To get a word in edge wise on AO-27 can be difficult. With a rubber duck, it is easy to work when there are no other signals. As the passes head South, there are some sources of interference on the up link. With 3 to 5 watts on 2 meters, it is difficult to get over these with just a rubber duck. This is where the added gain of 3 elements on 2 meters helps a HT have the effective power of a mobile station at 25 to 50 watts. This entire set up can be assembled and a highly mobile AO-27 station can be made.

The mobility of the AO-27 equipment is key to working unique locations. Adding 3 extra pounds on a backpack is well worth a few contacts from a mountain top. In the past working from over 14,000 feet required either a road up the mountain, an airplane, or a person who can pack a lot of equipment. The AO-27 HT station has enabled any one who can walk there to work from that location. This lets people who live close to the border on grid squares to hop across the border and work a few stations. Among the HT users it is very popular for people to roam across border at the spur of the moment. Also many have been known to pack an antenna and HT with them in the overhead bin of an airplane on business trips and vacations.

RS Satellites:

RS-12 is currently the best satellite left in the Russian Sputnik series which can be used reliably for SSB contacts from remote locations. RS-15 is still operational, but is not as strong or reliable when using a couple of mobile whips. Many contacts can be made on RS-12 just using a 2 meter whip and 25 to 100 watts for an up link. The down link can easily be heard on a 10 meter whip mounted on a car. With just a couple of basic 2 meter and 10 meter SSB rigs, a rental car can be come the roving ham station. The strong down link makes this very easy to do when outside of the big city noise.

RS-12 is not as popular as AO-27 for grid square chasers, but there are plenty of good stations on. Having a mobile station on this satellite gives a whole new crowd a crack at the rare grid squares. Some stations have been known to work from rare locations when AO-27 is not available or the weather is too bad to get out of the car. RS-15 has a much bigger foot print than RS-12, so it can provide better coverage, but this comes with a less down link signal. Most stations on RS-15 are fixed, but some contacts have been made from mobile stations.

FO-20 and FO-29

These two satellites are identical with respect to SSB or CW operations. FO-20 is a bit older and has a slight 3 KHz shift on frequency with respect to its younger sister. Both of these satellites can be worked with a few eggbeater antennas and a good radio. The setup that has been quite successful in operations from remote squares uses 3 M-Squared Eggbeaters. One 2 meter eggbeater antenna is used for the up link. The down link has a tendency to shift from Right Hand Circular to Left Hand Circular polarity during the pass. To compensate for the change, one standard RHP eggbeater is used and another is modified for LHP. With 50 to 100 watts and a good receiver like the FT-847, FO-20 and FO-29 can be worked from anywhere there is good open sky.

FO-20 and FO-29 do provide some excellent DX even from remote locations like Alaska. Most mobile stations operate from some vehicle and rarely set up out in the open. The requirement of more equipment and more complex antenna leads to fewer stations operating away from fixed stations. Field Day is the exception where there are many stations in the field.

AO-10:

AO-10 is a high flying bird that provides excellent DX almost half way around the world. The problem is the equipment needed for this bird is a little more than most can handle on the road. Perigee passes can be worked with smaller antennas, but limits the contacts. The fixed stations across the globe provide ample rare grids, but on occasion there are special stations on the air. AO-10 makes an excellent satellite to test the Field Day equipment and see just how far out it can be worked with those antennas that just fit in the car. Probably the one thing that makes AO-10 nice to work is how slow it moves. Setting up an Az-El rotor system in the field is tough, but computer control adds more things to go wrong . Just a simple laptop and pointing the long antennas that direction works well for many minutes.

Traveling Around:

The AO-27 equipment is by far the easiest to pack up in a nice fly rod case and hop onto an airplane. The elements for the antenna, the radio and the headphones do not add a lot of bulk or weight to even an over night trip. The one thing it does add is the extra time explaining what it is. On any given trip at least one airport x-ray operator or baggage clerk will ask about what is in the case. There is no problem with bringing the equipment, they are usually quite relieved to hear it is just some radio gear. The other explanations come when operating or carrying the equipment. It is always fun explaining that this is radio gear for talking on amateur radio satellites, and yes hams built the satellites!

The equipment for RS-12 can fit in a bit longer tube and a bit of space in the suitcase. The 48" fly rod tube fits all the whips you could ever want with very little rattling around in transit. The smaller mobile SSB rigs can usually be packed in with some soft items and survive very well even in the worst airports for baggage. The radios also need to have either cigarette outlet plugs or jumper clips for batteries. This equipment takes a small amount of room, but can provide some very nice contacts from remote locations.

The equipment for the Fuji Oscar satellites is a bit more bulky. Eggbeaters take time to assemble and disassemble. It is best to keep the antennas together in the back of a vehicle or trailer. Other antennas pointed by hand can be used, but will probably require more than one operator to point the antenna, tune the radio, talk, and write down call signs.

Radios that are smaller like the Icom IC-821 or Yeasu FT-847 are ideal for the semi-serious DX-pedetion. The size makes it ideal to put in a case or in suitcase. The flexibility of the FT-847 to work all the current SSB birds makes it very nice to pack along. The smaller the radio the better, but watch out for the performance of scanners. Many scanners have very wide front ends, and pick up all sorts of signals that cause problems. By the time the filters and preamps are added it is a mass of wires and connectors that is not so easy to pack or put together again. On any of the smaller radios, test it out close to home in a parking lot some where. It is always a good idea to find those little "gotchas" before getting out on the road.

The one item to pack along with the radio gear is the GPS receiver. The GPS receiver can tell when the border has been crossed into the next square. This can save many minutes of traveling just a bit further to ensure the line has been crossed. The GPS system, also provides an accurate clock. The clock can be used to set your laptop before the satellites start coming up. The other indispensable service the GPS provides is a time and location stamp in the form of a marker. When going back through the logs it is always reassuring to know which square you were in and when.

The GPS can also make the travel safer and quicker. Most GPS receivers have a 'track' or a memory trail of where it has been. Up in the mountain hiking, or just jaunting down a country road, it is very helpful to have that trail to get back. Fog can move in seconds in the mountains, having that trail can prevent going down the wrong draw and having to climb back up again. The GPS systems with a map can make things very quick getting through those unknown cities. Just knowing where the Interstate is in relation can save time wandering.

Chasing Squares on the Road:

You don't have to have a GPS to chase grid squares, although it helps. Using a map with coordinates can at least help point out where various cities are located. Add the Grid locator map, and it is quite easy to tell which grid square most cities are in. When it comes to the borders, it sometimes takes a better map to locate the coordinates. Some mapping programs like Delorme's Street Atlas will tell coordinates, and this can be fed into a converter program. The one thing that should be known on the road is which square you are in.

Planning square hopping can be great fun. Looking at certain maps, it is easy to look and see some rare grids with few roads, or lots of water, or easy to get to. Since the squares are about 67 miles North to South and 110 Miles East to West, plan accordingly. It is very difficult to legally or safely drive 110 miles in 75 minutes. Look for places where the squares meet and just hop across the border between passes. On most Intestates it is possible to work from three grid squares on three passes of AO-27 while just heading East or West. Plan the first pass close to the border of the second square and drive as far into the second square as possible, this should get 2/3rds the way through the second square. The third square can be worked on AO-27 once the border is crossed, and the satellite comes up in the West. When planning any square or sequence of squares leave the extra time for setup, construction, or other road hazards.

There are also many hazards when going to other squares. Look for radio towers, Neon signs, and electrical lines. These can all be source of noise. Move a bit further down the road and find a nice quiet spot where there is less noise. Look for locations that are also safe and legal. Most interstate will not allow stopping on the shoulder except in emergency. Look for those rest stops where there is plenty of parking and a good chance for a pit stop. Probably the worst hazard is the weather. Operating in a lighting storm with an antenna in hand can be very hazardous. After being reminded about this by a bolt only 150 yards away, I no longer operate when lightning is closer than 5 miles in the city or 10 miles on the mountain tops.

Not only weather can play havoc on a grid square hopping expedition, but many other factors. Having back up in the forms of other satellites or other radios can save a long quiet drive back home. Out in the field it seems the one thing that breaks is the one thing there is no replacement for. On longer trips, carry an extra element or two for the antenna and a complete set of extra cables. Ever since I started carrying an extra cable, it has never broken. That extra radio can come in very handy when the one on the car got too hot and the LCD is all black.

Some Fun Locations for operations:

Some locations are just awe inspiring just to be in like Yellowstone. The geysers and the wildlife give plenty to do during the day. As the night closes in, it is time to set up camp in one of the many campgrounds. Even among the trees of a crowded campground many contacts can be made. It is usually no problem talking about the beauty of the location while basking in the glow from the radio dial. It is a great way to sit back and think about the sights seen during the day and chat with a few friends where it is hot and sticky.

All is not peaceful in Yellowstone, radio wise. There are a few noise sources and things to watch out for in the night. In the campground rest rooms there are heaters that can drown out even 70 cm signals when the antenna is only 100 ft away. Some motor homes also have some rather noisy ignition systems. It is impossible to avoid noise whenever other campers are around. That is the other concern, other campers. Remember to have the antennas out of reach from the other campers, so they don't get burned. Also watch out for those cables at night, they can trip some one who is headed to the rest room.

Locations in Alaska can be great for getting away from noise. It is amazing what getting in the middle of nowhere can do for the noise floor. There are plenty of rare squares and plenty of passes on those polar orbit birds. In August in Barrow, Alaska, not a beep or buzz was herd on the 20 meter band, but the radio was working well for RS-12. Several passes were worked using the Icom 706 and a couple of whips on a borrowed car. The only problem is many of the passes were over the North Pole or sparsely populated areas. The satellites were very quite, hearing only my own voice echoing back. It is quite a change on AO-27 to hear only your own voice for the entire pass with not even a whisper form another station.

Some locations, a trip to Alaska is not needed, just a short hop in the old wagon. Living close to a grid square border, it is always tempting to drive 20 minutes North to test out a new configuration. This can provide many stations with that extra square, just a few miles away. It is common to hear some of the 'mobile' stations on AO-27 to be just across the border of the neighboring grid square for lunch. It provides an excuse to check out that little spot seen the last time you drove by that place.

Finally:

Don't forget to have fun! This is not work it is a hobby. Being ready to communicate via satellite can help out in an emergency, but enjoy it while you can. There are plenty of scenic locations and rare squares to visit. Use it as an excuse to see what it looks like in the neighboring square, county, state, or just over the next mountain. Operating via amateur radio satellite from remote locations can be great fun!!

Catch Ya' on the Birds

73

Chuck (KI0AG)

Grid squares worked from as of 7/31/1998:

FM29	FM28	FM19	FN03	FN02	FN01	EN92	EN91	EN82	EL29
EL29	EL19	EL18	EM26	EM20	EM18	EM16	EM13	EM11	EM10
EM09	EM08	EM01	EM00	DN91	DN90	DN86	DN85	DN82	DN81
DN80	DN74	DN73	DN72	DN71	DN70	DN64	DN63	DN62	DN61
DN60	DN56	DN55	DN54	DN53	DN52	DN51	DN50	DN46	DN45
DN44	DN43	DN42	DN41	DN40	DN38	DN36	DN35	DN34	DN33
DN32	DN31	DN30	DN28	DN27	DN26	DN25	DN22	DN21	DN18
DN15	DN14	DN13	DN07	DN08	DN09	DM99	DM98	DM89	DM88
DM87	DM86	DM79	DM78	DM77	DM76	DM69	DM68	DM59	DM58
DM57	DM56	DM47	DM46	DM42	DM41	CM96	CM95	CM94	CM97
BP83	BP74	BP73	BP72	BP71	BP65	BP64	BP61	BP55	BP53
BP46	BP41	BQ11							

Some Good Resources:

www.amsat.org - Has Grid Square converter on line and lots of good information on all the amateur satellites.

The ARRL World Grid Locator Atlas - Shows all 32,400 squares and gives a good history of the Maidenhead system.

www.garmin.com - A good site for looking at GPS units and links to GPS pages.

www.delorme.com - Maker of Street Atlas USA and many good maps with GPS Grids.

members.aol.com/Arrow146/index.html - Manufacturer of the Arrow 146/437-10 satellite antenna.

Intermediate Circular Orbits for Amateur Satellites

by Ken Ernandes, N2WWD

ABSTRACT

This paper analyzes the utility of the Intermediate Circular Orbit (ICO) for amateur radio spacecraft. The ICO has an altitude between 8,000 and 11,000 km and provides a "happy medium" between large footprints offered by high altitude satellites and less "path loss" offered by low-altitude satellites. The ICO is attractive either for a single amateur satellite or could be used to build a constellation of three satellites with nearly continuous coverage of the Earth's surface. Furthermore, the ICO could be extended to a constellation of six satellites, giving full global coverage. The ICO is thus presented as an orbit to consider for future AMSAT spacecraft projects.

INTRODUCTION

The amateur satellite community has continuous discussions and debates about orbits for future spacecraft. Since there is no orbit that accommodates the needs and desires of all operators, we analyze each orbit type to see which goals it satisfies and to what degree.

This is the second candidate orbit I have evaluated in this manner. (The first was the 19,000 km circular orbit -- see reference 1.) At the 1997 AMSAT Symposium I presented the attributes of the 19,000 km orbit. Marty Davidoff K2UBC presented some attributes of 8,000 to 10,000 km ICO's (see reference 2). I had considered the lower altitude at one time, but selected the 19,000 km orbit since an important goal of that analysis was trying to get as close to full global coverage as possible with only three satellites. This was, in my opinion, a good orbital choice for a conceptual satellite system proposed by Bill Tynan W3XO (see reference 3).

I decided to do similar analyses for other orbit types attractive to amateur radio satellite missions. The purpose is to have evaluations of viable orbit types readily available. This gives managers of future amateur satellite projects preliminary analyses of various orbits. Designers can use these analyses to evaluate compatibility with launch opportunities and help with trade studies of various spacecraft designs.

DESIRABLE ORBITAL CHARACTERISTICS

I define desirable orbital characteristics as those attributes that promote quality satellite communications. These include:

- Large ground coverage footprints
- Low signal free space "path loss"
- Frequent accessibility
- Accessibility at convenient times
- Ability to close coverage gaps with additional satellites in the same orbit type

I invite other AMSAT members to give me any other important characteristics to analyze against candidate orbits.

Ground Coverage

Large ground coverage footprints are desirable because they let us communicate with distant stations directly using the satellite. The larger the footprint, the longer the possible communications distance. Orbits with large footprints also give us longer pass time intervals and generally more coverage time per day. As you would expect, higher altitude satellites have larger footprints than lower altitude satellites. **Figure-1** shows how the footprint coverage (as a percentage of the Earth's surface) increases with altitude.

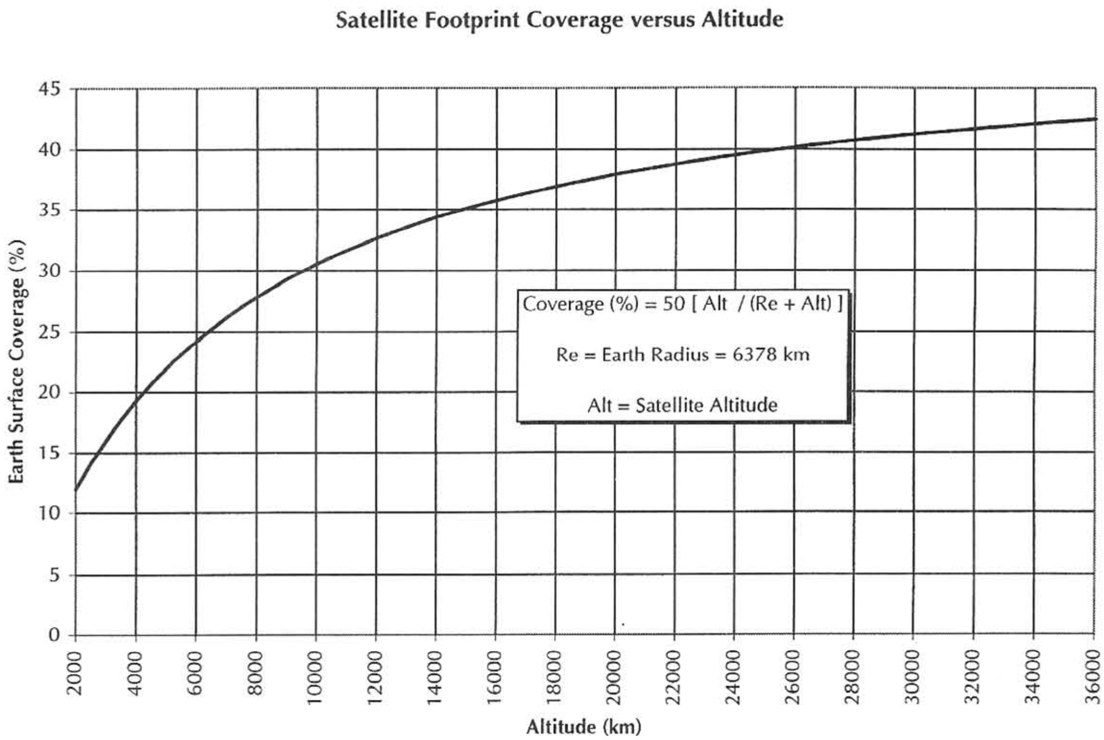

Figure 1., Earth Surface Footprint Coverage as a Function of Altitude

Notice that the gains in footprint size begin to diminish above a 24000 km altitude. Since the Earth is roughly spherical, the largest possible footprint size is one half (50%) of the Earth's surface.

Path Loss

As the satellite's altitude increases, our distance (or range) to the satellite also increases. The minimum range is when the satellite is directly overhead; the maximum range is when the satellite is at your local horizon. The free space "path loss" increases with the square of the range. **Figure 2** shows how the relative path loss increases with altitude when the satellite is both directly overhead and on the horizon. (Note: the "relative" path loss ignores the frequency-dependent component and only considers the range component.)

There is an important tradeoff between footprint size and path loss when deciding the satellite's altitude. If we were to choose an ICO at a 10000 km altitude, the comparison to the 19000 km medium altitude orbit and the 36000 Geosynchronous (or AMSAT Phase 3 satellite at apogee) is as follows.

The footprint coverage for the ICO is 30.5% of the Earth's surface; the 19000 km medium altitude orbit is 37.4% and the 36000 km altitude is 42.5%. Thus the 10000 km ICO altitude covers about 7% less of the Earth's surface than the 19000 km altitude and 12% less of the Earth's surface than the 36000 km altitude. If we do a direct comparison, the 19000 km footprint is 23% larger than the ICO footprint and the 36000 km footprint is 39% larger than the ICO footprint. Thus the ICO's footprint is noticeably smaller than that of satellites at the other two altitudes.

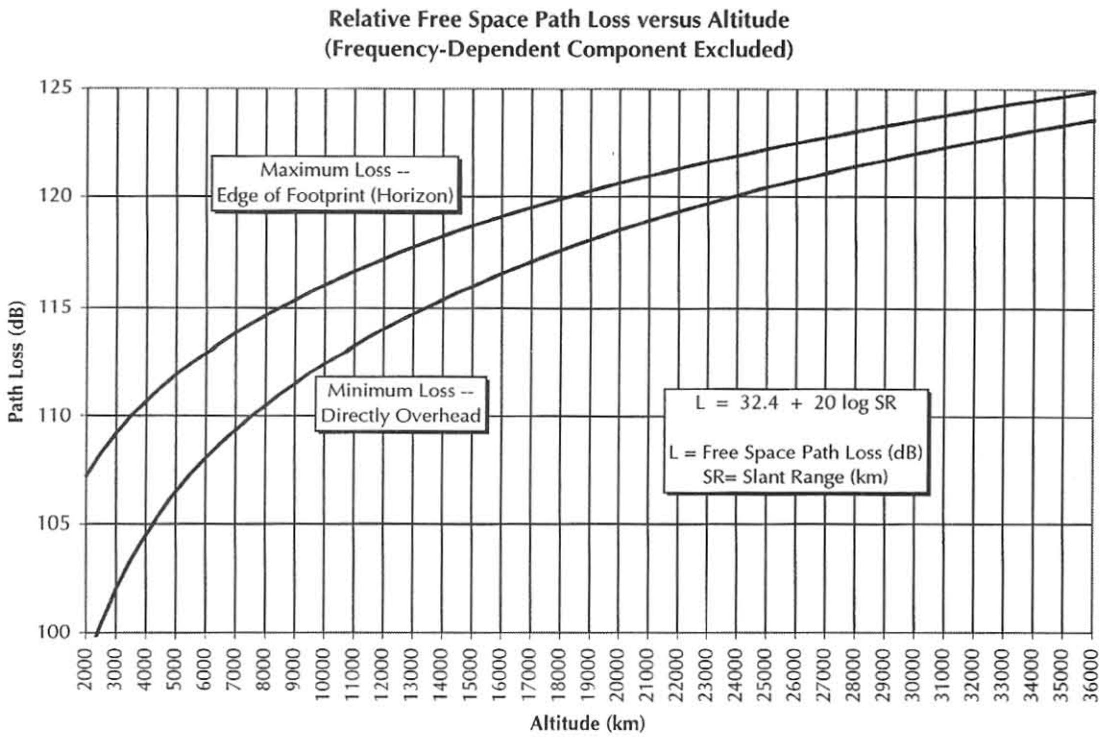

Figure 2., Relative Free-Space Path Loss as a Function of Altitude

Conversely, the ICO's path loss is much more favorable than for the other two altitudes. The ICO's path loss, when compared with the 19000 km orbit, is 4.2 dB lower at the horizon and 5.6 dB lower directly overhead. The ICO's path loss, when compared with a 36000 km orbit, is 8.9 dB lower at the horizon and 11.2 dB lower when the satellite is directly overhead. Thus the ICO has a considerable signal strength advantage over the other two orbit types.

Accessibility

The amount of access time a ground station has to a satellite in a circular, non-Geosynchronous orbit depends on the satellite's altitude and inclination and the station's latitude. This is what K2UBC calls Average Daily Access Time (ADAT -- see reference 2). The stations whose latitudes are within the satellite's footprint when it's at its maximum latitude (North or South) have the longest ADAT's. Since inclination specifies the satellite's maximum latitudes, we can "tune" accessibility to some degree when selecting the orbit's inclination.

When tuning the inclination of an orbit it may be desirable to optimize access to a particular latitude, but we should also consider the maximum latitude (North or South) to have access to the spacecraft. Any latitude closer to the equator than the optimized latitude will get reasonable coverage, so our main concern is the impacts to stations at higher latitudes. If the optimization doesn't eliminate or unreasonably limit coverage to the higher latitudes, then the latitude optimization is successful. Otherwise, we need to compromise by increasing the inclination to give acceptable coverage to the desired maximum latitude. This effectively increases the optimized latitude (i.e., moves it further from the equator).

To guarantee satellite access to some defined maximum ground station latitude, we need to identify not only the maximum latitude, but also the maximum elevation for that latitude. We then compute the largest acceptable difference between the maximum ground station latitude and the satellite's maximum latitude (i.e., its inclination). **Figure 3** graphs the maximum latitude difference for various satellite latitudes to get 10, 20, and 30 degree elevations at the maximum latitude.

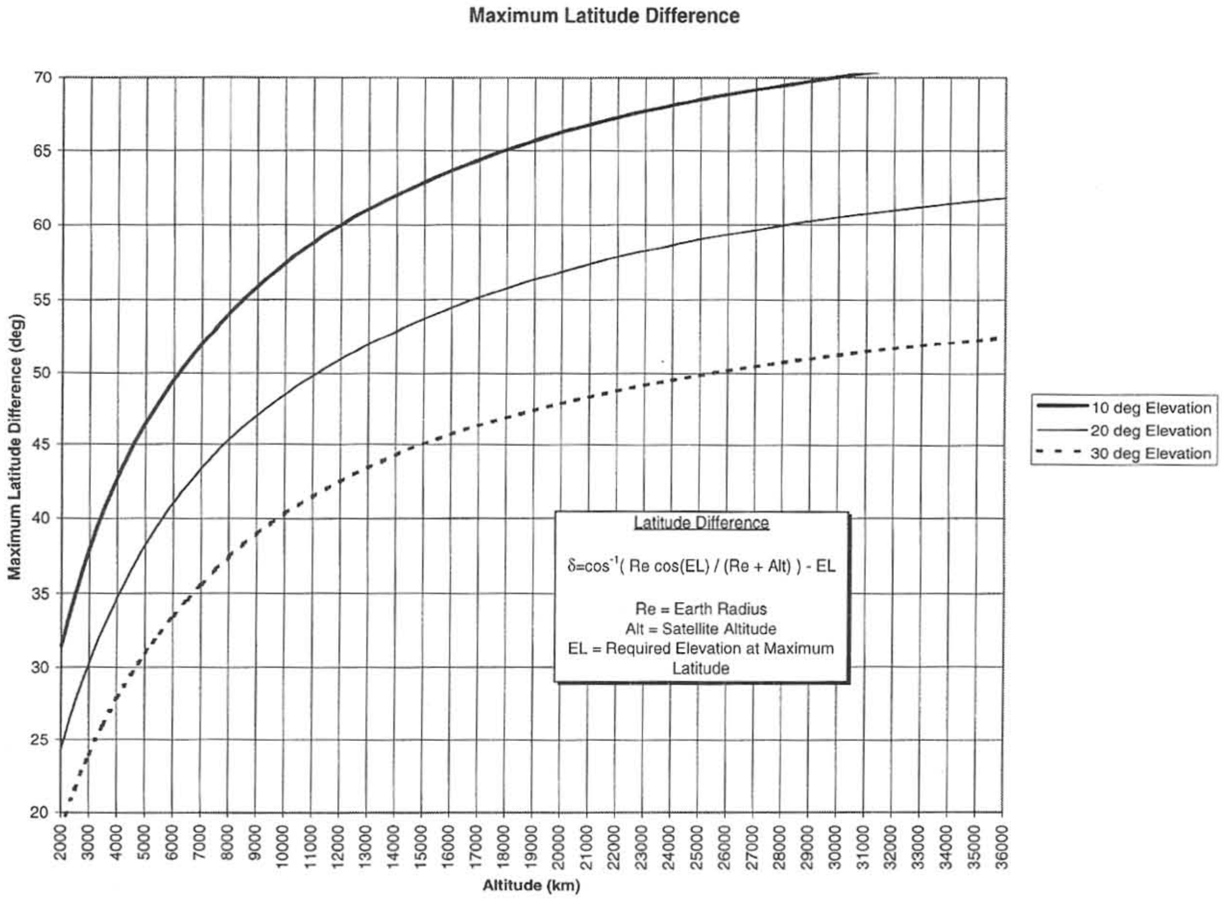

Figure 3., Maximum Latitude Difference between Optimum Latitude and Maximum Useable Latitude

Let's try an example to clarify how to use the information in **figure 3.** Suppose we have a 10000 km satellite altitude and we want to give 30 degree elevation passes to ground stations 65 degrees North and South of the equator. To meet these goals, the difference between the maximum latitude and the satellite inclination can be no more than 40.3 degrees (see the chart). The satellite's inclination must therefore be at least 24.7 degrees (i.e., 65.0 minus 40.3). If the satellite is in a retrograde orbit, the inclination can be no more than 155.3 degrees (i.e., the supplementary angle to 24.7 degrees).

Accessibility At Convenient Times

Whether we are choosing the orbit for a single satellite or a constellation that needs to be populated one satellite at a time, the ground track repeat interval is worth considering. If we want to give as many users access at convenient times, the satellite *should not* repeat its ground track in a short period of time. I generally recommend the satellite take at least a week to repeat its ground track. The intent is to accommodate most users by giving them a variety of pass times during the week.

The 10000 km altitude orbit repeats its ground track approximately every 29 revolutions, every 7 days. **Figure 4** gives example pass times for a station at a 45 degree latitude for a polar (98.7 degree inclination) 10000 km orbit. Typical pass durations are two hours.

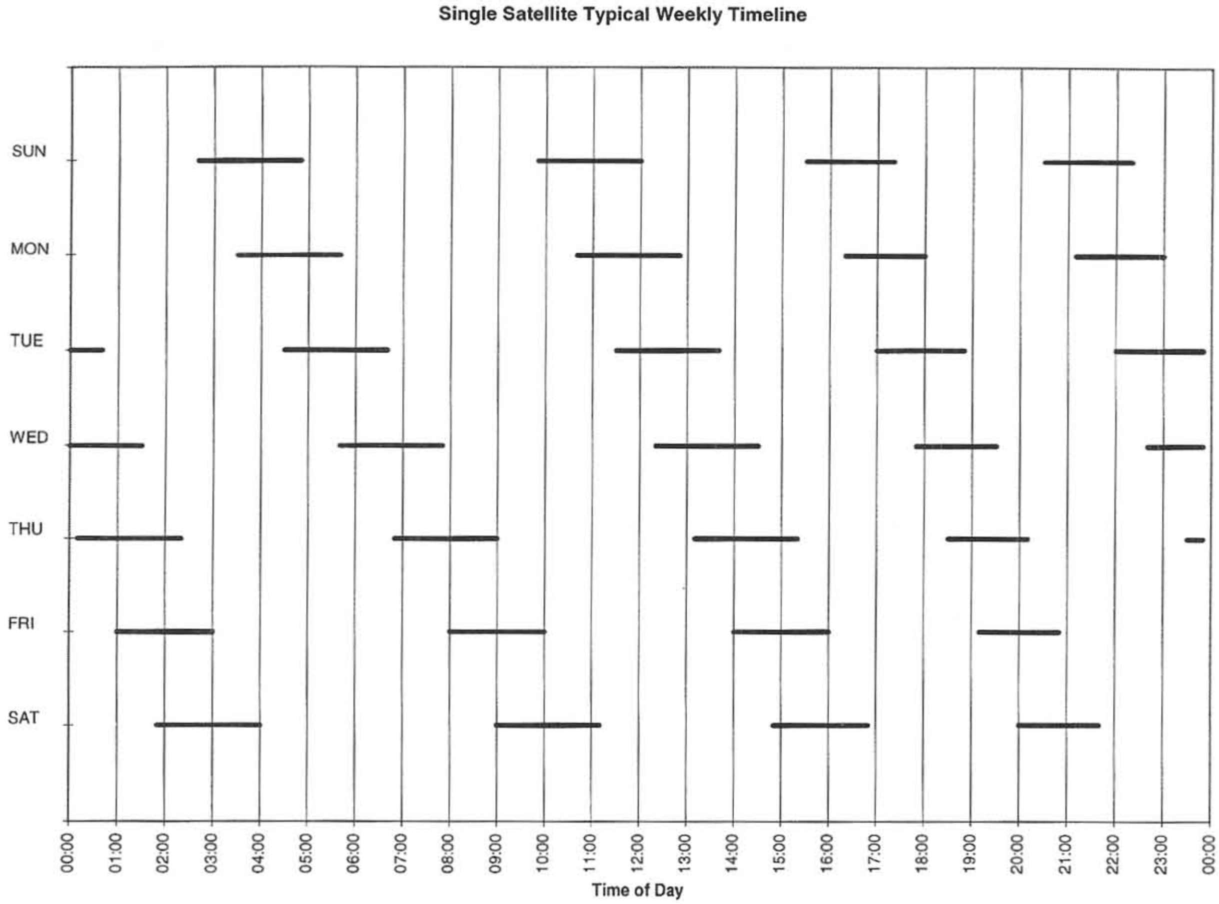

Figure 4., Sample Weekly Schedule for a Single Satellite in an ICO

Closing Coverage Gaps

We have already seen that the largest possible footprint for any satellite is one half of the Earth's surface. We can cover more than half of the Earth at a time by creating a *constellation* of two or more satellites. This can be done efficiently by creating what is called a Walker or Rosette Constellation (see references 4 and 5) that coordinates the orbits, thus minimizing redundant coverage. The basic technique uses circular orbits at the same altitude and inclination. We evenly space a consistent number of satellites in each orbital plane. The orbital planes are evenly spaced from each other at the ascending node and the satellites in adjacent planes are phased to close coverage gaps with minimal overlap. Using this technique, you can guarantee single satellite whole Earth coverage or even multiple satellite redundant coverage (as is used with the GPS constellation).

An optimum Rosette Constellation requires that you be able to choose the orbital inclination. Since amateur payloads usually do not get a choice of inclination at launch, we can either accept a less than optimum inclination or do an inclination-adjusting thruster firing to get the desired inclination. Since inclination changes are very expensive in general (and most expensive at lower altitudes), I am assuming that AMSAT would construct the constellation from whatever inclination we were given by the launch booster. Thus propellant carried by the satellite would initially be used to establish orbital altitude and along-track phasing. Remaining propellant would be used to do stationkeeping maneuvers over the satellite's lifetime to maintain the relative satellite phasing.

My initial goal for the ICO constellation was to try to get full global coverage (or close to full global coverage) with as few satellites as possible. However, I found I needed more than three satellites to get full coverage. Because of cost constraints, I am assuming it is unlikely that AMSAT could orbit a constellation with more than three spacecraft. I therefore designed a three satellite constellation, minimizing the impact of coverage gaps.

After examining the footprint of the 10000 km altitude orbit, it was clear that an equatorial inclination would provide mediocre coverage at middle latitudes and poor coverage at higher latitudes. I therefore chose another common inclination: a sun-synchronous orbit (98.7 degree inclination) as this would provide all-latitude coverage, although only high latitude stations would get 24 hour coverage. **Table 1** has sample Keplerian elements for a 3 satellite Rosette Constellation with a 98.7 degree inclination and a 10000 km altitude. **Figure 5** illustrates a "snapshot" of the coverage footprints for this constellation generated with the STK version 4.0 software.

Table 1., Polar ICO Sample Keplerian Elements

Satellite ID	ICO-1	ICO-2	ICO-3
Mean Motion (rev/day)	4.14505	4.14505	4.14505
Eccentricity	0.0001	0.0001	0.0001
Inclination (deg)	98.7	98.7	98.7
RA of Node (deg)	0.0	0.0	0.0
Arg Perigee (deg)	0.0	0.0	0.0
Mean Anomaly (deg)	0.0	120.0	240.0
Epoch Time	99180.5	99180.5	99180.5

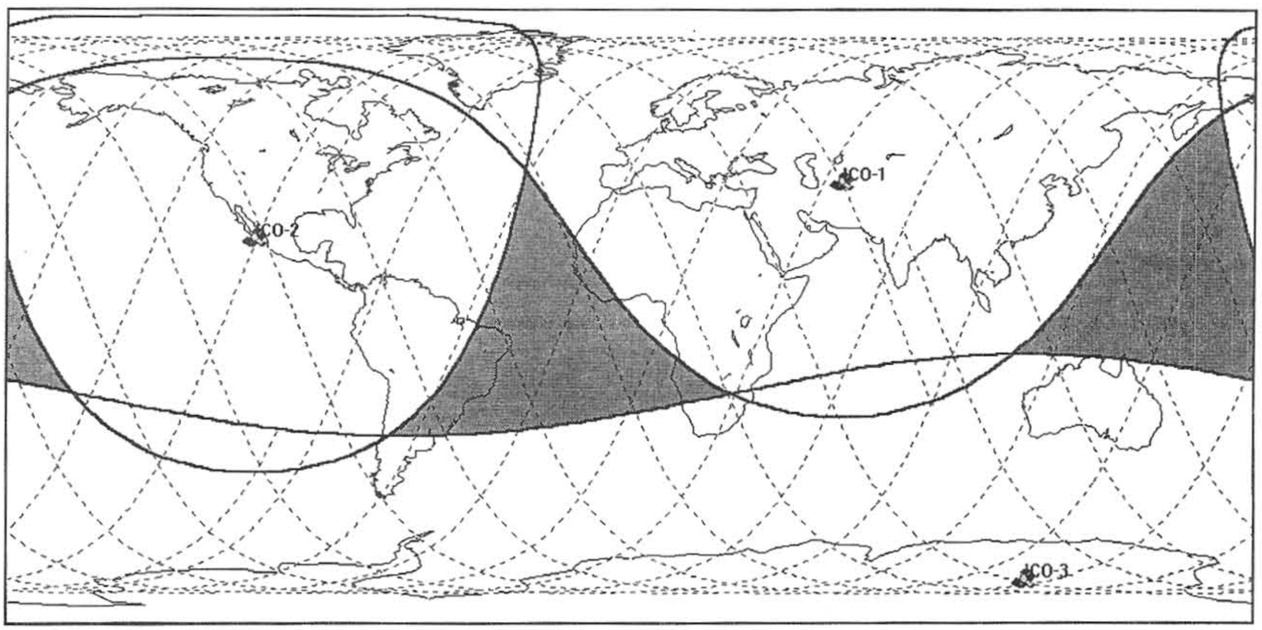

Figure 5., ICO Satellite Footprints and Two Triangular Coverage Gaps

Notice that the ICO constellation has two triangular coverage gaps near the equator. These two gaps rotate like pinwheels, moving along the equatorial region. Because of the high orbital inclinations, the latitudes closest to the equator have the longest coverage gaps. Lower inclinations will have shorter low latitude coverage gaps; inclinations as low as 53 degrees (or as high as 127 degrees) will still guarantee continuous coverage at the high latitudes.

If you want a 10000 km altitude constellation with continuous global coverage (i.e., no low latitude gaps), you need 6 satellites. The full coverage constellation would effectively double the 3 satellite constellation with a second orbital plane also containing 3 satellites. The second orbital plane would have its ascending node offset 90 degrees from the first orbital plane; the satellites would be phased 60 degrees in the along track direction relative to the satellites in the first orbital plane. **Table 2** has sample Keplerian elements for the satellites in the second ICO plane.

The second plane covers the relatively small coverage gaps by doubling the number of satellites in the constellation. This is a *very expensive* option especially considering that continuous coverage is a *desirable feature* and not an absolute requirement. Since the cost to benefit ratio is not very favorable, it's not likely that AMSAT would consider this option in the foreseeable future.

ISSUES AND CONSIDERATIONS

The considerations and issues are real-world constraints and derived requirements that would cause us to accept a less than optimal orbit choice. These include:

- Initial orbit given by the launch booster
- Ability of the spacecraft to change the initial orbit (delta-V)
- Stability of the selected orbit
- Orbital environmental issues (such as radiation)
- Which geographic areas will get the best coverage and which areas will get poor or no coverage
- Whether or not the selected orbit allows for passive or simple attitude control techniques

Booster Orbit Insertion

Since it's unlikely that AMSAT will be able to secure a dedicated launch in the near future, our orbit will begin with what the booster provides to the primary payload. I thus chose a sun-synchronous inclination hoping to be able to maneuver it to ICO altitude. However, I found that I needed much more delta-V than would be reasonable to establish this orbit.

Delta-V Requirements

The ideal situation always is to have the satellite deployed directly into its desired orbit by the launch booster. Otherwise the spacecraft must carry on-board propellant to maneuver to the ICO. If the orbit is much lower than the ICO, you need an unreasonable amount of delta-V to get the desired orbit. For instance, a single Hohmann Transfer from a 1000 km altitude to a 10000 km altitude would require more than 2300 m/sec of delta-V. (Just for reference, this is approximately 65% more delta-V than Phase 3D's thrusters will need to get it to its final orbit.) A practical minimum starting altitude is about 3500 km for a circular orbit to an ICO; elliptical orbits need to be examined case-by-case to determine the delta-V needed to establish an ICO.

Table 2., Polar ICO Second Plane Keplerian Elements

Satellite ID	ICO-4	ICO-5	ICO-6
Mean Motion (rev/day)	4.14505	4.14505	4.14505
Eccentricity	0.0001	0.0001	0.0001
Inclination (deg)	98.7	98.7	98.7
RA of Node (deg)	90.0	90.0	90.0
Arg Perigee (deg)	0.0	0.0	0.0
Mean Anomaly (deg)	60.0	180.0	300.0
Epoch Time	99180.5	99180.5	99180.5

Reference 8 gives performance profiles (circular and elliptical orbital altitudes versus payload weight) for today's launch boosters. I have identified a variety of candidate launch profiles on some of the more popular boosters. However, none of them appear to be used frequently. Thus the most significant issue when considering an ICO for a satellite's orbit is what launch opportunities are available.

Orbital Stability

Mission planners consider orbital stability for two reasons. First, there is the concern that strong perturbations could cause the orbit to change so significantly that the satellite is no longer in its intended orbit. (AO-13, which experienced catastrophic orbital decay from the effects of Lunar and Solar gravitational perturbations, is the most extreme case.) Second, if we have a constellation of satellites, uneven perturbations alter the orbits unevenly, eventually destroying the effectiveness of the constellation.

The major perturbations at the ICO altitude are Lunar and Solar gravitational attractions. These perturbations tend to have the greatest effects on highly elliptical, high inclination orbits. Because the ICO is circular by nature, the expected effects are minimal. However, a complete analysis of these effects should be done for any candidate orbits.

Orbital Environment

One spacecraft design concern is how harsh is the space environment in which the satellite will operate. Designers need to consider significant environmental hazards that threaten the long-term health of on-board subsystems. The major environmental hazard near the ICO altitudes is radiation.

One important reason K2UBC suggested the 8000 to 11000 km altitude range for the ICO was that these altitudes are just above a high radiation region. Satellite mission planners avoid continuous orbital operations in altitudes between 2000 and 8000 km because this is a very strong area in the Van Allen belts (see references 6 and 7). Upsets from high energy particles trapped in these belts can have a devastating effect on on-board electronics, especially digital computers. While shielding components offers some protection, it is best to operate outside the regions of strongest radiation.

Geographic Coverage

As I mentioned in the *Closing Coverage Gaps* section, stations at the lowest latitudes will have the longest gaps between passes with the polar inclination. A lower inclination would shorten these gaps. The best way to reduce the low latitude coverage gaps is to find a launch close to the optimal inclination for the three satellite constellation.

Attitude Control Options

Amateur spacecraft generally have two goals when considering attitude control requirements: the need to orient the communications antennas toward the Earth and whether or not to try to maximize solar cell collection by orienting them toward the Sun. Antenna orientation can be most critical for all but the lowest altitude satellites; lack of attitude control at the ICO altitudes could easily negate any path loss advantage over a higher altitude satellite.

On the positive side, lower altitude satellites can generally take advantage of passive (e.g. gravity gradient) or simple (e.g. magnetorquing) attitude control techniques. Since the Earth's magnetic field strength drops off as an inverse cube, the ICO altitudes are perhaps the highest altitude in which a practical magnetorquing system could be implemented. Depending on the design of the spacecraft, magnetorquing could be considered for a primary or secondary attitude control actuator for an ICO.

SUMMARY

The ICO is a candidate orbit for amateur spacecraft. However, its greatest drawback is finding an acceptable launch opportunity. If a suitable launch opportunity can be found, this orbit gives an excellent combination of large footprints, relatively low free space path loss, and the possibility of using magnetorquing for attitude control. The ICO is also a candidate for multiple satellite constellations.

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THE YEAR 2000 TRANSITION
YOUR PC AND AMSAT SOFTWARE

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Abstract:

As we approach the year 2000, there are some items we need to begin to check out in our computers and the software that is running on them to be sure that the date and time sensitive software will function during and after the transition from December 31, 1999 to January 1, 2000.

The PCS

Most computer software that uses the current date and time, gets that information from the PC operating system. The operating system, DOS, Windows, etc., is just software that disappears when the PC is turned off. From where then, does the operating system get this information?

At boot time the operating system is loaded and reads the CMOS Real Time Clock (RTC) which remains running on a backup battery when the PC is powered off. This RTC is hardware in the PC. The CMOS RTC maintains a two digit year value, so the PC BIOS appends these two digits to a pair of stored century digits making the four digit year value that the operating system obtains.

The RTC does not have the century digits and therefore cannot increment them when the year changes from 1999 to 2000. The RTC then just turns over from 99 to 00. The earlier PC BIOS systems only stored the century value of 19. No one was worried about the year 2000 back then. It was a long way off. Now when the year rolls over from 1999 to 2000 you would logically expect this to cause the programs run in those PCS to think the date is 1900. If the program takes its date input directly from the BIOS, that is what will happen. However, if the program gets the date from the operating system, it will think the year is 1980. This is because the operating systems that were designed back in 1984 had no need for supplying current dates earlier than the 1980's. So when the PC boots up with the RTC showing the year 00, the operating system tries to make this 1900, but discovers this is an invalid date and defaults to 1980. How many of you remember booting up one of the older PCS that had a dead ROM backup battery, or even no RTC at all? It probably showed the date of April 1, 1980.

Generally, machines that have been manufactured more recently have BIOS systems that have the ability to decide that the century year is either 19 or 20. You might infer that deep in the BIOS there must be some decision tree that says if the year digits are between 80 and 99, for example, the century digits are 19 and if they are between 00 and 79 they are 20. This would mean that all would be ok until 2079. However, this is not the case. In windows 95 you can set the date to any year from 1980 through 2099. The next time you boot up, the date is remembered, that is if your PC is Year 2000 (Y2K) compliant).

The Tests

Your PC will be Y2K compliant if:

1. The RTC two digit year date is read at boot time and is furnished to the operating system by the BIOS as a four digit year value which will increment from 1999 to 2000 at midnight.

2. Then after rebooting, the correct 2000 date will be furnished to the operating system by the BIOS.

3. The year 2000 will correctly accept February 29, 2000 as a valid date. The leap year rules say that any year evenly divisible by four, shall have an extra day added, EXCEPT for century years, EXCEPT for century years evenly divisible by four hundred. In other words, the years 1600 and 2000 are leap years since they are evenly divisible by both four and four hundred. However the years 1500, 1700, 1800, 1900 and 2100 which are evenly divisible by four, but not by four hundred, are not leap years. How can you tell if your PC is Y2K compliant? There are three manual tests you can make which will help you determine this.

First, set your system date and time to December 31, 1999 and the time to about two minutes before midnight. Turn your PC off and wait for three or four minutes. Then reboot and check that the system date and time displayed are a few minutes after midnight on January 1, 2000.

Secondly, set the date to any date after January 1, 2000, except February 29, 2000. Power down the PC and reboot. Check that the date shown is still the same date you set.

Lastly, try to set the system date to February 29, 2000.

If any of these tests fail, your PC is not Y2K compliant. If you want to perform a more thorough test, there are software programs available which can perform these tests for you. Also, in some cases, there are software solutions available that can correct for certain types of non-compliance for Y2K. One Internet site to visit for a more complete discussion of this problem and a free test program is http://www.rightime.com.

The Software

OK, so lets assume our PCS are Y2K compliant. We ought to be home free, right? Wrong! Our software must also be Y2K compliant. Back when early software was being written, the ability to conserve memory was paramount. If you could find a way to store data in memory in a compressed way, you did it. It cost more processing time to compress and uncompress the data, but it saved memory. Memory cost more than processing time back then. One of the minor memory savings used was to store year values in two digits rather than four. In other words store 1985 as just 85. After all, everybody knew that the century value was 19 and it would be assumed that way by any software writer.

As a result, in many cases, only two digit year values are contained in the data input to date and time sensitive programs. One example of this is seen in the Keplerian elements data. Remember the Epoch entry? It is in the form YYDDD.xxxxxxxx, where YY is the two digit year value. The satellite tracking programs written beginning in the middle to late 1980s have had to interface with these two digit year values. In many cases, the orbital calculation algorithms in these programs used the two digit year values throughout.

A typical tracking program looks at the Keplerian elements and then calculates forward from the Epoch time in the elements to the current time to determine the current position of the satellite. This means that the year, day and fraction of a day values in the Keplerian elements are the beginning point of the calculations. The current year, day and fraction of a day are the target of the calculations. The program must determine the exact difference in time from the Keplerian element Epoch time and the current time. This involves mathematical operations on the year, days, hours, minutes seconds and fraction of seconds involved. Leap year days and Century days have to be accounted for also. This gets rather messy. So the Epoch times involved are converted to Julian days. Julian day one was January 1, 4713 BC. January 1, 2000 will be Julian day 2,451,545. There are mathematical formulas that let you input two different Gregorian calendar dates and times, with four digit year values, convert them to Julian dates and obtain the difference between the two dates in days and fractions of days. These formulas, take into consideration all leap year and century days. This really simplifies things. This difference in time is the input to the orbital calculation algorithms that let us determine the current satellite position from the Keplerian elements.

If there are tracking programs still out there which do not use Julian dates in their calculations, they are in deep trouble. However, even those programs that do use Julian date calculations can still have problems. Remember, that the Julian dates are calculated from Gregorian date inputs that contain a four digit year value. NASA has said that the Keplerian Element format will remain the same and that the year value will just roll over from 99 to 00 with the transition to the year 2000. When the tracking program looks at the Keplerian elements for a satellite, how then will it know what century value to use with the two digit year value in the Epoch date? Somewhere along the calculation train, a decision must be made.

One way is to make the assumption, for example, that any Keplerian Epoch year value 78 through 99 has a century value of 19, and any year value 00 through 77 has a century value of 20. Once this has been done, the use of Julian day calculations will safely allow you track a satellite right through midnight December 31, 1999 into January 1, 2000 without a glitch.

However, there is another glitch to look for. In some orbital calculations it is necessary to calculate a value called the Sidereal Time value at January 1, YYYY at 00:00:00.000Z. This value is used throughout that year. Here again, the assumption above must be applied to determine which century should be applied to the two digit year value. In other orbital calculations, the Julian date difference between the Keplerian Epoch year value and the Julian day value for January 1, 2000 is used. Still, it is necessary to convert the two digit Epoch year value to a four digit year value to obtain the Epoch Julian date.

Lastly, a less troublesome problem may arise when the Keplerian Elements are updated. Most tracking programs have a Keplerian update routine which protects against updating the elements for any given satellite with elements that are older than the ones already on file. Imagine what will happen when the first set of new Keplerian elements are issued in 2000. Some Epoch dates will have year values of 00 and some will still have 99. It usually takes one or two issues of Keplerian elements before all the satellites have a year value from the new year. In the case above, those satellites with Epoch year values of 99 will still update OK as long as the complete Epoch date is later than the ones already on file. However, unless some programming has been done to recognize 00 as representing 2000 and 99 as 1999, the 00 Epoch year elements will be rejected as being older than the ones already on file.

Some programs may permit updates overwriting existing elements without regard to the Epoch value. This will be the work around for those programs where the normal updates are rejected. Others which are not compliant in this regard may require that the Tracking program Keplerian data base file be deleted completely before each update until the new Keplerian element files contain satellites with all Epoch year values of 00. This will be done automatically in those programs which do not create a Keplerian element data base file and instead, just read in the distributed Keplerian Element file itself.

What has been done

OK then, just what is the status of our AMSAT distributed tracking programs with respect to Y2K compliance? First, some background. Back in 1985 when I first changed the ORBITS programs from an interpreted Basic program to a compiled Quick Basic program I ran up against this Y2K consideration. I decided at that time I didn't want to hear from a lot of people in fifteen more years, much less pay the postage for replies, etc. So I made the decision to force the user to input the Epoch year in a complete four digit value separate from the Epoch day. I then tested the program across the 1999/2000 transition boundary and it worked as it should have. I was happy and confident that I would never have to worry with that problem again. Never say never!

Time went by and in 1994 I began making inquiries as to what NASA was going to do about the published Keplerian elements. Were they going to change the format of the Epoch day or were they just going to roll the year value over to zero (00). The answer I received was inconclusive. "We didn't know yet." At that time I also began making inquires of a few of the AMSAT software authors as to whether their programs were Y2K compliant. I received some answers saying that it didn't appear so and a few that said yes. One said his program wasn't compliant and didn't expect it would be updated.

In June, 1996, I e-mailed as many of the software authors as I could find, asking them to make a Y2K compliance check of their programs and let me know what the status of the programs were, and whether or not they would be made compliant or not. My concern was that we should stop offering any programs that were not going to be made compliant. As a result of that inquiry we stopped offering one program. The author said that he did not intend to update it..

Then in October, 1997, at the AMSAT Symposium in Toronto, Philip Chien, KC4YER, and I met with Ken Ernandes and asked him if he could develop a set of test Keplerian elements for December, 1999 and January, 2000 that I could send to the software writers for their use in performing actual tests on their programs. He kindly agreed to do so and in a few weeks I received a TEST2000 zipped package via e-mail which I then sent to all the tracking software developers I could think of. Just for the fun of it, I decided to test the ORBITS programs again with the test Keplerian elements. It worked beautifully, tracking right up to midnight on the evening of December 31, 1999 and then into January 1, 2000 without a hitch. Then I tried to update the 1999 elements with the ones having 2000 as the Epoch year. Ugh!!! It refused to update, claiming the elements were older than the ones already in file. Back to the keyboard and compiler again. It had been so long since I had compiled a new version, I had a problem remembering how to get the compiler set up. I did get the fix in and it is now fully Y2K compliant..... I think. Remember, "Never say never."

The replies began coming in following the Y2K tests and the results were as follows:

Software distributed by AMSAT-NA:

APRTRACK
This program was not Y2K compliant as of June, 1998. However the author has said that it will be brought into compliance and made available on the TAPR web site before 2000.

INSTANTTRACK
This program is not Y2K compliant through version 1.00b and earlier. However a patch will be made available for this popular program on the AMSAT Web site, probably this year

MACDOPPLER
This program is fully Y2K compliant according to the author.

NOVA FOR WINDOWS
Both the 16-bit and 32-bit versions are fully compliant according to the author.

ORBITS II & III
There is a problem updating the Keplerian elements in versions earlier than 5.01. This has been corrected in version 5.01. All other operations are OK. A work around for the problem in earlier versions is to delete the ELEM?.DAT files and recreate them anew with each update until all Epoch years in the elements are 2000. The program is ok after that until 2078.

QUIKTRAK
This program is not Y2K compliant and the author has said it will not be updated. The program is no longer being distributed by AMSAT.

SATELLITE PRO
This program is not Y2K compliant in versions issued earlier than June, 1998. The current version is Y2K compliant according to the author. Users having the earlier version will be able to download the required updated file later this year. The original associated KEPS LOADER program written by a different author is not Y2K compliant. However, the author has stated that it would be made compliant before 2000.

SATSKED
No information available.

STSORBIT PLUS
This program is fully Y2K compliant with versions 9748 and later according to the author. Updates are available from its web site. The older STSORBIT (not PLUS) program, version 9201, for older PCS has not been tested for Y2K compliance and there are no plans to update it at this time.

THE STATION PROGRAM
This program is fully Y2K compliant according to the author. Updates are available from its web site.

WINSAT
The current 16 bit WINSAT program is not Y2K compliant and will be replaced with a 32 bit version which will be compliant.

WISP16
This sixteen bit version of WiSP may not be Y2K compliant. At any rate, it will not be updated. The program has been left on the AMSAT ftp site with the caveat that it may not be compliant and will be removed at a later date. This will allow the opportunity for Windows 3.1 users to become familiar with the program before being required to upgrade to WiSP32 for Windows 95/NT.

WISP32
This program appears to be fully Y2K compliant with version WISP3210 and later. It will continue to be carried on the AMSAT ftp site.

Tracking hardware distributed at one time or another by AMSAT-NA:

KANSAS CITY TRACKER/TUNER
The KCT/T has no Y2K compliance concerns and is mentioned here only for the benefit of those users who may wonder.

SATTRACK III & IV
Y2K revisions to the firmware have recently been completed and tested and will be released to the owners shortly.

TRACK BOX
This unit is supposedly Y2K compliant from what I have been told, however no confirmation of this has been received from the persons responsible for firmware updates.

Summary

I suggest you visit some of the web sites listed in the resources below and find out more about the Y2K problem. You can also find other sites on the Internet by doing a search for the subject. Run the three simple tests to see if your PC will make the transition and if not, download a simple program to be run at boot time to see if that fixes the problem. There are such programs available on some of the Y2K web sites. Check with your PC manufacturer to see if there are ROM BIOS updates or boot time programs available for your PC that will fix the problem. After all is done, if your PC still fails Tests 1 and 2 above, you have the worst possible Y2K scenario. If you have date/time sensitive programs running on that PC, you should consider replacing it. If the PC fails Test 1 and passes Test 2, then at least you can manually set the date after booting it up. If it fails Test 3 however, there is no work around and all dates following February 29, 2000 will show the wrong day of the week. This may or may not be a problem for your particular applications.

Once you have run through the tests covered earlier in this paper, checked out your application programs and have satisfied yourself that all is well, then you should not have any further date/time problems, right? Remember, never say never. Those of you with some of the older GPS units, watch it on the evening of August 21, 1999 when the week counter rolls over from week 1023 to week 0. Also, watch out for the year 2038 when the signed long integer variable in the compiler that compiled your program is too small to contain the Julian date values. When this happens, I don't expect to still be around. However, I can look ahead and imagine that those who are, may wake in the middle of the night or look up from their work, depending on where they are, and wonder, "What was that"?

Sources:

Pete Woytovech, Senior Programmer Dell BIOS Development, *The Century Rollover and the PC System Date*, http:/www.dell.com/r&d/vectors/v/v3_cent.htm.

RighTime™ (The RighTime Company, Miami), http://www.rightime.com.

J. David McLaughlin, Systems Coordinator Simco County Mental Health Education, *Testing Your PC's Hardware Year 2000 Readiness*, http://www.mhcva.on.ca/Y2K/pctests.htm.

JStation - An Update

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Introduction.

JStation is an implementation of an automated satellite ground station written in Java™.

JStation was first presented at the Toronto AMSAT-NA meeting in 1997, and the first public release was made available on the internet in April 1998.

The software release includes the complete source code for the system.

The software will run (without recompilation) on any hardware/software platform that fully implements the Java 1.1 Virtual Machine. I have successfully run the software on Windows/95, Windows/98, Window/NT, Linux all running on Intel hardware platforms, and Linux and Solaris running on a Sun SPARC platform.

Minimal amount of C code to provide interface to serial ports, Kansas City Tracker and SASI Linux device driver.

Software Components.

- Satellite Tracking.
- Satellite Scheduling (priority based).
- Rotor Control.
- Radio Control.

- Kiss Protocol.
- AX.25 Protocol.
- Pacsat Broadcast Protocols.

- Status Display.
- Directory and Message Viewer.
- EIS Image Viewer and Manipulator.
- Message Composer.

Supported Hardware.

- KCT Tracker/Tuner (Windows/95).
- TrakBox (Windows,Linux,Solaris).
- Icom-821 (direct serial port).
- SASI Tracking Controller (Linux).
- KISS Mode TNC.

Main Program Window.

The main program window displays the list of satellites currently being tracked, and includes:

- Next AOS or LOS time.
- Current latitude and longitude of the ground track of the satellite.
- Azimuth and elevation relative to the ground station.
- Doppler corrected downlink frequency.
- Doppler corrected uplink frequency.

Note that if the uplink frequency is set to 0.0, the uplink is disabled, and no attempt is made to transmit to the satellite.

When a satellite is above the horizon, the display line color changes from black to red if the satellite is being worked, and blue if it above the horizon but not being worked.

Each satellite is given a priority to determine which one is worked if 2 or more are above the horizon at the same time.

Also included on the display are:

- **Call**: the callsign of the source of the last packet received.
- **BBStat**: the last BBStat status message received.
- **PBList**: the last PBLlist status message received.
- The **Status** line at the bottom will display information about directory entries received and file fragments received.

To view a list of downloaded messages or the directory for a satellite, you select the **View Directory** menu item, and then select the satellite you wish to view.

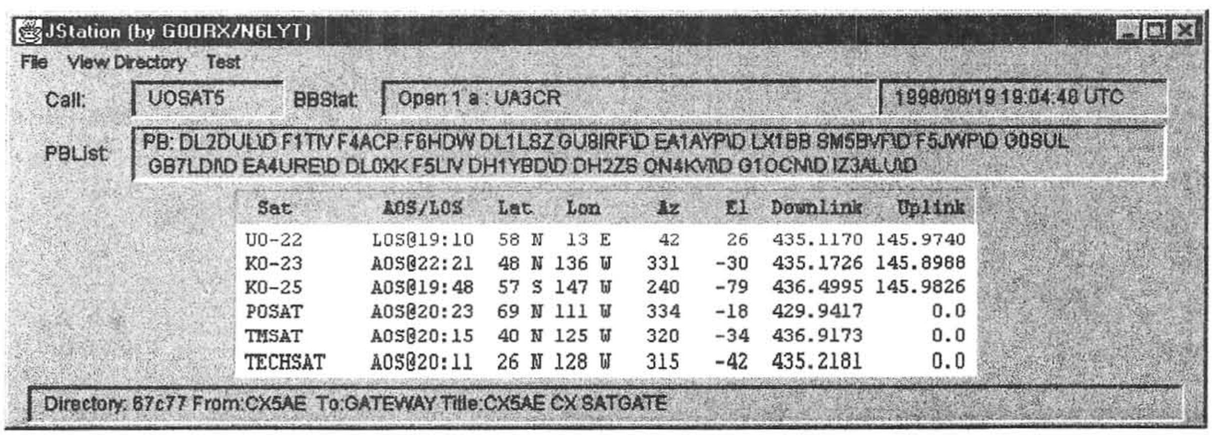

Fig 1: main program window.

Directory Window.

The directory screen by default displays a list of downloaded files.

To view most messages, you click on the message line and the message is displayed in the window below. This works for:

- uncompressed text messages.
- compressed text messages using ZIP or PKZIP (single files only).
- Activity Log.
- Broadcast Log.
- Call Log.
- TLE Files.
- KEP Files.

GIF, JPEG and EIS images will be displayed by popping up an image window.

The are several menu options that allow you to:

- Change the sort order of the list.
- Filter the list to include only certain types of messages.
- Delete/Extract messages.
- Reply to a message.
- Compose a new message.
- View the Directory or the Downloaded messages.

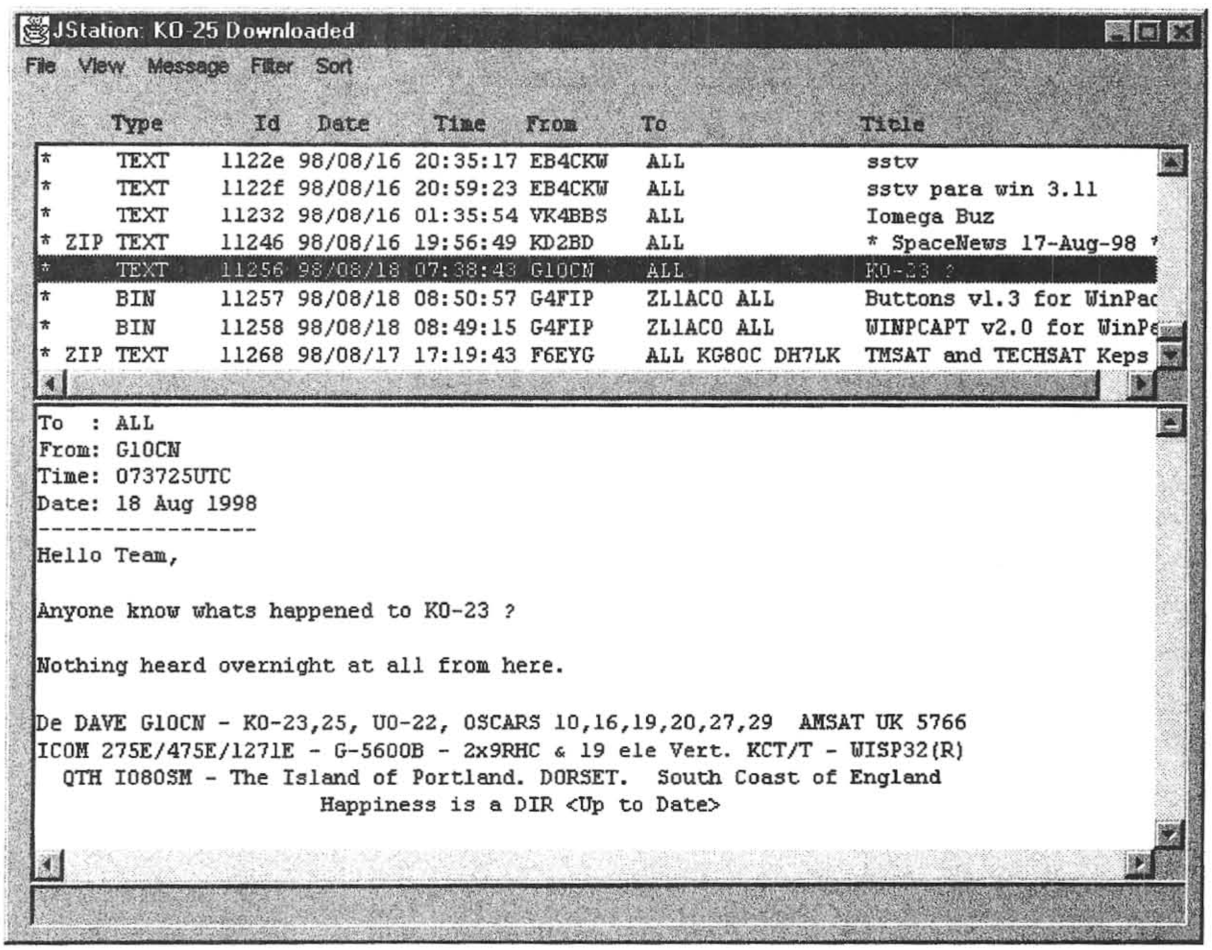

Fig 2: Directory Window

Message Composer Window.

When you select the reply or compose menu from the Directory Window, the Compose Message window is popped up. This can be used to create a simple uncompressed text message, a simple compressed text message, or to send a file.

By default, the window comes up in the text message mode, by clicking on the File button, the text entry area is replaced with a file selection display. which lets you pop up a file system browser to select the file to send.

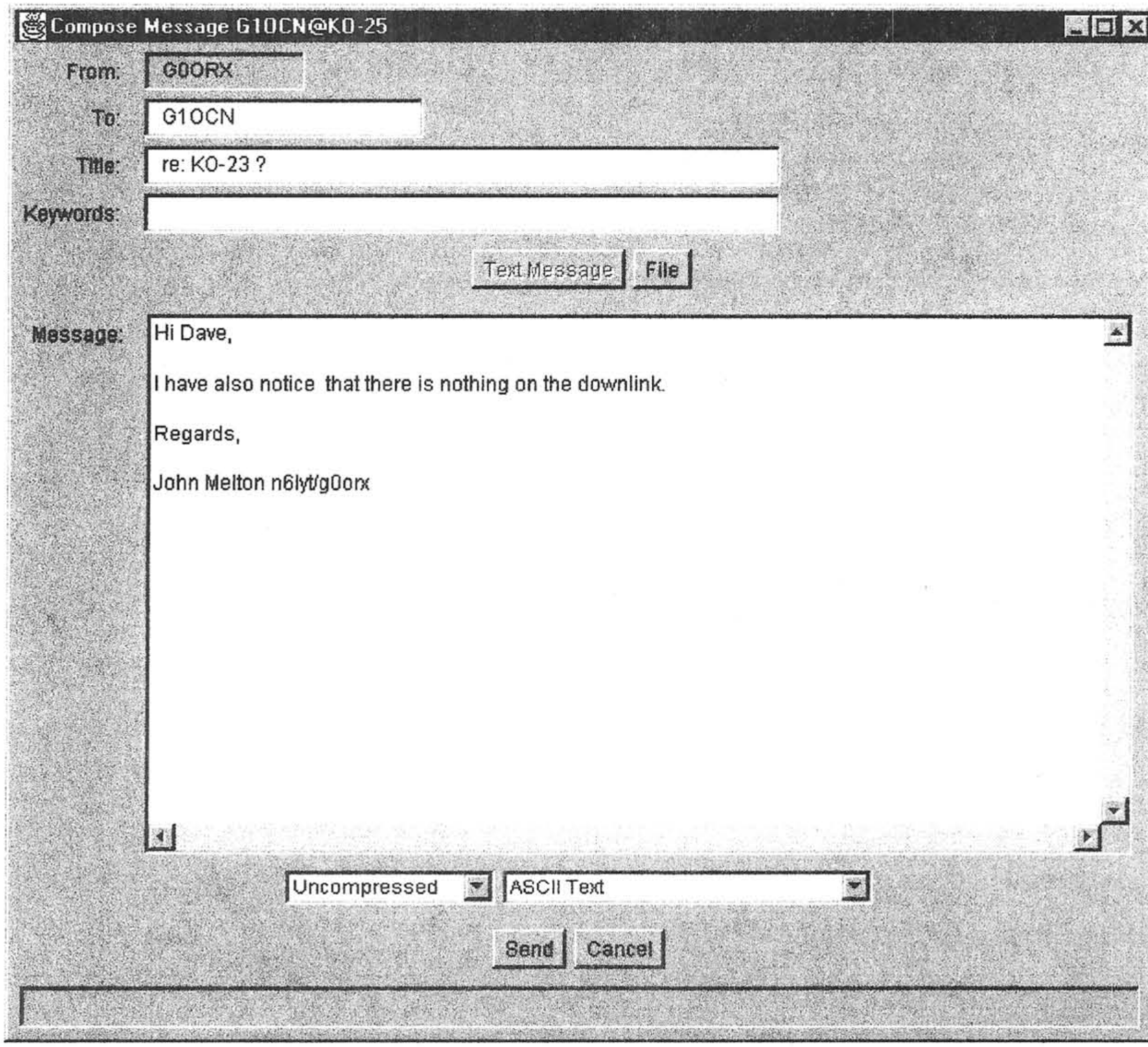

Fig 3: Message Composer Window - text message

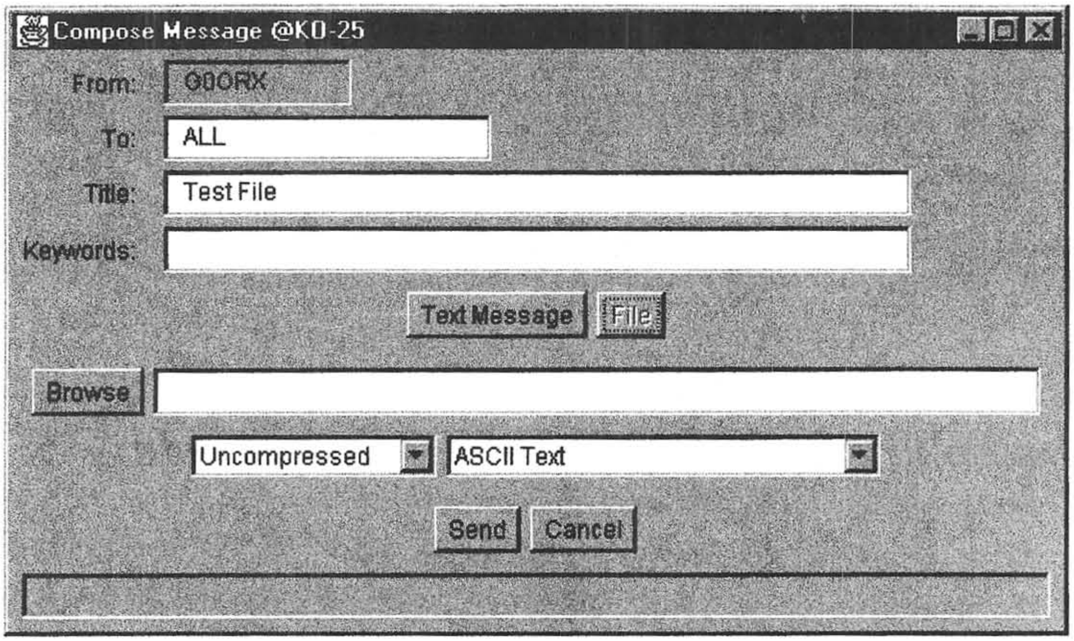

Fig 4: Message Composer Window - File

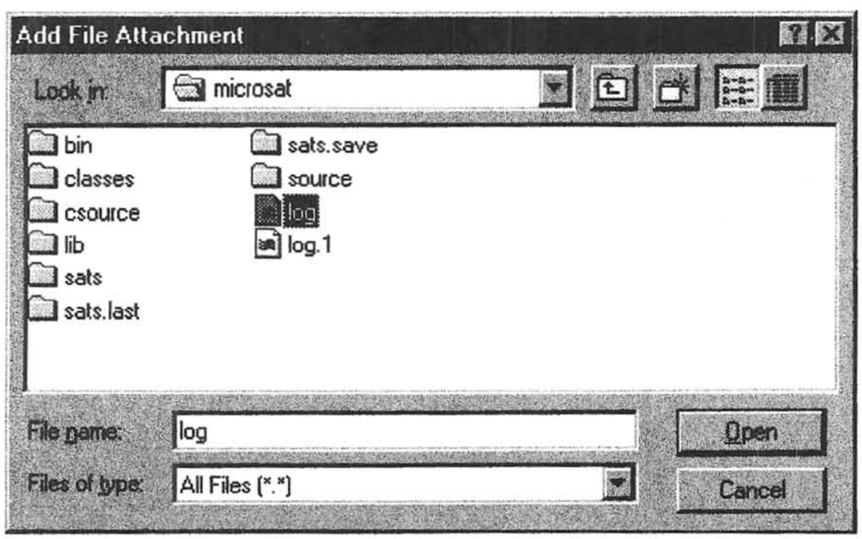

Fig 5: File System Browser

EIS Image Viewer.

Several of the satellites have onboard CCD cameras to take pictures of the earth. Currently KitSat-B (KO-25) is taken images.

There are 2 cameras, one takes a wide-angle image and the other a narrow-angle image zoomed in and centred on the wide-angle image. The images are identified in the directory with a source address of EIS (Earth Imaging System) and the file name of either KBIWxxxx (wide-angle) or KWINxxxx (narrow-angle).

If you select a downloaded EIS Image from the directory window, a popup window will be displayed with the decoded image displayed in it along with the date and time the image was taken and the calculated latitude and longitude of where the ground track was at that time.

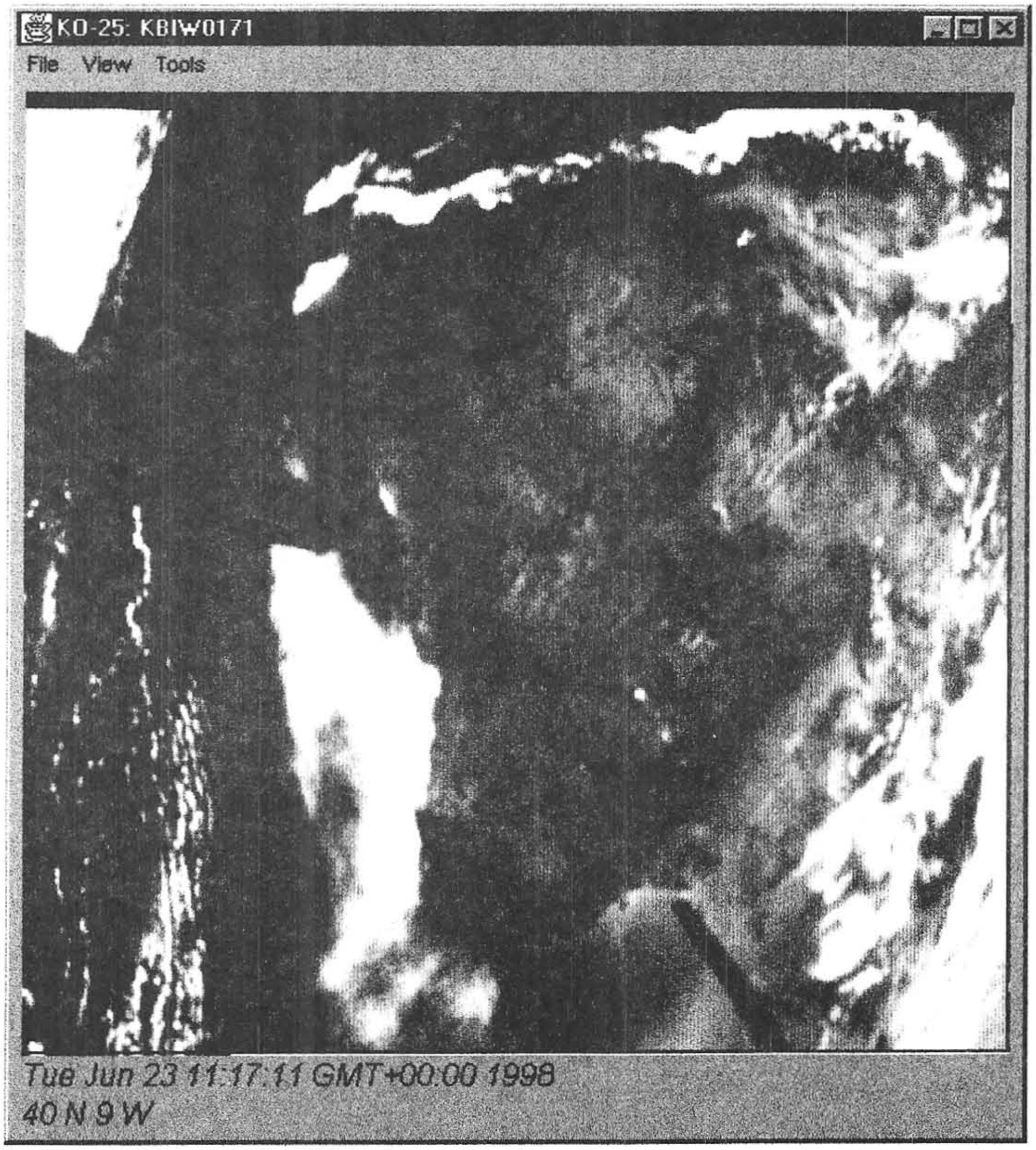

Fig 6: EIS Image Window

EIS Image manipulator.

Clicking on the Tools menu will bring up the Image Manipulation tool. This allows you to:

- Adjust the brightness of the image.
- Rotate the image.
- Contrast Stretch the image.
- Edge Enhance the image.

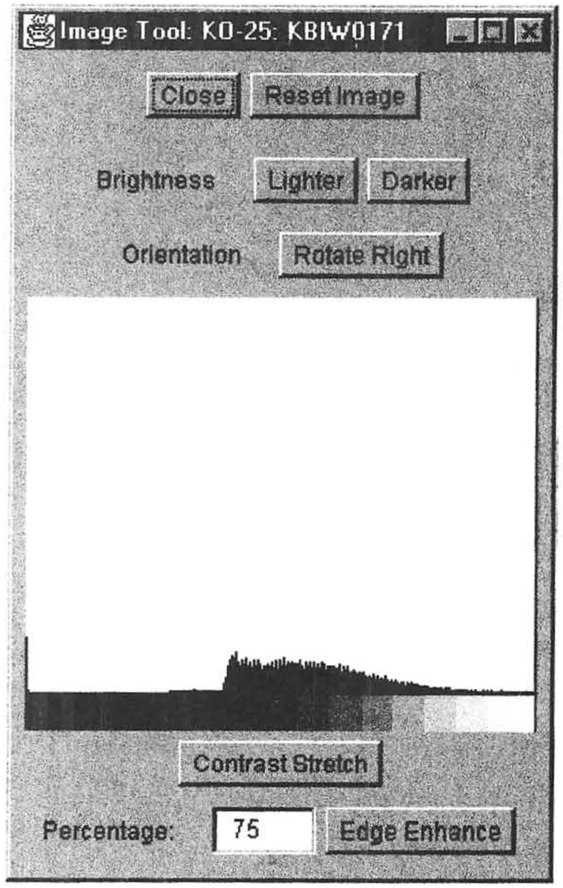

Fig 7: Image Manipulation Tool

To contrast stretch an image, you select the range of pixel values using the left and right buttons of the mouse to select the range of pixel values from the histogram to be stretched across the full range of grey scale values.

This can be useful to enhance images that have a lot of the pixel values grouped in a small range of values.

The Edge enhancement feature performs a convolution algorithm on the image to determine where edges are and to lighten or darken pixels around them to bring out the edge details. The Percentage value defines the percentage weighting to give to the centre pixel of a 3x3 block of pixels.

Results of running the Edge Enhance algorithm.

Fig 8: Edge Enhanced Image

Current/Future Developments.

- Move to JDK 1.2.
- Move to Java Comm Library to replace custom interface to serial/parallel ports.
- Move to Java 2D to replace custom image manipulation algorithms like edge enhancement.
- Configurable protocol modules for different satellite to allow support for weather satellites and other protocols such as P3D telemetry.
- Graphical User Interface for configuration.
- Ability to move messages to sub directories for filing.
- New message indicator.
- Multi-file zip file support.
- Printing.
- Automatic element update from satellite file.
- More buttons on Graphical User Interface to supplement menus.
- TNC mode switching.

Want to help?

If you are interested in helping to develop this software package, let me know what areas you are interested in.

Trade Marks.

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An Omni-Directional Antenna for Receiving Mode-J, LEO Satellites

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1 Introduction

In the first part of this paper, we analyze the performance that can be expected from using an omni-directional, full-wave-loop, turnstile antenna. This antenna consists of two perpendicular loops in phase-quadrature with a small reflector underneath. The antenna analyzed is similar to the "eggbeater" sold by a well-known manufacturer. The major advantages to this type of antenna are that there is no need to "point" it using azimuth/elevation rotors and there is no need to switch polarization.

In the second part of this paper, we present the design of an easy-to-build version of this type of antenna. This design uses specially shaped loops that allows a direct feed to 50-ohm coax with no phasing or impedance matching lines.

2 Performance Analysis

In this section, the expected down link signal-to-noise ratio is calculated at several elevation angles for the modulation modes available on FO-20 and KO-23. This includes CW, SSB, 1200 bps BPSK, and 9600 bps FSK. While not an exhaustive list, these satellites are representative of most mode-J satellites and the resulting performance data can be easily used to predict the performance for other satellites.

2.1 Antenna Characteristics

This antenna consists of two perpendicular loops in phase-quadrature with a ½ wavelength diameter reflector underneath. A drawing of the antenna is shown in Figure 1. EZNEC[1] was used to model it to obtain the radiation gain patterns. EZNEC was also used in the design phase to calculate the loop dimensions and reflector spacing.

This antenna is horizontally polarized and is omni-directional within about 1 dB in the azimuth plane. The calculated elevation pattern when mounted at a height of 40 feet above ground is shown in Figure 2. While the maximum gain is shown to be an impressive 8.77 dbi, the pattern consists of many thin lobes with deep nulls between the lobes. The thin lobes are the result of the ground reflection. All turnstile antennas have this type of pattern over ground.

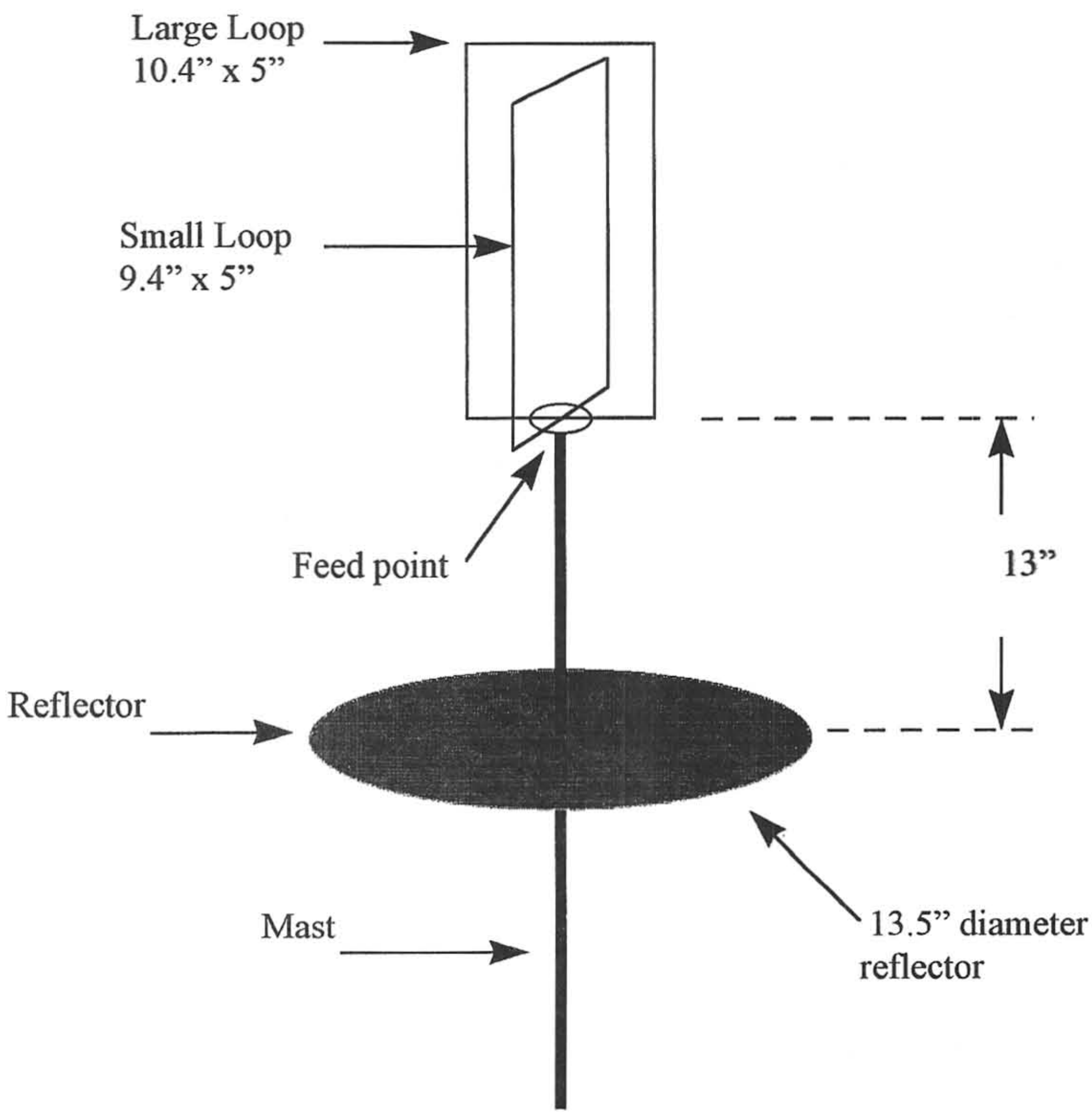

Figure 1
Antenna Design

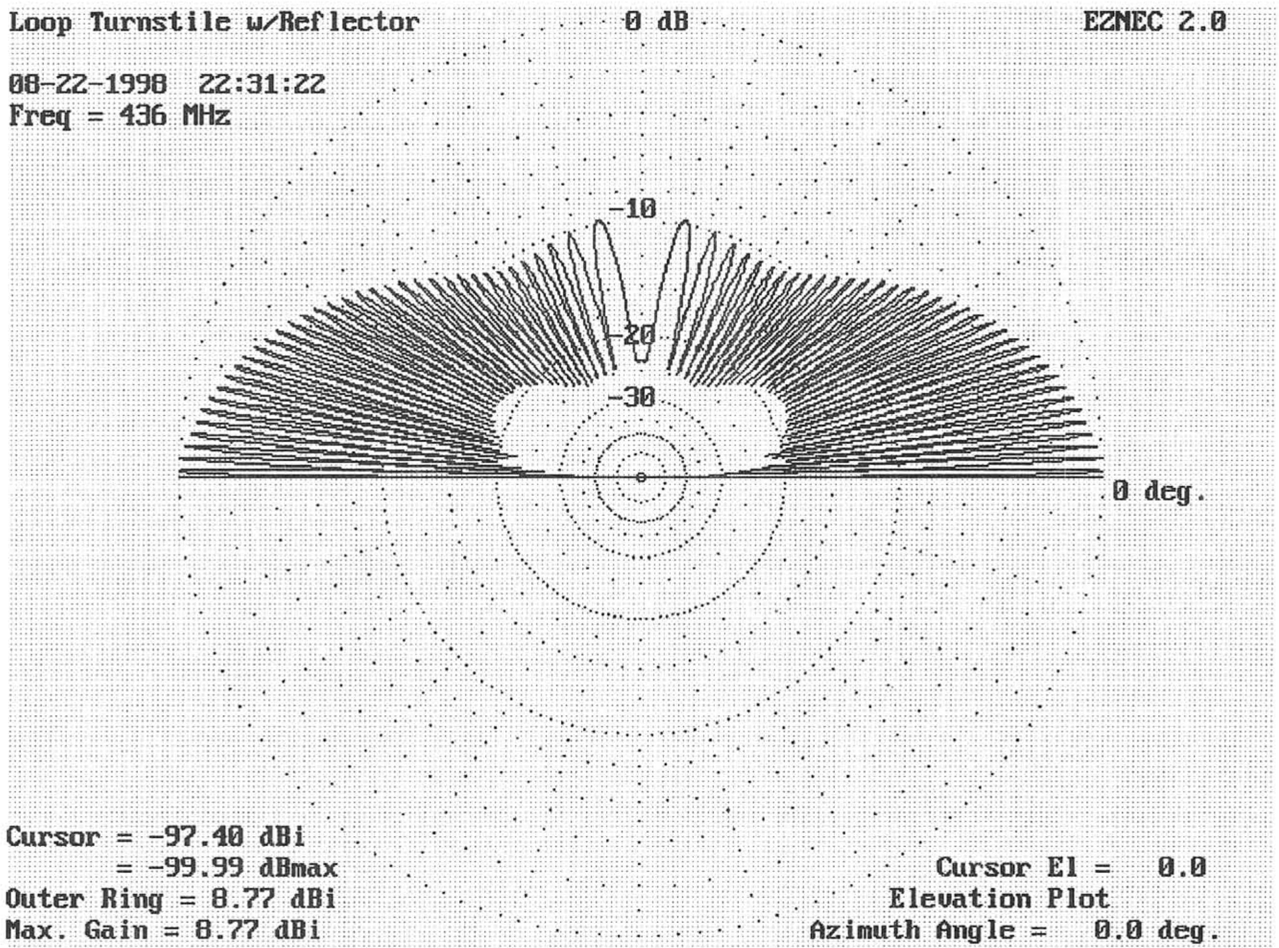

Figure 2
Elevation Pattern

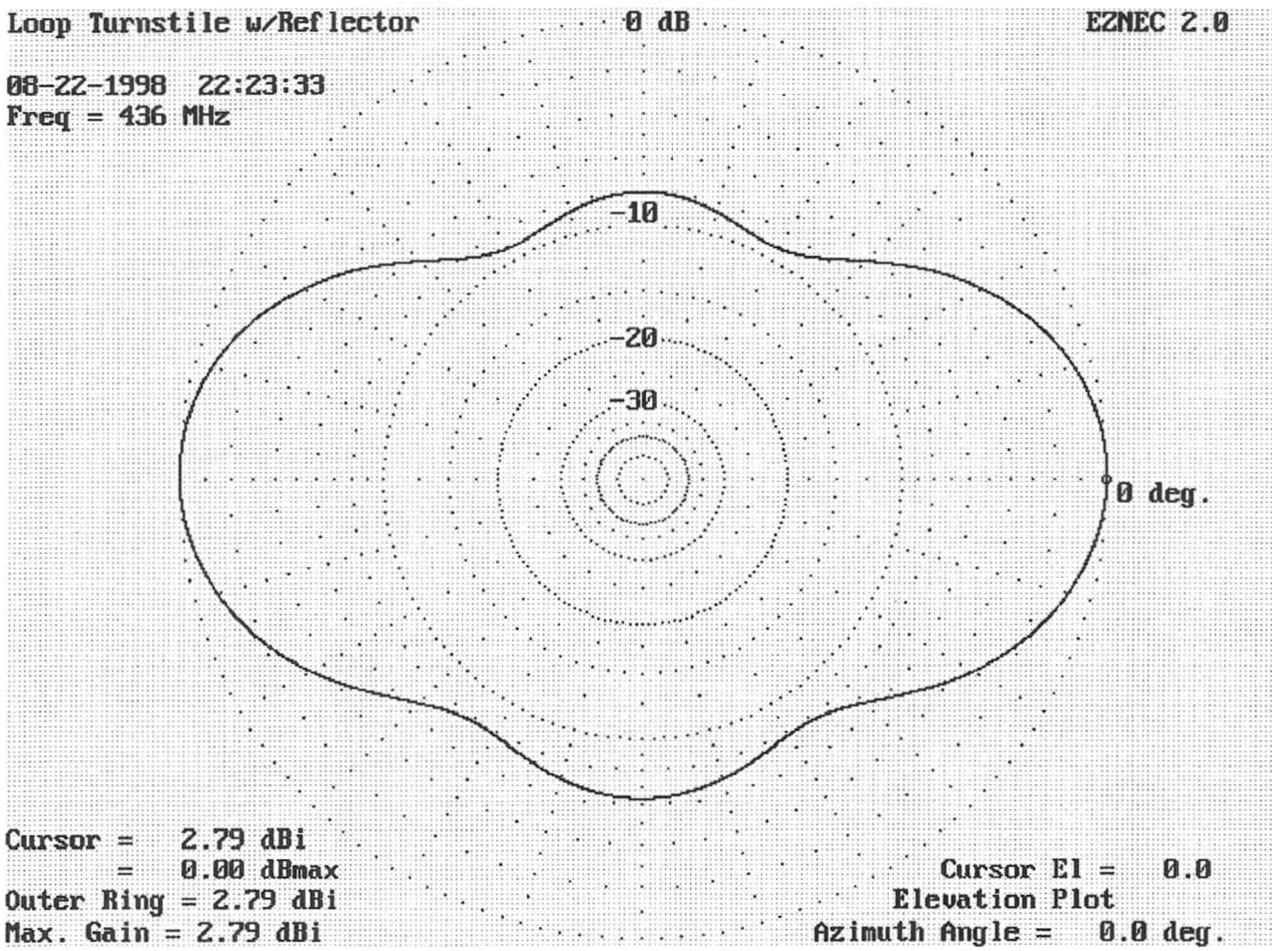

Figure 3
Free-space elevation pattern

In real life, due to effects such as multi-path, the effective gain is less than this calculated maximum and more closely follows the average gain over a small angle. We have estimated this by using the free-space pattern, shown in Figure 3, and adding 3 dB to account for the ground reflection. The resulting elevation gain pattern is summarized in Table 1.

Elevation Angle degrees	Gain (dBi)
0	5.8
5	5.8
10	5.5
15	5.1
30	2.9
45	-.8
60	-3.3
75	-2.7

Table 1
Antenna Pattern
Summary

2.2 Satellite Characteristics

The FO-20 and KO-23 satellites were selected for analysis because they are fairly typical of the current mode-J satellites. FO-20 has an analog transponder and a 1200 bps digital transponder. KO-23 has a 9600 bps, digital transponder. Characteristics for the satellites were obtained from the AMSAT-NA web site[2]. Note that since the author was unable to obtain the current operating transmitter power or antenna specifics for KO-23, 2 Watts and 0 dBic are estimated values based on the information available.

Satellite	Apogee	Perigee	CW Beacon	Analog Tx Power	Digital Tx Power	Antenna Polarization	Antenna Gain
FO-20	1745 Km	912 Km	60 mW	2 W PEP	1 W	circular	4 dBic
KO-23	1300 Km	1300 Km			2 W	circular	0 dBic

Table 2
Satellite Characteristics

2.3 Receive System Characteristics

In order to provide a meaningful analysis, we assume receive system performance that can reasonably be expected of an amateur satellite station. Thus good, but not state-of-the-art, practices are assumed. For example, a receive pre-amp with .9 dB noise Figure is assumed to be mounted at the antenna. While better pre-amps are available, they are expensive and not commonly used in amateur satellite stations.

The assumptions for receive system characteristics are summarized in Table 3 below.

System Noise Figure	.9 dB
CW bandwidth	500 Hz
SSB bandwidth	2500 Hz

Table 3
Receive System Characteristics

2.4 Receive System Noise Temperature

The received noise power comes from two sources, noise from the receive system, and noise picked up by the antenna. Our .9 dB noise-figure pre-amp, mounted at the antenna, gives us an equivalent noise temperature of 67K. We assume an average sky temperature of ~150K.[3] Approximately half the noise picked up by the antenna is from the warm earth (~290K) and half is from the sky. This gives us a total system noise temperature of 287K.

The noise power is a function of the receive bandwidth used and so depends upon the type of modulation used on the down link. The noise power is easily calculated using:

$$N\ (dBm0) = 10\ \mathrm{Log}\ (b\ T_{sys}\ BW)$$

Where:

N = noise power in dBm0
b = 1.38×10^{-20} (Boltzman's Constant)
T_{sys} = System Noise Temperature (Kelvin)
BW = Receive System Bandwidth (Hertz)

2.5 Received Signal Power

The signal power received at the antenna depends on the power transmitted by the satellite, the free-space path loss, and the effective gain of the satellite and ground station antennas. We ignore losses from the atmosphere and ionosphere at 436 MHz since they are generally small.

On an analog transponder, the power transmitted by the satellite depends on the number of users. Based on FO-20's 100KHz transponder bandwidth, and the author's operating experience, 5-10 simultaneous transmitters would seem to be a reasonable assumption. To be conservative, we shall assume 10 simultaneous transmitters.

Since the satellites have circularly polarized antennas but the receive antenna is horizontally polarized, we must subtract 3 dB from the antenna gains to account for the polarization mismatch.

2.6 Signal to Noise Ratio Analysis

For each satellite and down link modulation type, we calculate the expected signal to noise ratio at a variety of elevation angles. For analog modes we calculate the received signal power and the received noise power and subtract. For digital modes, we calculate the Eb/No ratios and express them in dB. The results for FO-20 at perigee and apogee and for KO-23 are shown in tables 4,5 and 6.

Elevation Angle (Degrees)	CW (Beacon) SNR (dB)	SSB SNR (dB)	Eb/No (1200 bps) (dB)
0	15.4	13.7	23.8
5	16.7	15.0	25.2
10	17.8	16.1	26.3
15	18.7	16.9	27.1
30	19.5	17.8	28.0
45	18.1	16.3	26.5
60	17.0	15.2	25.4
75	18.4	16.7	26.8

Table 4
FO-20 at Perigee

Elevation Angle (Degrees)	CW (Beacon) SNR (dB)	SSB SNR (dB)	Eb/No 1200 bps (dB)
0	12.4	10.6	20.8
5	13.3	11.5	21.7
10	14.0	12.2	22.4
15	14.5	12.7	22.9
30	14.6	12.9	23.0
45	12.8	11.0	21.2
60	11.5	9.7	19.9
75	12.8	11.1	21.2

Table 5
FO-20 at Apogee

Elevation Angle (Degrees)	Eb/No (9600 bps) (dB)
0	12.2
5	13.2
10	14.1
15	14.8
30	15.2
45	13.6
60	12.3
75	13.8

Table 6
KO-23

2.7 Discussion

As can be inferred from the tables, this simple antenna provides fairly good performance on analog modes. The signal to noise ratio, while not always "armchair" copy levels, generally will allow Q4 or Q5 copy even at relatively low elevation angles.

For the 1200 bps digital mode, the SNR is high enough to allow excellent copy over most of a satellite pass.

At 9600 bps, the SNR is marginal. While some copy should be possible, reliable operation does not appear likely given the assumptions used in the analysis. A satellite in a lower orbit with more transmit power may be usable. This is an area where some experimentation is in order.

Of course these results depend on a clear line-of-sight to the horizon. This means that the antenna should be mounted as high as possible and above trees, buildings and other obstacles. The minimum usable elevation angle is largely dependent on the height of the antenna relative to its surroundings.

3 Antenna Design

In this part we review the theory of operation and provide the overall design. A major design goal was to allow the antenna to be easily constructed.

3.1 Theory of operation

For a turnstile antenna to operate properly, the currents in the two radiating elements must differ by 90 degrees. Traditionally, this is accomplished by using a quarter-wave phasing line. A better approach, however, is to make the elements "self-phasing." That is, the element impedance is designed so that when they are fed in parallel, the current in one leads by 45 degrees and the current in the other lags by 45 degrees.

In order to accomplish this, we design one of our loops for an impedance of 50 + j50 ohms and we design the other for 50 – j50 ohms. When we tie the loops together, the impedance presented to the feed point is 50 ohms resistive but the currents in the loops are in-quadrature. This eliminates the need for any phasing lines and also the need for any impedance matching lines thus making construction substantially simplified.

To prevent the coaxial feed line from skewing the current in the loops, we do need a 1:1 BALUN. This is easily accomplished by running the coax through a stack of 4, FT50, low-permeability (u=10) ferrite toroidal cores to make a W2DU style BALUN at the feed point. Note that this antenna was designed for receiving only.

A ½ wavelength diameter reflector is used to increase the gain at low elevation angles. This helps improve the DX capability on analog modes. It is installed 13 inches (approximately ½ wavelength) below the bottom of the loops. The reflector improves the free-space gain by approximately 1.5 dB at 0 degrees elevation.

This design is for the frequency range from 435MHz to 437MHz which covers all current 70 cm band amateur satellite down links.

3.2 Loop Design

The loops are made of ½" wide by 1/8" thick aluminum trim bar. This is readily available at neighborhood hardware stores. Do not substitute any other material as the dimensions are critical for proper self-phasing action. The loop design details are shown in Figure 4.

At the ends of each loop, there is a hole for a #8 bolt drilled ¼" from the loop end. The ends of the loops are rounded in a ¼" radius. This detail is shown in Figure 5.

3.3 Feed Design

The loop feed is also important for proper operation. The loops must be fed in-phase to the extent possible. One end of the big loop and an end from the small loop are connected together with a short "L"-shaped jumper made from 2, #8 ring-lugs and a very short piece of #14 copper wire. The other end of the big loop and the other end of the small loop are similarly connected with the short jumper. It does not matter which ends are tied together. A 2-foot length of RG-58 coax is used to feed the loops. The coax center conductor and shield are each soldered to the center of a jumper using the shortest leads possible. Four, Amidon, FT50 (u=10) ferrite toroidal cores are slipped over the coax close to the loop ends to form the BALUN. The other end of the coax is directly connected to a low-noise pre-amp.

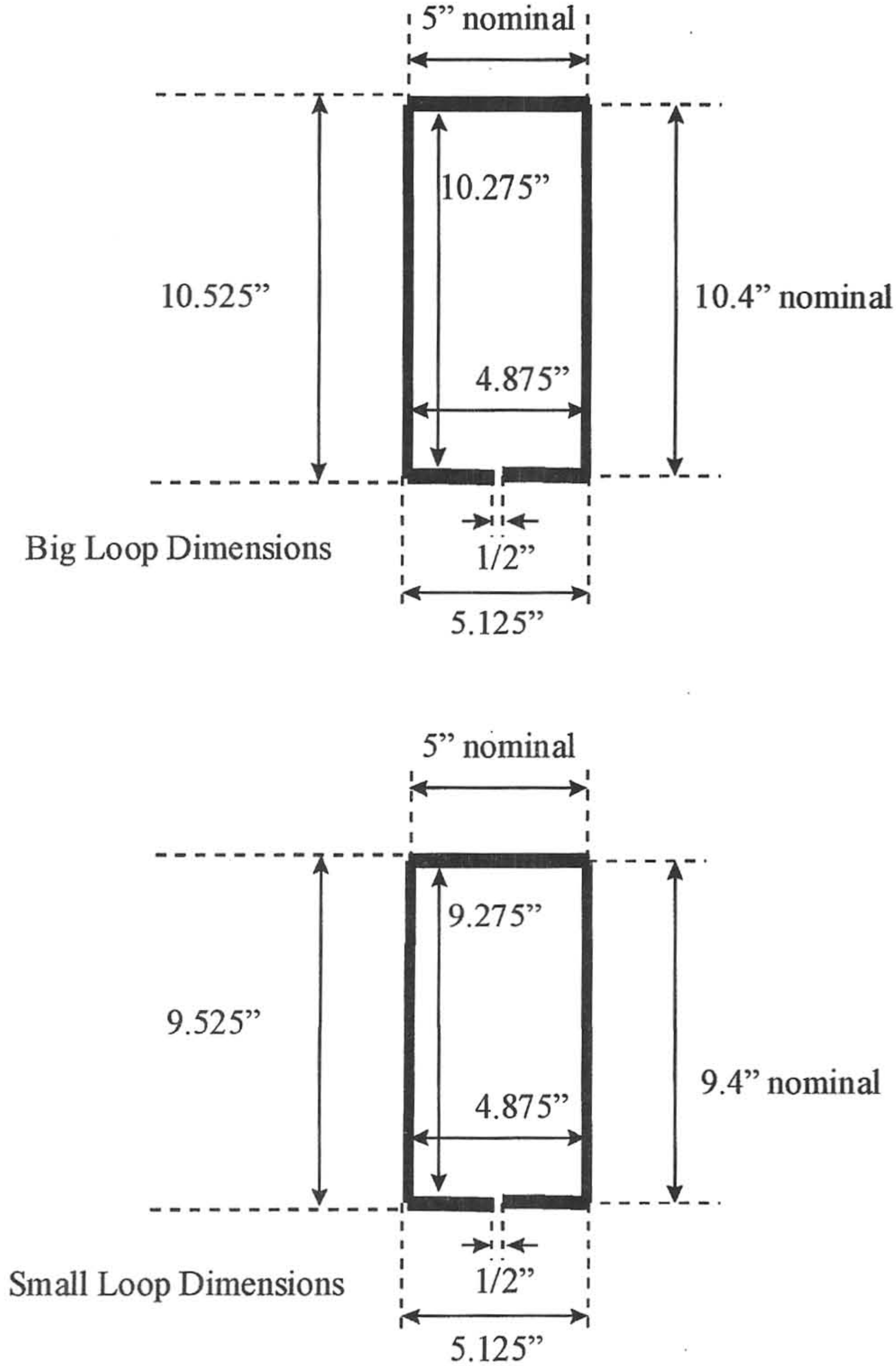

Figure 4
Loop Design Details

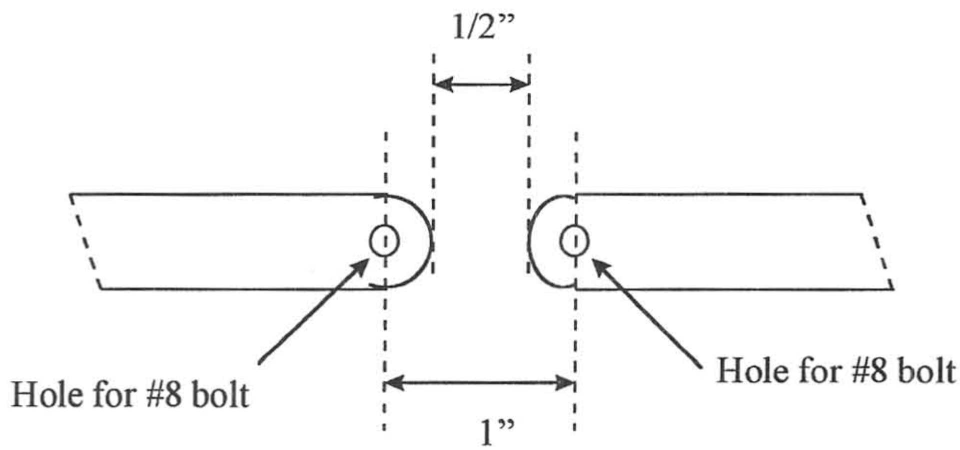

Figure 5
Loop Ends Detail

3.4 Reflector Design

The reflector is made of perforated aluminum sheet metal. This is not very critical. If desired, 8 radials could be used instead with only a minor decrease in gain. The reflector is a 13.5" diameter circle with a hole in the center for the mast. It is mounted 13" below the bottom of the loops.

3.5 Assembly

The overall design can be found in Figure 1. PVC pipe components were used in the prototype to mount the loops to the mast. The loops were bolted together at the top with a nylon nut, bolt, and spacer to add mechanical strength. The exposed nylon was painted to prevent UV deterioration.

4 Conclusion

In the first part of this paper we analyzed the performance to be expected using a full-wave-loop turnstile antenna. This antenna is omni-directional and thus does not need to be pointed via azimuth/elevation rotors. Since it is horizontally polarized, it does not need polarization switching for RHCP Vs LHCP satellites. The calculations predict that this antenna should provide good performance when used on current satellites in CW, SSB, and 1200 bps digital modes while 9600 bps operation appears marginal.

In the second part of this paper, a novel design for this antenna was presented that does not require the traditional phasing or impedance matching lines. This dramatically simplifies construction. In order to verify this design a prototype was constructed by the author. The SWR was measured and found to be about 1.2:1 over the design frequency. The prototype was then used for on-the-air tests to check on the performance. While only analog transponder operation was tested, the antenna has performed as predicted.

The author welcomes comments, suggestions, and/or questions. He can be reached via email at aa2tx@amsat.org.

5 References

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[1] Lewallen, Roy. EZNEC V2.0. Software, calculates antenna radiation patterns.

[2] AMSAT-NA on the Internet at: www.amsat.org

[3] Kraus, John D. 1986. *Radio Astronomy,* 2nd Edition. Cygnus-Quasar Books, Powell, Ohio.

SETI on the Cheap: Affording the Ultimate DX

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Abstract

Since the cancellation of the NASA SETI (Search for Extra-Terrestrial Intelligence) program in 1993, the world's radio amateurs have embraced the quest for the ultimate DX. Project Argus, the nonprofit SETI League's coordinated all-sky survey, went on the air in 1996 with five small amateur radio telescopes in Europe and North America. That network has now grown to over sixty active stations on six continents. But if we are to achieve the dream of real-time, all-sky coverage, we're going to need 5,000 such microwave receiving stations scattered around the globe -- about as many participants as now use ham satellites.

The greatest barrier to amateur SETI participation is financial. The typical amateur radio telescope costs about as much as an EME station or top-of-the-line OSCAR rig. The Argus network, however, will only achieve full strength when SETI stations are as affordable, and as accessible, as amateur optical telescopes are today. This paper explores technological initiatives which we hope will make that possible. We conclude that the $500 SETI station is not that far away.

Introduction

Perhaps ET is not calling home at all. Maybe he's calling us. As widely reported in the amateur radio literature, the Search for Extra-Terrestrial Intelligence (SETI), once a multi-Million dollar NASA venture, is now in private hands. In 45 countries on six continents, hundreds of dedicated experimenters, many of them radio amateurs, are now using their backyard SETI stations to seek out that elusive needle in the interstellar haystack. You can't buy a radio telescope at your local Radio Shack store. But if you're reasonably handy with tin-snips, know which end of the soldering iron is the handle, and have a few hundred (to a few thousand) dollars to invest, you too can join the search for our cosmic companions.

What We're Looking For

Our Earth is surrounded by a telltale sphere of artificial radiation, now extending out to about 50 light years, and still traveling outward at the fastest possible speed: the speed of light. This radio, TV, radar and microwave pollution is readily detectable to any local civilization which has radio astronomy. We figure that some of the countless beings living in the light of distant suns may also pollute their radio environment, and we stand a reasonable chance of detecting them.

But don't expect to tune in alien "I Love Lucy." Interstellar signals will be so weak that our eyes and ears will never recognize them. The most we can hope for is order in the cosmic chaos, patterns which could not have been produced by any natural mechanism which we know and understand. These hallmarks of artificiality are evident to computers, and it is your home computer which will sift through the cosmic static in search of ET (see **Figure 1**).

Now, where on the dial should we look? It's highly unlikely that ET honors the FCC's band plans, so we can only guess as to their likely channel lineup. There may well be many good frequencies for SETI, but what they have in common is their ability to pass unimpeded through the interstellar medium. Since the space between the stars is most transparent in the microwave spectrum, that's where we'll start our search.

Satellite TV is broadcast in the microwave region. So are radar, cellular telephone, and much of Earth's telecommunications relay signals. There are also navigation signals from the swarm of Global Positioning Satellites surrounding our planet. If we're going to seek out weak signals from the stars, we need to search in the gaps between our own transmissions. One such interesting gap (there are others) is the resonant frequency of hydrogen atoms, 1420 MHz, and many amateur and professional SETI stations start out there.

What You'll Need: The Antenna

Although other configurations are sometimes used, the hands-down favorite for snagging alien photons is the parabolic reflector, or dish antenna. A 3 to 5 meter diameter dish (that is, 10 to 16 feet) is just about the right size to stand a reasonable chance of SETI success. The classic C-band backyard satellite TV dish is ideal. These have high gain, narrow beamwidth, work over a wide range of frequencies, and are readily available for next to nothing. And if you're a satellite TV fan, chances are you already have one.

Around the country millions of TV viewers are upgrading to Ku-band Direct Broadcast Satellite (DBS) reception. Its half-meter dishes are very appealing. That leaves millions of C-band BUDs (Big Ugly Dishes) sitting around gathering rust. Many SETI enthusiasts have found neighbors anxious to have these eyesores taken off their hands (see **Figure 2**).

You can use your satellite TV dish to focus 1420 MHz energy, but not its C-band feedhorn. Plan on building or buying a larger tin can to capture these longer wavelengths. A commercial feed which will directly replace your TVRO horn (see **Figure 3**) can be purchased for around $150. If you want to use your BUD to watch TV and do SETI in the background, you can mount your SETI feedhorn next to your TVRO one, and multi-task (see **Figure 4**).

What You'll Need: The Preamp

The purpose of a preamplifier is to take an impossibly weak signal from space, and turn it into merely a ridiculously weak one. You used one of these for satellite TV (it may have been called an LNA, LNB, or LNC), but it probably doesn't work on ET's channel. Fortunately, radio astronomy preamps for the desired frequency range (see **Figure 5**) are readily available from a number of sources. Price varies from about $50 for a kit preamp up to perhaps $200 for the top of the line, assembled and tested one. The preamp mounts directly to the feedhorn with a coax connector, and drives the coaxial feedline which runs inside to your receiver. You'll also need to run juice from a 12 volt power supply up to your preamp, either through the feedline or on a separate length of lamp cord or speaker wire.

What You'll Need: The Receiver

Once you've amplified your weak alien signal, you need to break it down to audio components which your computer can analyze. This is the job of a microwave receiver. The earliest amateur SETI stations employed ham radio's old standard, the venerable Icom model R-7000 microwave scanner, and its successors, the IC R-7100 and R-8500 (see **Figure 6**). These highly capable receivers are still a good bet if you can find them, though their $2000-plus price tag exceeds the cost of all other parts of your SETI station combined. Fortunately, some less costly alternatives are just beginning to emerge.

For years ham radio operators have been converting microwave signals down to frequency regions which their existing short-wave receivers can process, and SETI is no exception. For just over a hundred dollars in kit form (twice that if already assembled), you can today buy a downconverter which will shift the most interesting radio astronomy frequency down to the popular two meter band, for reception in your existing VHF rig (see **Figure 7**). And by adding a $100 2-meter SSB receiver kit to that downconverter (see **Figure 8**), enterprising experimenters have been building their own complete SETI receivers for a small fraction of the cost of commercial units. We hope such packaged special-purpose receivers will come on the market as manufacturers recognize the market potential of SETI.

Lately, receivers-on-a-card are all the rage. For example, Rosetta Labs of Australia makes its WinRadio scanning receiver card (**Figure 9**) to plug directly into the motherboard of your personal computer. Though the stock WinRadio is not ideal for the SETI application, look for Rosetta Labs and other vendors to come out with special purpose SETI receiver cards in the months ahead. Integrated directly into the computer (see below), they promise ever improving performance at significantly reduced cost.

What You'll Need: The Computer

The purpose of the SETI computer is to run the software which recognizes ET amid the cosmic din. A good bit of number-crunching power is required. The technique is called Digital Signal Processing, or DSP, and is the one part of the SETI task which has grown in power at an amazing rate. Raw computer horsepower seems to double every year or so, which means today's home computers are 1000 times more powerful than those of just ten years ago, and 1,000,000 times more powerful than those of two decades past!

We start by breaking down the receiver's audio into ones and zeroes, using a circuit called an Analog to Digital Converter, or ADC. There's a very capable ADC in your garden-variety $29 sound card, and that's what most of us are using.

DSP software comes in a variety of flavors, with the most popular varieties being shareware for the DOS and Windows environments. As for the computer on which this software runs, a high-speed Pentium is nice, but not essential. Many a SETI enthusiast has used the old 486, which his or her Pentium recently replaced, as a dedicated signal processing machine. And a few SETIzens have even resurrected their old 386 and 286 machines for DSP use. The rule seems to be, any computer you can get your hands on will be more sensitive than your own eyes and ears, in separating the alien wheat from the cosmic chaff.

Putting It All Together

All the bits and pieces can be a tad intimidating, but you won't be going it alone. The SETI League is the world's leading grass-roots SETI organization, with hundreds of members in dozens of countries on six continents, and growing. Our website (http://www.setileague.org/), technical manuals and volunteer regional coordinators have already helped hundreds of individual experimenters to get their stations up and running, and stand ready to assist you as well. SETI league members come from all professions, educational levels and walks of life. We share a common curiosity about the beyond, as well as a conviction that we can make a difference.

What We've Heard So Far

Organized SETI has been going on for nearly forty years. About once or twice a year, we detect something strange, a signal which we just can't explain away. Unfortunately, none of these tantalizing candidate signals has yet proven conclusive. SETI demands the most stringent level of proof, if it is to answer the fundamental question which has haunted humankind since first we realized that the points of light in the night sky are other suns: Are We Alone?

The granddaddy of all SETI candidate signals was detected at the Ohio State University radio telescope in 1977. It is universally known as the "Wow!" signal, after the word scribbled in the margin of the computer printout when investigator Dr. Jerry Ehman first noticed it (see **Figure 10**). The "Wow!" was even mentioned in an episode of Fox TV's "The X-Files." After over 100 follow-on studies, the "Wow!" has never repeated. But today's amateur SETI stations are *just as powerful* as the Ohio State facility was twenty-one years ago, when the "Wow!" was detected. Thus it is our hope that, when enough private SETIzens are up and running, the next "Wow!" will prove less elusive.

We've already had a few close encounters. The SETI League's *Project Argus* search of the heavens went on the air in April 1996, initially with just five observing stations (our overall plan calls for 5,000). Only three weeks later, two radio amateurs in England detected the anomaly seen in **Figure 11**. At first glance, this seemed to be just the sort of signal we'd expect from Beyond. It turned out to be a classified military satellite -- beyond Earth to be sure, but hardly the ET we were seeking.

Our next interesting signal (see **Figure 12**) came from the 1.3 Watt beacon transmitter aboard the Mars Global Surveyor satellite, clearly detectable at several million kilometers from Earth. Then there are the "wigglers" (**Figure 13**) which have tantalized amateur and professional SETI researchers alike. After initial excitement and considerable troubleshooting, hams have determined these to be radio frequency interference (RFI) from the very computers we have been using to do the signal analysis!

Such detections give us ample encouragement that our systems are up to the task not just of alien detection, but also of recognizing a genuine signal amid an increasingly polluted RF environment. Now all we need is enough participants around the world, coordinated through the Internet, so that no direction in the sky shall evade our gaze. You can join the global net we're stretching to snag that slippery fish in the cosmic pond.

Finding Out More

Check out The SETI League, Inc., a membership-supported, nonprofit educational and scientific organization, on the Internet at http://www.setileague.org/. Leaders in the privatized search for life in space, The SETI League offers technical support, coordination, books, conferences, and a host of related activities for the aspiring SETIzen. Our extensive web site (over 1300 documents totaling more than 42 MBytes, and growing every week) is aimed at the dedicated amateur radio astronomer who's willing to learn. There you'll find sources for the hardware and software discussed above, along with hundreds of pictures showing how others have put their stations together. We have a Technical Manual to help you build, and even our own songbook for those who wish to sing SETI's praises. For membership information, email your postal address to join@setileague.org, or drop us a line at PO Box 555, Little Ferry NJ 07643 USA. We Know We're Not Alone!

Sources

Item	Model	Supplier	Address	Telephone
Feedhorn	1.4 GHz Cyl	Radio Astronomy Supplies	190 Jade Cove Drive Roswell GA 30075	(770) 992-4959
Antenna	Classic 12	Paraclipse Inc.	PO Box 686 Columbus NE 68602)	(402) 563-3625 (tel) 564-2109 (fax)
Preamp	SETI-LNA	Down East Microwave	954 Route 519 Frenchtown NJ 08825	(908) 996-3584 (tel) 996-3702 (fax)
Receiver & LO Kits	R-2 SETI LM-2	Kanga US	3521 Spring Lake Dr. Findlay OH 45840	(419) 423-4604
Converter	1420-144 RX	Down East Microwave	see above	see above
Software	FFTDSP	Mike Cook	501 E. Cedar Canyon Rd. Huntertown IN 46748	(219) 637-3399
	SETIFOX	Daniel B. Fox	911 E Miller Dr. Bloomington IN 47401	(812) 336-8238
PC Receiver	WinRadio	Rosetta Labs	222 St.Kilda Road St. Kilda 3182, Australia	(+61) 3 9525 5300 (tel) 3 9525 3560 (fax)

Acknowledgment

Major portions of this paper first appeared as "Search for ET From Your Own Backyard!" in *Satellite Times* 4(7):10-14, May 1998.

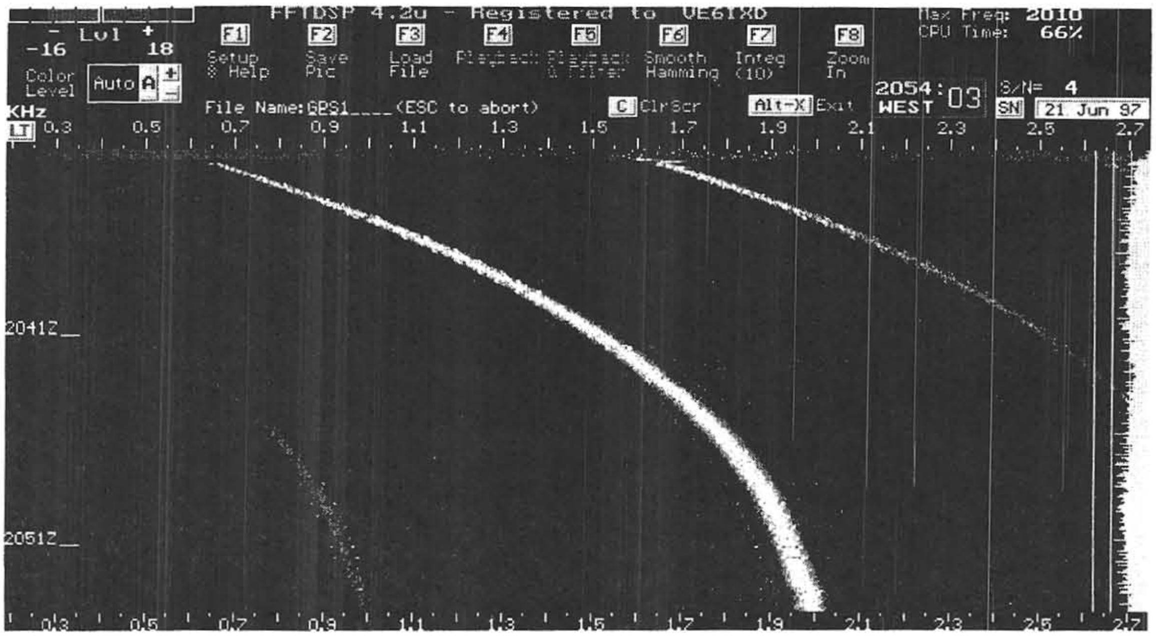


Figure 1
GPS interference received by SETI League member VE6IXD

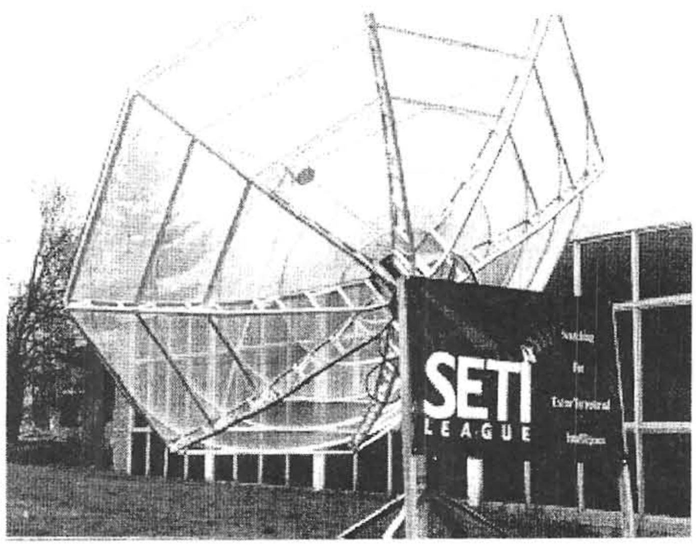


Figure 2
12-foot Paraclipse satellite TV dish at SETI League headquarters in New Jersey

Figure 3
N6TX with Radio Astronomy Supplies feedhorn for the 1420 MHz SETI band

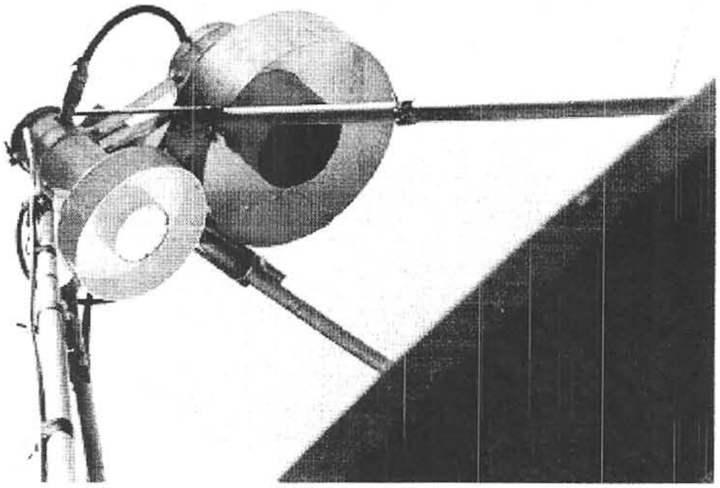


Figure 4
SETI League member EA3UM uses multiple feedhorns on his SETI dish

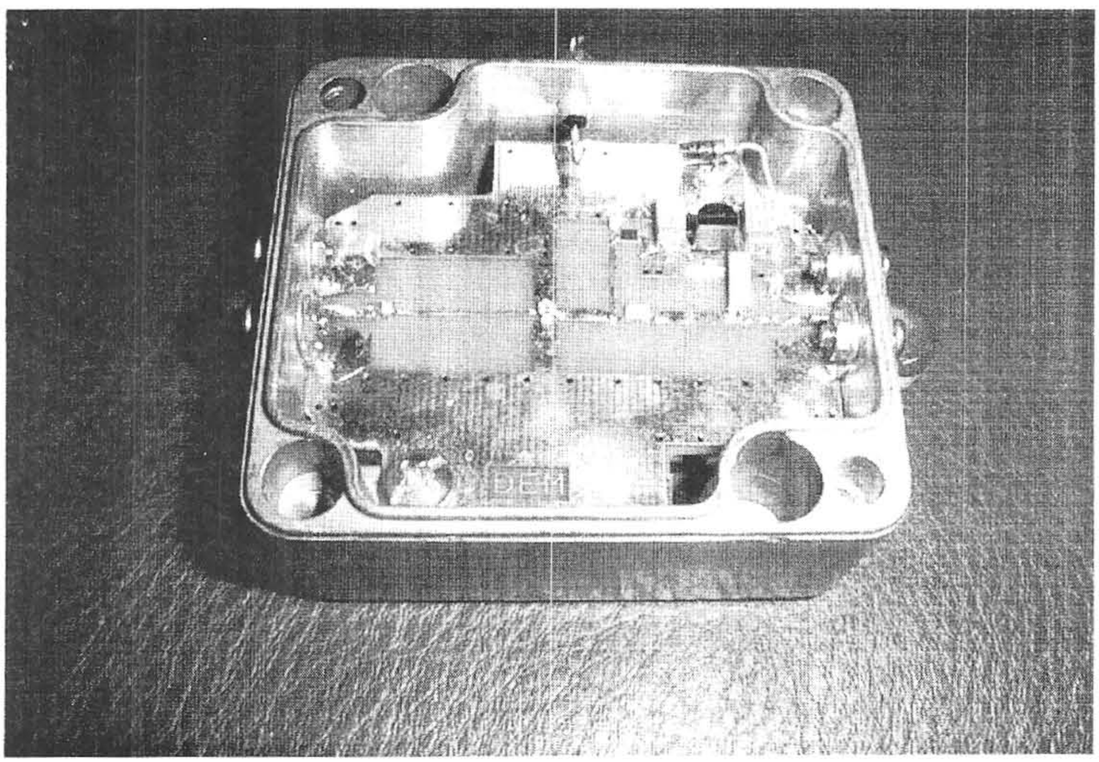


Figure 5
SETI League GaAs MMIC preamp, offered commercially by Down East Microwave

Figure 6
Icom R-7000 microwave receivers have long been popular for SETI

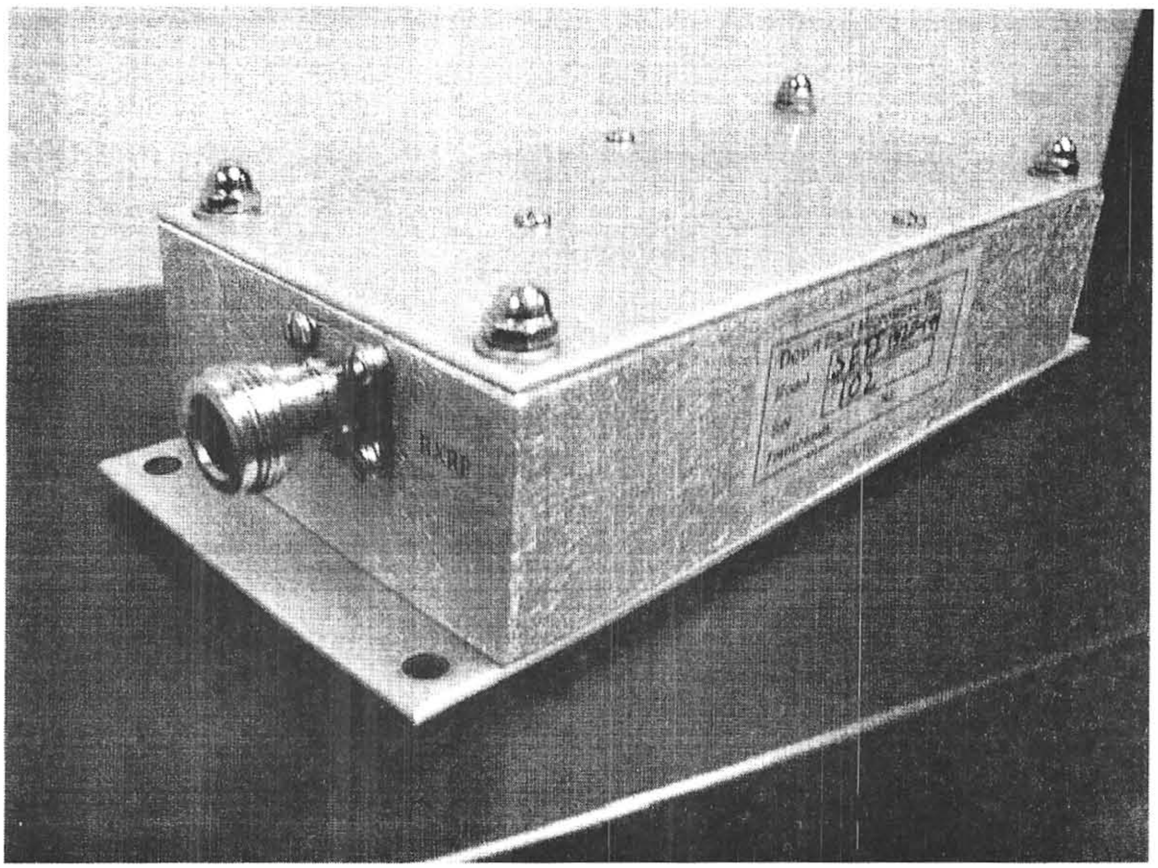


Figure 7
1420 to 144 MHz downconverter, offered commercially by Down East Microwave

Figure 8
Combining the Down East Microwave converter kit with a Kanga R-2 direct-conversion 2-meter SSB receiver kit makes an ideal SETI receiver, for under $400

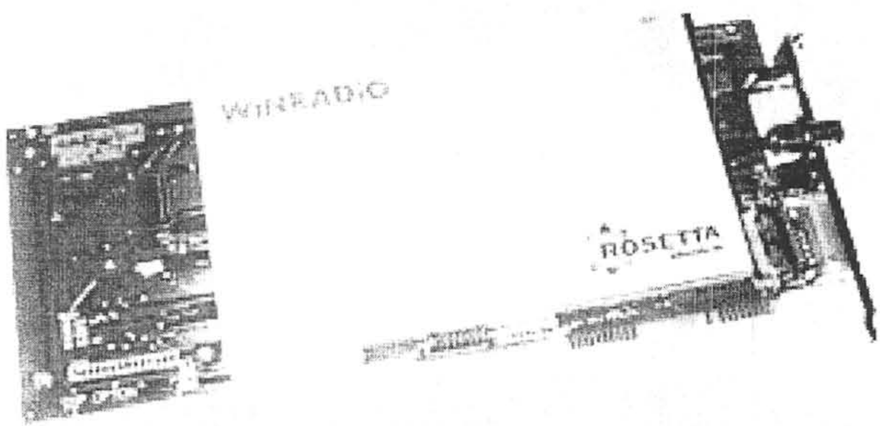


Figure 9
The popular WinRadio cards from Australia plug directly into your SETI computer's EISA bus, for digital signal processing of extra-terrestrial signals

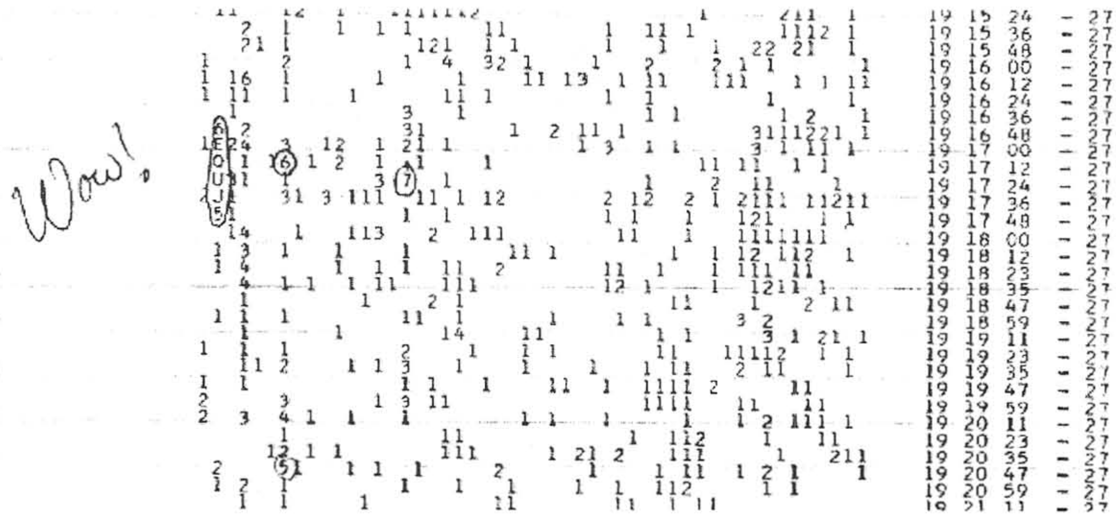


Figure 10

The enigmatic Ohio State University "Wow!" signal, captured by the "Big Ear" radio telescope on 15 August 1997, remains unexplained after more than 20 years of follow-on analysis. This is the best known of dozens of SETI candidate signals.

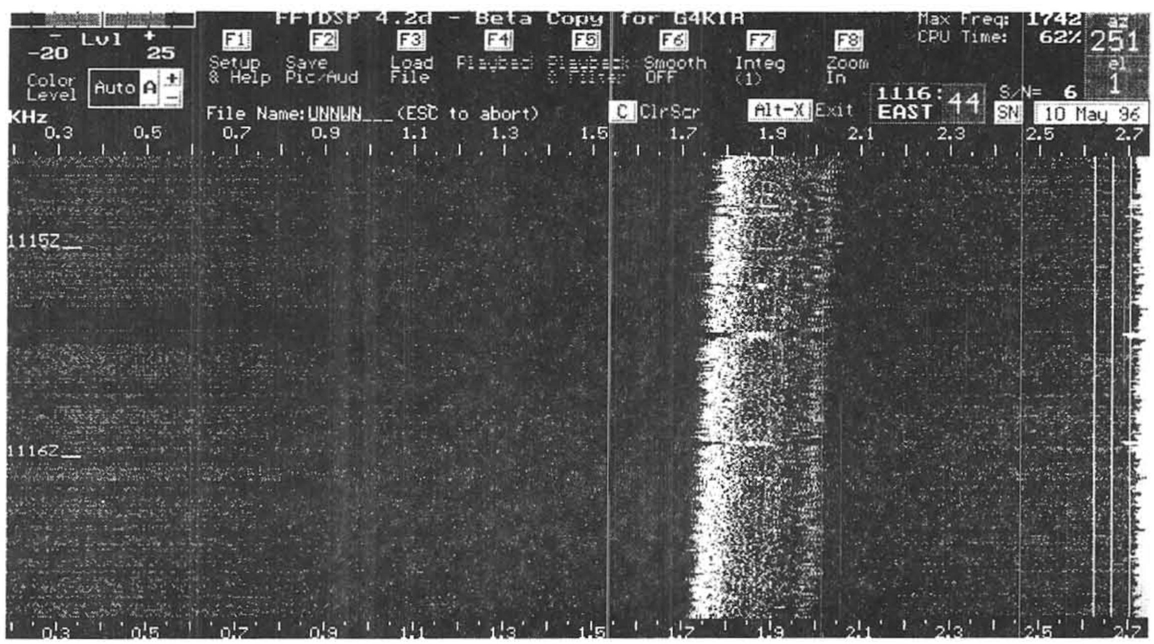


Figure 11

The SETI League's own first "Wow!" signal was received by G4KIR on 10 May 1996, just three weeks into the Project Argus sky survey. It turned out to be interference from a classified military satellite.

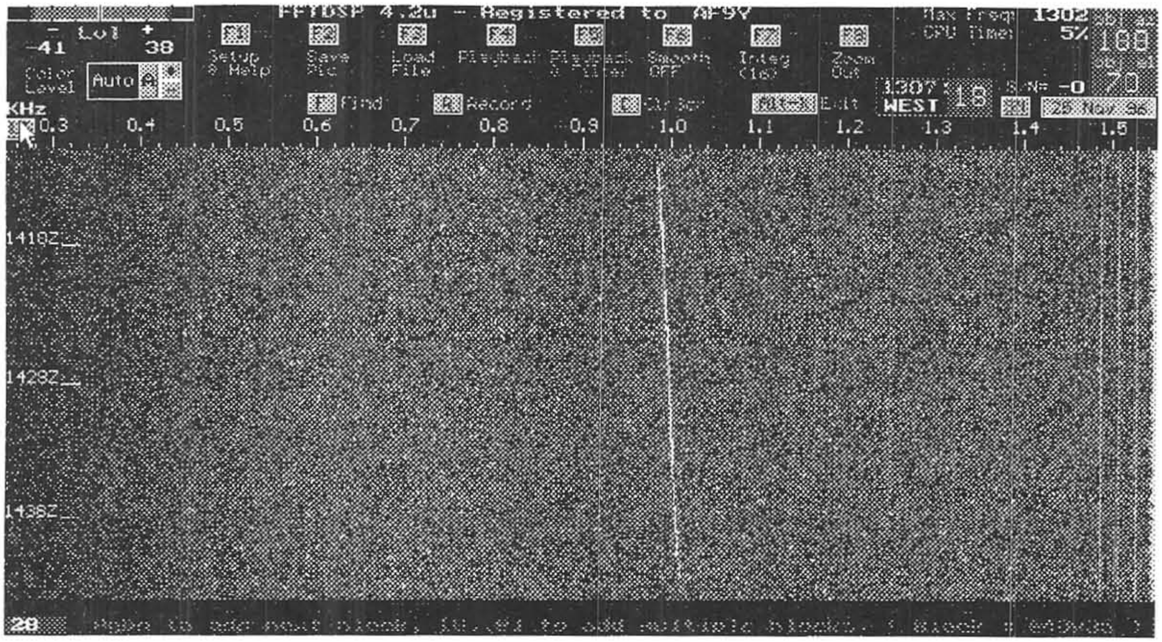


Figure 12
AF9Y and others were easily able to detect the 1.3 Watt omnidirectional beacon from the Mars Global Surveyor spacecraft, at over 5 million km from Earth.

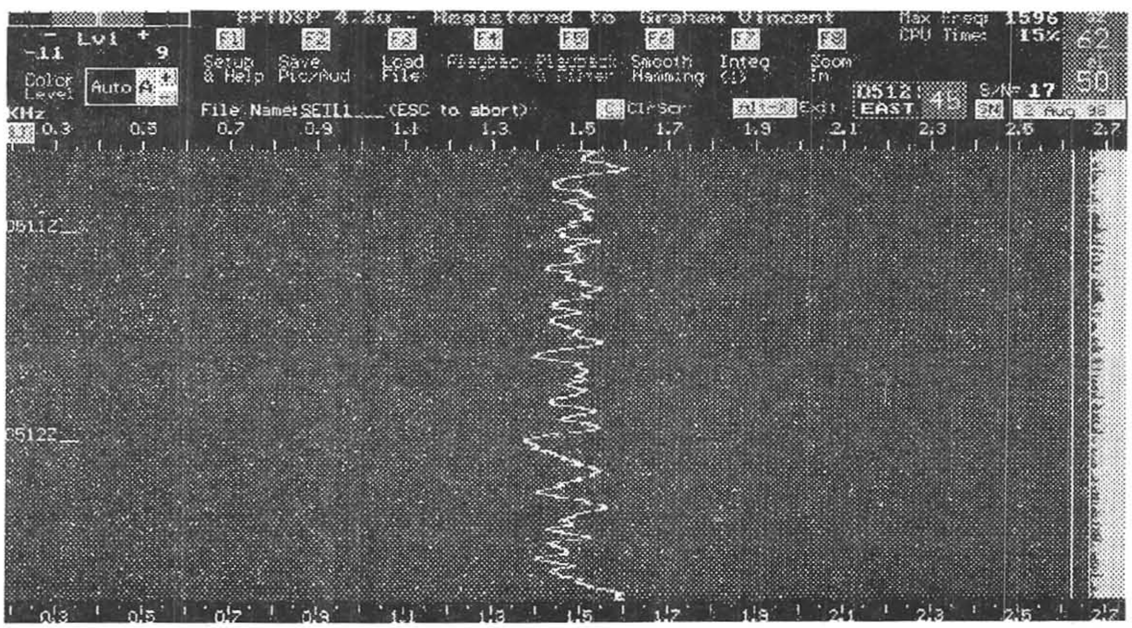


Figure 13
"Wigglers," a common form of interference to SETI stations, appear to originate within the very computers used to perform real-time Digital Signal Processing.

TRAKNET,
An AMSAT Mobile Satellite System

Bob Bruninga, WB4APR
115 Old Farm Court
Glen Burnie, MD 21060

There are two distinct advantages of the global nature of satellites which cannot be easily met with terrestrial systems: wide-bandwidth-point-to-point and mobile applications. With the availability of telephone, cable, and the internet to link *HAMS* at fixed sites to each other routinely, we are wasting a lot of potential of our very valuable AMSAT resources by ignoring mobile applications.

HAM radio is on the move. Many hams only have time to play radio while mobile, and similarly, whenever a ham contemplates a long trip, his HAM radio is high on the packing list. Although many dream of taking along an HF mobile to play with and to report their progress back home, the $1000 to $2000 investment is just too much of a risk. Two meters is fun, and can bring emergency aid, but it just doesn't provide the nationwide coverage that is needed for the mobile *HAM* traveler far from home, the offshore boater, or first-response teams arriving in a disaster area. In many cases, just a brief position/status report or message is all that is needed to assure the health and welfare of the traveler or to summon assistance or alert other comms channels.

What we need is a new perspective which takes advantage of some very unique capabilities to exploit a small portion of our AMSAT on-orbit capacity to the mobile requirement. This capability *exists* and the hardware is already in orbit! There are several AMSAT's that have *very easy* uplinks which can be hit from the mobile using only a 2 meter 25 watt FM mobile radio. The ubiquitous radio that *everyone* has... These satellites are the under utilized 1200 baud Pacsats.

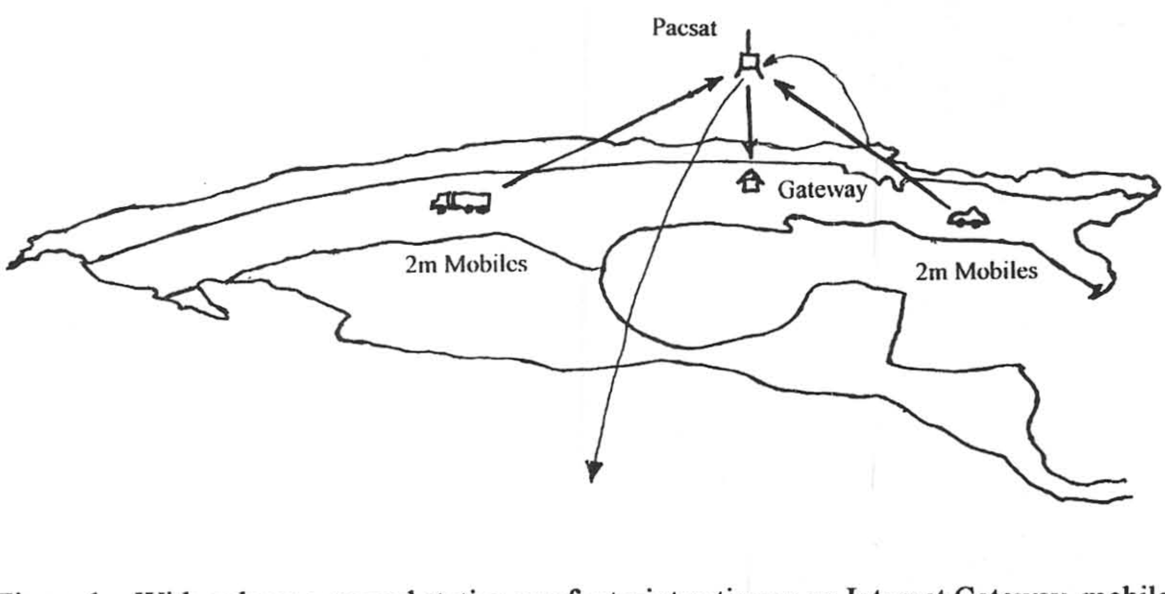


Figure 1. With only one ground station per footprint acting as an Internet Gateway, mobiles over half of the USA can be tracked per pass. Mobiles transmit using conventional 2 meter FM mobile radios and standard AX.25 APRS packets. A slight ($3) mod to any TNC can configure it for the required manchester uplink of the 1200 baud Pacsats.

UPLINKS: Lets look at the 1200 baud PACSAT uplinks. These uplinks are unique for several resons that make them ideal for the mobile environment as follows:

1) A 2m omni antenna has a 9 dB advantage over a similar 435MHz omni due to the 3 times larger antenna aperture

2) There is no tuning or tracking required on the uplink since the doppler on 2m is less than 3 KHz.

3) Any 25 watt mobile 2m FM rig can be used as the transmitter

4) Many TAPR-2 compatible TNCs can be modified for the uplink for $3

5) World Wide Coverage

6) NO software or hardware on-orbit modifications to the satellite!

Reportedly stations running as low as 7 watts into an indoor omni antenna have reported success with the 1200 baud PACSATS. This means that even back-packers with an HT and handheld gain antenna could get emergency or priority traffic into a Pacsat... from anywhere on earth! Figure 2. shows one pass of the APRS/MIR experiment on 11 March 1998 when the MIR digipeater was activated for APRS UI packets. It shows how easily a space based digipeater can be used for station position/status and brief messaging.

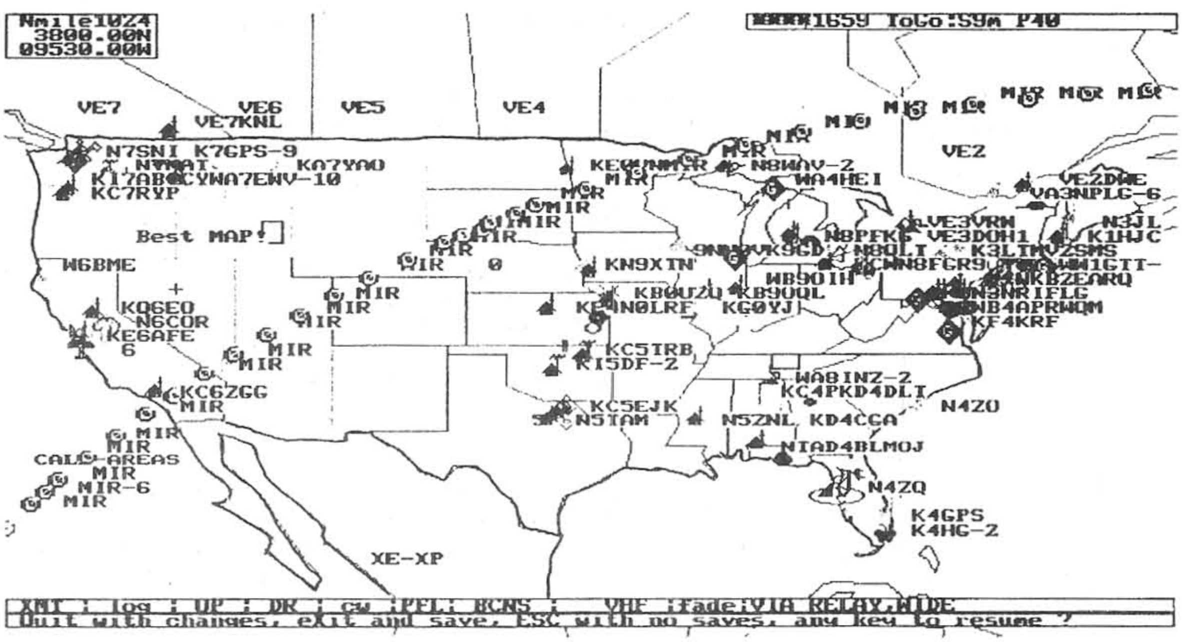


Figure 2. This is an APRS screen capture after the third pass of MIR during the special APRS-MIR tests conducted on 11 March 1998. It demonstrated the potential of using an amateur satellite digipeater for relaying mobile position/status/messages.

DOWNLINK: OK, so the 2m UPLINK is easy and anyone can do it, so what about the downlink? This is not so easy. The path loss omni-to-omni is 9 dB worse, the satellite is only transmitting a watt or so for another 13 dB worse performance, plus it *requires* doppler tuning, a $250 PACSAT modem and a $1000 all mode UHF receiver! In most cases, all successful Pacsat stations use high gain antennas and automatic tracking to make up for the more than 22 dB performance difference on the downllink. This is not something that most operators will want to add to their mobile. But what if the mobile application did not need to receive data via satellite, but only send it?

TRAKNET: The combination of EASY uplinks, *minimum* downlinks, and an application that often only needs an uplink via satelite, such as the mobile position/status report is the whole idea behind TRAKNET. Only a few automated downlinks are needed every 1000 miles or so to receive the mobile data and to provide it into a nationwide system of linked ground stations. These ground stations relay the mobile position/status reports onto local mobile vehicle tracking channels and onto the internet. Anyone may access the data live on VHF, HF or via the internet.

Since this idea was first propsed in the May/June 1993 and 1995 issues of the AMSAT-NA Journal, the ground based tracking and worldwide distribution mechanism via the Internet has been fully implemented and is in daily use. This system, called APRServe, was pioneered by Steve Dimse, K4HG, to support the growing worldwide Automatic Position Reporting System, APRS. Thus, TRAKNET is not just a future idea, it is *online now*, awaiting only some more automatic PACSAT dowlink stations.

There are two internet sites for APRServe. If you connect using a WEB browser, you will only see the captured position reports. But if you TELNET to these sites, you will be connecting to a live feed of all packets captured everywhere!

www.aprs.net port 23 serves all APRS packets worldwide
www.aprs.net port 10001 serves all AMSAT/MIR packets.

WORLDWIDE MESSAGE INFRASTRUCTURE: It is important to note that not only can the internet sites feed data directly to on-line users live, but because of the APRS software used by these users while they are logged on, their stations automatically become gateways to all other VHF or HF users that their station sees. Thus we have worldwide mobile communications that is transparent to the users! Here is how it works:

1) Every station logged on to the APRServe sites above, feeds everything they hear on their local VHF or HF nets into the APRServe system.

2) APRServe then removes all dupes and sends it out to ALL logged on users. THus everyone sees everyone and everything. THe bandwidth of the internet is easily able to keep up with this throughput. Even with over a thousand users live, the total bandwidth is still on the order of about 1200 baud average due to the low duty cycle of each stations transmissions in APRS.

3) Now, if in the APRServe stream, the local station sees a *message* addressed to another station that is within RF range, then this station will act as an IGATE and will forward that single message out onto the local RF channel.

Thus any station that is near an active IGATE has transparent two-way message communications with any other similar station anywhere in the world where there are other IGates. It is important to note that this process is completely transparent to the callsigns of the IGates, and thus the mobile user does not need any a-priori knowledge. In the case of TRAKNET, the PACSAT downlink stations just feed any UI packets from the birds into this existing infrastructure just like any other IGate station, and thus the packets are distributed worldwide.

Currently there are automatic feeds of MIR packets, and maybe some DOVE packets, but we still need some PACSAT stations. N3NRU in Pennsylvania is now on line with an automatic PACSAT downlink feeding APRS mobile position reports to the nearest Internet Gateway where they are being distributed nationwide. The following web page at the Naval Academy displays the last 8 passes of MIR downlink:

http://web.usna.navy.mil/~bruninga/aprs.html

But the problem is that we need more sites listening to the PACSATS mostly because setting up an automatic PACSAT ground station is not trivial and the guys who play with the WEB and APRS all day are not the same guys that are necessarily fully invested in PACSAT hardware... All we need are probably 5 stations scattered over the continental USA to implement a reasonable TRAKNET system.

MOBILE STATION: A mobile station consists of nothing more than a typical 2 meter FM radio and a modified TAPR-2 compatible TNC and a laptop or GPS. Optional accessories are a GPS for moving position reports, and a laptop for entering messages. Most modern TNC's will accept the GPS data directly and will transmit the data in a timed packet burst. There is even a tiny handheld TNC's called the APRS Mic-Encoder that includes front panel switches for selecting 1 of 7 pre-canned status messages without needing a laptop to change the status report. The modifications to the TAPR-2 TNC are to simply EXclusive OR the transmit data with its 1200 Hz clock and to filter the result to the Mic input of the radio.

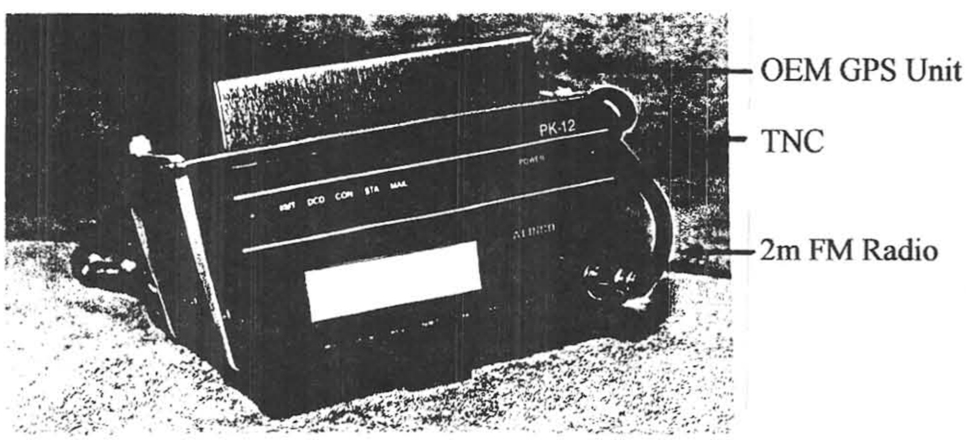
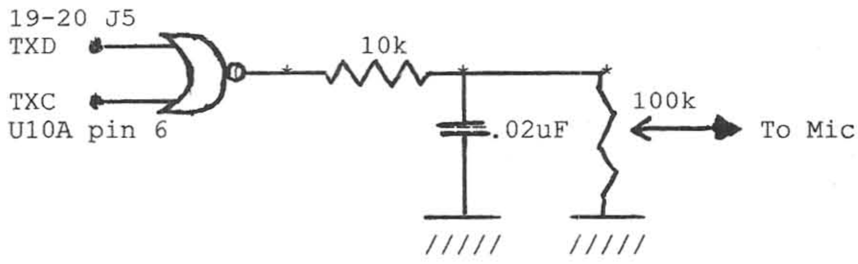


Figure 3. A position tracking mobile needs nothing more than a conventional 2m mobile FM radio, a TNC and a GPS. The TNC transmits the mobiles position report once a minute during an overhead 1200 baud Pacsat pass.

The following circuit will do this with nothing but an 89 cent standard 400 quad 2 input NAND gate connected as an XOR gate or using a single XOR gate out of a 7486 chip. Just connect to the two points shown.



TRAKNET PROTOCOL: The problem with any Amateur satellite is the very low bandwidth available compared to the very large worldwide amateur population. At first glance, the prospect of increasing the number of users on a Pacsat channel by a hundred fold raises lots of red flags in the minds of those stations who already find the 10 minutes of a satellite pass to be too short for any meaningful dialoge. But what if each of these hundreds of new users was limited to only a few seconds per orbit? Then as many as 200 stations per footprint could be tracked. That is the only objective of the TRAKNET protocol, to allow everyone to transmit a few single 1 second position/status reports during the closest point of approach over their location. If only one channel is designated for TRAKNET, then the other 3 channels are free to normal PACSAT use and no ammount of congestion on the TrakNet channel can interfere with existing users on the other three.

APRS/MIR TEST: This capability to share a 1200 baud satellite channel was demonstrated very successfully with a 98% success rate for over 100 stations via MIR during the 11 March 1998 test. To keep the display uncluttered, only one pass out of several is shown in Figure 1.

TRAKNET SATELLITES: There are currently four 1200 baud Pacsats on orbit. One, WO-18 has actively invited UI frame digipeating and leaves DIGIPEAT on most of the time. The problem is that the WO-18 downlink is difficult to receive un-attended due to a spur tone in the middle of the data which makes receiver lock a difficult and manual process. AO-16 has had its digi ON for the last 6 months and welcomes APRS testing when there are no other users logged on. Blind uplink testing, however, is restricted to 145.94 and only on Tuesdays. Other PacSats occasionally have DIGIPEAT turned on, but there is no formal policy. The purpose of this article is to encourage the designation of one good channel as a gathering point for TRAKNET experiments, and then progress can be made and the potential of TRAKNET can be evaluated. Here are the frequency plans of the existing traknet capable PACSATS:

DIGIPEATER	FM Manchester UPLINKS CHANNELS							DOWNLINK
AO-16		.860		.900	.920	.940		437.051
LO-19	.840	.860	.880	.900				437.153
WO-18				.900				437.104
IO-26			.875	.900	.925		.950	435.822

ADVANCED TRAKNET CONCEPTS: Even though TRAKNET is a fully functional system now, using only existing hardware and software, if it became very popular and lives up to its full potential, there are many things that can be done to improve the throughput of the system. Lets define these by phased improvements:

PHASE-1: This is the existing system using existing PACSATS (WO-18 and AO-16) and existing flight software. The only requirement is that DIGI be turned on. This phase can be extended by gaining formal permission to use more of the PACSATS with DIGI on, such as LO-19 and IO-26. Also permission to use the single frequency of 145.900 on all satellites would make mobile operations easier.

MOD-1: UI DIGI only. This change is a simple modification to the Pacsat DIGIpeater software routine to assure that the DIGIpeater only digipeats UI frames. This prevents it from being abused by CONNECT attempts between ground stations or new users. So far, this has not been a problem, and is not expected to be a problem due to the low effeciency of such use.

MOD-2: TRKNET Alias. This step greatly simplifies mobile scheduling by changing the DIGIpeater ALIAS on all of the TRAKNET PACSATS to the generic call of TRKNET. Thus, *any* TRAKNET PACSAT will digipeat *any* mobile position/status report on 145.900. This provides up to 24 different generic TRAKNET passes per day for the mobiles.

MOD-3: DIGI-ALWAYS. Since all packets to be digipeated by the Pacsat could all use the identical digipeater callsign of TRKNET, it is actually not needed. The Pacsat digi could simply be configured to digipeat *any and all* UI frames that it hears on the uplink. This saves 7 bytes per packet for a 10 to 20% channel improvement on the congested uplink.

PHASE-2: Store-and-Forward. The straight digipeater mode for TRAKNET had the advantage of already existing with no on-orbit software changes required. But it also requires a ground station in every footprint worldwide and single downlink errors result in lost data. If the flight software were modified, however, to keep a continuous running buffer for all uplinked UI frames, then several advantages would accrue:

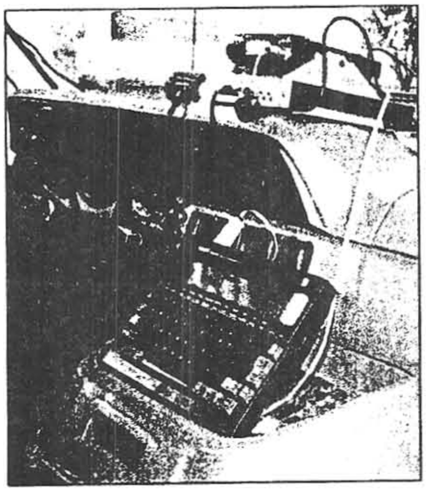
1) Far fewer downlink stations would be needed. Two in North America, and one in Europe, the MiddleEast, Australia, and Japan.

2) The repetitious downlink would assure 100% success on the downlink.

3) Distant, DX and 3rd-world areas would be covered. Uplinks from the most distant regions of the world including the Poles would all appear in the downlink.

Since a complete message or position/status report can easily fit in an 80 byte packet, only a 10 K buffer would support over 120 mobiles. As usage grew, a worst case buffer size would need to be no bigger than about 32K over a full 20 minute USA pass assuming a 33% channel effeciency on the 1200 baud uplink. Plus, a new compressed APRS position format has been incorporated into APRS that reduces the size of a position report packet to only 22 bytes, thus gaining almost 400% in channel capacity!

ADVANCED MOBILES: While the preceeding was written to emphasize the ease of using the PACSATS by anyone for emergency or priority status/position reporting, there is certainly no reason why a full two way PACSAT communications system cannot be added to most mobiles. Omni PACSAT downlinks are possible and the addition of only a modest gain antenna will certainly help. Advantages are the small size of a 6 dB two element UHF antenna and the SHORT cable run found in a mobile. Rather than a $1000 SSB rig, a $90 QRP HF rig and a UHF downconverter could do just as well.



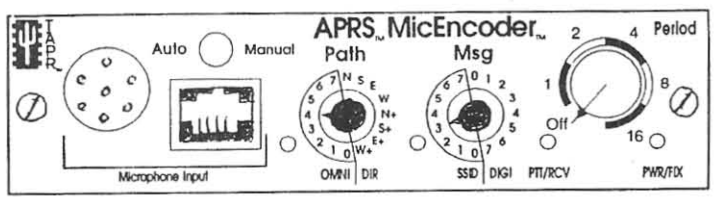


Figure 4. A position tracking and status reporting mobile would need a keyboard as shown here for initiating messages. But a simpler method is to use the front panel switch built into the APRS position reporting Mic-Encoder. The switch permits selection of one out of 8 pre arranged messages without having to have a mobile computer.

CONCLUSION: The advent of the handheld GPS unit for under $150 and vailability of cheap, second hand laptops has brought thousands of mobile amateur radio operators into the world of mobile data. Similarly, the state-of-the-art in automatic PACSAT ground station capability has been improving with many recent software packages to make un-attended automatic ground station possible. And lastly, we have had a system of linked ground stations via the internet capability for over two years! The problem is that these two communities of expertise have so far had little cross-interests. It seems that the time is now to merge these technologies into a new amateur application that takes advantage of the unique capabilities of each and fuels the develpoment of an Amateur Radio Mobile Satellite System.

Nanosatellite Program – A Challenge to AMSAT for Collaboration to Use the Amateur Bands

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Abstract

A program is being funded by the AFSOR and DARPA to provide $100k each for ten universities to build ten nanosatellites (1kg –10kg). They will also provide the launch on the space shuttle on the SHELS launch platform in December of 2000. Teaming of universities, industries and other organizations is highly encouraged. This program provides an exceptional opportunity of OSCAR groups nation wide to support universities in this effort and show them how to do it the low-cost, innovate and faster "AMSAT" way. These nanosatellites could have transponder payloads for use by the amateur community as well as many other experiments that would be useful for future amatuer satellites.

Introduction and Motivation

The Space Systems Development Laboratory at Stanford University is one of a few universities in the United States that has an active university support program for students to build microsatellites and operate them in space. There have been many students and faculty that have interest in such activity, but due to perceived difficulty establishing such program these programs never been too successful.

During the Micro-Nanotechnology for Micro-Nanosatellites Workshop sponsored by the Air Force Office of Space Research (AFOSR) and the Defense Advanced Research Project Agency (DARPA) at Albuquerque, New Mexico on April 21, 1998, there was a call from the organizers of the conference to find ways to do more space experiments with smaller satellites at a lower cost. There was a challenge given to the workshop sponsors that they should consider funding a university nanosatellite development program and provide launches for these satellites.

The AFOSR and DARPA responded to this challenge and at the meeting established the Nanosatellite Program that would provide funding of $100,000 each to ten universities starting in October 1998 to build ten nanosatellites for launch at the end of the year 2000. As seen below, the nanosatellite is defined as weighting 10 Kg or less.

Program Definition

The following is a broad area announcement of this program published in June 1998.

Special Topic: University Nanosatellite Program

Points of Contact:
Howard Schlossberg, AFRL/AFOSR, (202) 767-4902
Joe Mitola, DARPA/STO, (703) 243-9830
Maurice Martin, AFRL/VSS (NRC), (505) 853-4118
Dr. Bill Clapp, AFRL/VSD, (801) 626-7272

This topic is only open to U.S. colleges/universities or consortia of universities. AFOSR and the Defense Advanced Research Projects Agency (DARPA) are jointly funding up to 10 research projects centered on the design and demonstration of nanosatellites. (Satellites sized 1 - 10 kg). These grants of $50k/year over two years will be awarded for universities to design, assemble, and conduct on-orbit experiments for these satellites. AFOSR and DARPA encourage universities to pursue creative low-cost space experiments to explore the military usefulness of nanosatellites. Experiments in formation flying, enhanced communications, miniaturized sensors, attitude control, maneuvering, docking, power collection, deorbit at end of life, or other on-orbit demonstrations of advanced space technology are of particular interest. Universities are encouraged to secure additional funding, hardware, and use of facilities from industry or government agencies and to identify the dollar value of these resources in the proposal.

Universities interested in payload development only are encouraged to team with universities who will be proposing satellite fabrication. Consortia of universities may submit proposals for multiple satellites but must have at least as many universities as the number of satellites proposed. Proposals should address the specific satellite research issues to be addressed and the anticipated satellite capabilities, and provide a plan for completing the project. A single university may submit multiple proposals and depending on the teaming arrangements may be part of more than one award. The proposal should provide specifics related to mission objectives, research issues to be addressed, estimated size and weight, experience in space research hardware fabrication, partners, key personnel, and a student management plan. Proposals should be less than 10 single-sided pages, be submitted by 30 Sept 98.

It is highly desirable that a large number of the research projects result in launch-ready nanosatellites. The satellites should be ready for launch not later than Sept 2000. Universities may arrange their own launches or may design to an AFRL-funded DoD or NASA shuttle launch on or after Dec 2000. Satellite dimensions must accommodate ten satellites and the deployment structure fitting within a shuttle hitchhiker payload volume of 54" x 42.5" x 24." Example satellite envelopes are 20" x 19" x 7.5" or 25" x 12" x 10.5", but other dimensions will be accommodated to the extent possible. Satellites should comply with shuttle design restrictions and withstand launch environments of both the shuttle and standard small launch vehicles. The operational life of the satellites may be any length of time greater than 1 month, but a design life of at least 4 months is highly encouraged. AFRL will supply the deployment structure and separation systems, payload integration, and assist with other system level concerns such as securing frequency clearances, clarifying launch environments, etc.

AFOSR and DARPA are interested in proposals from university coalitions to design, fabricate and prepare for launch sets of three nanosatellites capable of demonstrating formation flying, on-orbit local area communication networks, and other distributed satellite capability. It is desired that the satellites have hardware that permits 1) accurate relative position determination, 2) thrust capability for precise orbital insertion for formation flying (minimal thrust expected after insertion), 3) local communications with at least one satellite having ground link capability, and 4) on-board memory for storing both uplinked commands and experiment data for downlink. Universities are encouraged to find low-cost and innovative ways of implementing the above functions or may propose alternate means of maintaining formation such as tethers or something other than active attitude and orbit control. Proposals need only address a level of on-orbit collaboration deemed feasible and may identify specific hardware to be provided by the government. Universities are not limited to the ideas presented, and may request assistance from AFRL, AFOSR, and DARPA in developing and implementing operational concepts of interest to DoD. These three satellites may have additional technology payloads as size, weight, and power allow. To facilitate teaming among universities and with government space laboratories and industry, AFRL is sponsoring a web site at www.vs.afrl.af.mil/nanosats/ with university points of contact and general information regarding individual programs. This site will also contain information of general interest regarding launch environments, ideas for experiments, free hardware, technical interchange meetings, etc. Additions or corrections to the website may be emailed to martinr@plk.af.mil.

Launch Opportunity

One of the suggested launch environments, and separation system may be the Shuttle Hitchhiker Experiment Launch System (SHELS) launch platform. The SHELS system shown in Figure 1 is a non-canister ejection system for deployable payloads up to 400 lbs. that mounts to Orbiter sidewalk on shelf system. It provides deployment velocities of 1.5 ft/sec to 3.0 ft/sec (adjustable). The tip-off rate is less than 3 deg/sec and provides more volume to payload than traditional hitchhiker ejection system. The total volume allowed is 54" x 42.5" x 24" (approximate).

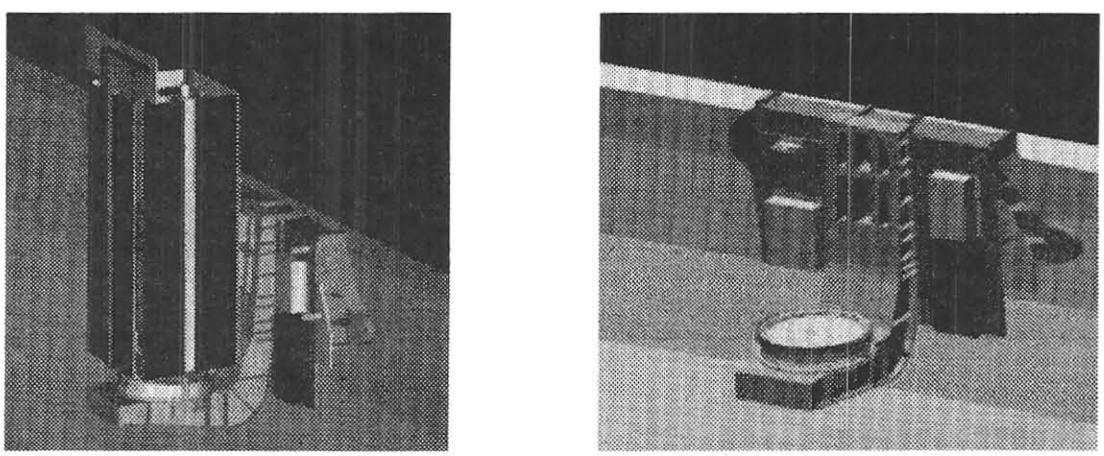


Figure 1 SHELS Launch Platform on NASA Space Shuttle

It has a simple marmon band and pyrotechnic bolt cutter interface. The four primary components are the umbilical capability (optional), ejection system, support shelf including thermal shroud, Multipurpose Interface Box (MIB).

This launch system would allow stacking 10 nanosatellites of dimensions 20" x 19" x 7.5" or 25" x 12" x 10.5". After launch from the shuttle, the carrier below would eject the nanosats.

A Challenge to AMSAT-NA for Collaboration

The challenge to AMSAT-NA is to aggressively contact possible universities that could participate in this program and with the help of AMSAT members that have expertise in designing and building microsatellites submit a proposal to be part of the nanosatellite program.

This would generate some modest funds of $100,000 to start their program and generate a lot of future AMSAT members and expertise to build new OSCAR satellite. There have been several attempts by AMSAT members in the past to form teams to build microsatellites but without the direct help of AMSAT have not been successful. The consuming efforts by most members on the P3D did not allow AMSAT to support these programs until now. With the efforts on P3D now coming to a conclusion, AMSAT-NA can generate some excitement by increasing their capability to build micro and nanosatellites at modest costs.

What can AMSAT members think of to do with one or two or more nanosatellites that would really stimulate the amateur/OSCAR community? Building AMSAT support groups for universities now to be part of the team can provide support that will make university winners in this program. This proposal is ten pages long. It is needs to be submitted by September 30, 1998 and selected universities will be allowed to charge expenses back to October 1, 998 even though the award will likely occur in November or December 1998.

Summary

The Nanosatellite Program for universities provides funding and a launch for ten nanosatellites. The AMSAT-NA community should be part of this program in supporting universities and helping build the next generation of OSCAR satellite builders and operators.

With AMSAT's help, universities that may not have been capable of participating in this program can now become competitive winners. Building micro/nanosatellites is an exciting and educational experience as many veteran OSCAR builders can testify. How about helping the communities experience this excitement and support your favorite university?

The Program at Stanford University is a direct result of the help AMSAT provided in the project with Weber State University in 1988-1990 in building the current OSCAR microsatellites. We thank you for that help and now challenge you to do the same for other universities.

An EZ-Sat Update

by Frederick J. Winter, N2XOU (fwinter@ix.netcom.com)
and Ken Ernandes, N2WWD (n2wwd@amsat)

ABSTRACT

This paper provides an update for our EZ-Sat project. The plan for this satellite is to provide additional entry-level amateur communications capability, using some of the most commonly-owned HAM equipment. This project benefits the AMSAT community by adding a new satellite that can be operated with modest equipment and from a portable or mobile station. The design, construction, and operation of such a system provides a practical telecommunications curricula supplement to several Undergraduate-level programs. The ultimate project goal is to develop a series of simple, yet effective spacecraft carrying amateur radio communications payloads. Prototype construction is underway. Brassboard performance results will be discussed.

INTRODUCTION

This EZ-Sat project intends to provide a basic orbiting amateur communications capability from a spacecraft built and controlled by Undergraduate students. While educational goals are held at a high priority the possibility of finding a home with other satellite projects currently under development will be considered as well . The educational benefits are that an amateur satellite project with real technical obstacles as well as real life tradeoff considerations can provide the students with a practical and interesting application of classroom material. AMSAT benefits by getting a new entry-level satellite with potential to spur new interest in amateur satellite communications.

The authors completed preliminary experiments to confirm architecture and have begun the process of prototype development.

The ground station capability at Suffolk County Community College is in full operating order and the continued development of expertise at handling the equipment is in full effect. The ground station taken in combination with the EZ-sat project enables students to visualize satellite communications on every level.

PROJECT RECAP

goals

The primary goal as stated previously is to build and orbit a working amateur communications spacecraft. We believe a new "EZ-Sat" accessible with common and affordable amateur radio equipment would be a welcome addition to the amateur satellite "fleet."

Other important goals include:

- The spacecraft must be simple in design and construction to include undergraduate student involvement.
- Develop a base of expertise in spacecraft design, analysis, construction, and project coordination and management.
- Develop a satellite Command and Control (C^2) infrastructure capable of handling multiple satellites.
- Maximize the applicability of these projects to the telecommunications and other curricula at the college.
- Make the experience rewarding.

conceptual design

We propose a single frequency satellite using a communications payload with a 2 meter FM uplink and a 10 meter SSB downlink. The reasons we chose this frequency arrangement are:

- The popularity of 2 meter FM amateur radio transmitting equipment.

• Availability of 10 meter SSB receiving equipment in general HF transceivers, 10 meter single-band transceivers, and communications receivers.

• Low satellite power drain using SSB transmit.

• Manageable antenna sizes.

• Relatively low Doppler frequency shift simplifies operation.

• Usability by most amateur radio license classes including the US "no-code" Technician license.

We also propose the use of a small, inexpensive microsat spaceframe, using passive thermal and attitude control designs.

This satellite will operate in a Low Earth Orbit (LEO), but will be capable of operating effectively in virtually any orbit. Because of the single frequency operation, the satellite's transmitted energy will be concentrated on a single, communications channel with a relatively strong downlink signal.

The spacecraft's 2 meter FM receiver will be designed to be as sensitive as possible; analysis of the link margin will determine the exact sensitivity goal for the receiver. However, the initial goal is to allow for enough margin for an uplink signal of 5 watts of ERP, assuming a satellite elevation of 30° and a 1000 km orbital altitude. Because of this sensitivity and the popularity of the FM band, the receiver will require sharp filters to reject adjacent signals and will likely use CTCSS tone squelch to reject on-frequency signals not intended for the spacecraft.

TECHNICAL UPDATE

A brass board unit consisting of purchased transceiver equipment and home-brew interfacing circuitry has been assembled and tested with good results. This brassboard effort is now being translated into a printed circuit prototype. The prototype system will consist of a standard 2 meter FM receiver and a 10 meter SSB transmitter employing a double conversion scheme. 2.5 watts of output power is the design goal to work within the confines of a self imposed 5 watt total power drain and a 50% estimated efficiency.

We are still seeking technical support in two basic areas: a basic microsat design and methodization of spacecraft assembly.

In addition we are not ruling out the consideration of phasing into existing project platforms should they find our effort compatible with their project goals.

For spacecraft assembly, we are still seeking advise on construction methods for both mechanical and electronic assemblies. Some specific areas include the choice and application of thermal coatings and solar arrays as well as the use of epoxies or other stiffeners for electronic assemblies to ensue they survive the launch or other mission-related mechanical stresses.

OTHER REQUESTED SUPPORT

One of the most important considerations is finding a ride to orbit. We are still very interested in learning the process by which amateur radio spacecraft get a "free ride" as ballast on space launches. Specific individuals to contact and any advise in this area would also be welcome.

Another important area in which we still seek AMSAT expertise in securing donations of "scrap" material such as solar cells and storage batteries for the construction of the spacecraft. Again, names of specific individuals to contact would be very helpful.

ACKNOWLEDGMENT

The authors extend their thanks to Suffolk Student Glenn Leheneff for his contributions in the design and fabrication of mock-up housings for the project.

SUMMARY

Brassboard construction and testing is complete providing verification of planned architecture.

Prototype is under development, parts lists are compiled and purchasing is underway.

Construction and testing is on the horizon if you'll pardon the pun.

ABOUT THE AUTHORS

Frederick J. Winter, Ph.D., holds a Technician Class license and has enjoyed a career as an Engineering Consultant, a Microwave Communications Engineer, and most recently a Professor of Engineering Science, ElectricalTechnology, and Telecommunications. Teaching at the undergraduate level at Suffolk Community College and at the graduate level at Polytechnic University (formerly "Brooklyn Poly") provides Mr. Winter with students who are interested in advanced technical projects.

Kenneth J. Ernandes, BS, ME. holds an Extra class license and was formerly a USAF Captain, and Orbital Analyst Instructor for NORAD/ Space Command. Ken received air combat maneuvering training in the F15 Eagle. Achieving Scholarship status, Mr. Ernandes has enjoyed a career as an Engineer and a Satellite specialist who is well known to AMSAT as well as NASA. Mr. Ernandes has computed orbits for Amateur Spacecraft and is a recognized expert in orbital mechanics.

ADVANCING RADIO COMMUNICATIONS TECHNOLOGY WITH THE CITIZEN EXPLORER MISSION

THE COLORADO SPACE GRANT COLLEGE
AT THE
UNIVERSITY OF COLORADO AT BOULDER

Authored by: Jeffrey Baltrush, Michael Forman, Elaine Hansen, Stephen Horan, Ellen Riddle, Dan Rodier

ABSTRACT

Students of the Colorado Space Grant Consortium (CSGC) are currently developing Citizen Explorer I (CX-I) – a low-cost small satellite designed to measure atmospheric ozone and UV radiation and transmit that information directly to educational, scientific, and amateur radio communities around the globe. CX-I will be the first of a series of small satellites in the Citizen Explorer Program. This program was created to advance radio communications and small-satellite technology, increase general environmental awareness, and to transform math, science, and engineering education from classroom theory into exciting reality. K-12, university students, and amateur radio enthusiasts, along with mentors from academia, industry, and government, will take an active part in the design, development, and operation of these satellites.

ADVANCING RADIO COMMUNICATIONS TECHNOLOGY WITH THE CITIZEN EXPLORER MISSION

THE COLORADO SPACE GRANT COLLEGE
AT THE
UNIVERSITY OF COLORADO AT BOULDER

1.0 MISSION SUMMARY

The Colorado Space Grant Consortium (CSGC) at the University of Colorado in Boulder has a long history of student-developed space payloads. This organization was started in 1989 with a NASA grant, and continues to support student space research. The latest CSGC project combines the experience gathered during three NASA sounding rocket missions, two Space Shuttle Get-Away-Special experiments, and a Space Shuttle Hitchhiker mission to create a multidisciplinary small satellite program. This program, the "Citizen Explorer," which began in the fall of 1996 was created to increase general environmental awareness and to transform math, science, and technology education from classroom theory into exciting reality.

Students at CSGC are currently developing Citizen Explorer I (CX-I) -- a low-cost, robust, small satellite designed to advance radio communications and to measure ozone in our atmosphere. CX-I is the first of a series of small satellites planned as part of the Citizen Explorer Program. K-12, undergraduate, graduate students and amateur radio enthusiasts will take an active and significant part in the design, development, integration, testing, operation, and data analysis of the CX-I mission, thereby utilizing and boosting their enthusiasm for space.

The program enables amateur radio enthusiasts, K-12 students, and teachers to become actively involved in real and useful measurements of the environment by directly receiving data from the satellite and by assisting in ground-based measurements. In addition, the program enables undergraduate and graduate students, with mentors from academia, industry, and government to design, build, test, and operate a real satellite.

The CX-I satellite will advance radio communications technology by:

- Providing an operational demonstration of a beacon mode functionality-where the spacecraft downlinks a condensed summary message to the ground users effectively asking for support.
- Measuring UV radiation reaching the spacecraft and the ground, providing a measurement of solar radiation affecting an orbiting spacecraft and the Earth's surface.
- Providing an operational demonstration of the Point to Point Protocol (PPP) used for digital data communications.
- Providing a flight demonstration of on-board autonomy and of the migration of this autonomy from ground to space
- Providing an operational demonstration of a COTS (Commercial Off The Shelf) processor as the on-board control computer.

The CX-I satellite will provide measurements of ozone and aerosols in the Earth's atmosphere along with variations in ultraviolet radiation effecting the atmosphere and reaching the Earth's surface. These measurements will be freely available to the amateur, scientific, and educational communities. Space-based measurements obtained by a single spectrophotometer flying on CX-I will be directly available to a network of users as they are downlinked to amateur radio enthusiasts and K-12 schools. Hand-held instruments developed and operated by K-12 students will extend these measurements. Undergraduate and graduate students with advise from mentors from academia, industry, government, and the AMSAT community will be responsible for the construction and operation of the CX-I satellite. Schools, institutions, and

amateur radio operators interested in the scientific and engineering measurements provided by CX-I will be able to get their amateur radio license and directly receive and display realtime spacecraft telemetry via a personal UHF receiver linked to their PC.

The CX-I mission seeks to increase the pool of space advocates, space buffs, and space amateurs. To receive CX-I transmissions, individuals (mostly teachers) at participating schools will receive their HAM licenses-hopefully bringing this experience into classrooms across the US and the world.

1.1 MISSION OBJECTIVES

CX-I is a mission designed to help educate students of all ages in space, science, and technology. Specifically, the goals include:

1.1.1 EDUCATIONAL OBJECTIVES

- Directly downlink science and engineering data to participating amateurs at K-12 schools world-wide
- Enable receipt of data at schools using low-cost ground stations (<$500)
- Provide the means for students of all ages to take an active part in experimental observation and analysis of their environment with student-built ground instruments, and to share this data via the Internet
- Encourage teachers and staff at K-12 schools to obtain and use amateur radio licenses

1.1.2 TECHNOLOGY OBJECTIVES

- Advance radio communications technology
- Demonstrate a "Beacon Mode" communications concept
- Provide measurements of solar UV radiation effecting the spacecraft and reaching the Earth
- Demonstrate spacecraft autonomy and the ability to migrate autonomy
- Demonstrate the Point to Point Protocol (PPP) for spacecraft-to-ground communications
- Demonstrate an on-board processor built from COTS equipment

1.1.3 SCIENTIFIC OBJECTIVES

- Provide global total ozone observations that complement similar data sets
- Provide a continuous measurement of solar UV radiation reaching the spacecraft.
- Provide a network of ground UV monitoring sites
- Provide observations of aerosol optical depth to assist in modeling surface level UV flux

2.0 RADIO COMMUNICATION

The CX-I satellite will conduct technical investigations of interest to the AMSAT community. An operational analysis of a new communication concept called the "Beacon Mode" will address and aim to improve the current practice of radio communications. In addition to spacecraft health, status and science data, a summary of spacecraft status and a request for attention by ground controllers will be downlinked. Demonstration of this concept will assist in increasing the autonomy of future spacecraft missions, thereby decreasing the cost of mission operations.

In addition, CX-I will be flying a COTS processor. Studies of the radiation effects on this processor will be useful in evaluating the use of COTS processors in the space environment.

Finally, the Citizen Explorer Program will promote awareness and interest in radio communications technology at all educational levels.

2.1 BEACON COMMUNICATIONS RESEARCH

A new communications concept, called the "Beacon Mode," provides a way to operate a spacecraft and monitor its health without extensive day-to-day attention by ground controllers. Instead, the spacecraft will use onboard software to determine whether it is healthy or whether attention by ground controllers is needed. During nominal operations, the spacecraft will transmit one of a limited number of monitoring messages to the ground. Amateurs teamed with K-12 students will monitor these messages. Based on the urgency of the message, spacecraft engineers and operators at the Mission Control Center will be contacted to monitor the spacecraft and correct the situation if necessary.

Earth-orbiting missions traditionally schedule ground operators and engineers in the Mission Control Center during four to twelve passes per day to receive and monitor engineering telemetry. The proposed beacon approach can reduce this monitoring by the Mission Control Center to a few minutes per day. Meanwhile, amateurs and students around the world will be able to participate first-hand in the mission by receiving and monitoring the realtime spacecraft telemetry stream and performing an independent assessment of the spacecraft's condition.

The objectives of the Citizen Explorer "Beacon Mode" are to demonstrate new concepts in spacecraft communications including:

- The summarization of the spacecraft condition with a limited number of messages to indicate its need for contact with ground engineers and operators.
- The ability and interest of amateurs and K-12 students to participate in space missions and to extend the traditional Missions Control Center. Functions will include
  - Monitoring and evaluation of spacecraft health and status from telemetered data by amateurs and K-12 students from telemetered data.
  - The receipt of these messages by participating amateurs and K-12 students and relay of messages to the Mission Control Center.
  - The relay of telemetry data received at a participating school to the Mission Control Center.
- A significant reduction in the amount of time that the Mission Control Center needs to be staffed.
- The applicability of this concept to other amateur, NASA, and commercial spacecraft.

2.2 ON-BOARD AUTONOMY AND AUTONOMY MIGRATION

The key technologies needed to implement on-board automation and the migration of this autonomy from ground to space have already been prototyped and demonstrated by the Colorado Space Grant Consortium as part of the ground support system used for the DATA-CHASER experiment flown in August 1997 on STS-85. These technologies consist of:

- An intelligent onboard system which is capable of monitoring health and status and alerting other onboard software
- Onboard scripts to determine if an alarm is valid based on context checks
- Actions generated by onboard scripts including selecting the appropriate beacon message for downlink, reconfiguring the spacecraft, and/or safing the spacecraft.
- Data summaries to enable ground users to diagnose the situation

These key technologies are a part of the Citizen Explorer system design and are being included in its implementation. They will be thoroughly tested as part of an end-to-end software systems test, and used as a support tool for integrated spacecraft testing.

Several mission simulations are scheduled where a selected set of schools and amateur sites will participate in mission simulations to train users and to verify the distributed software and communications components in a realistic end-to-end environment. These users will then be able to participate in the Citizen Explorer mission after the launch and to help train new users and install new receiver stations as the mission matures.

2.3 COTS FOR ON-BOARD PROCESSOR

The central C&DH system will be based on COTS PC hardware, which has been ruggedized and miniaturized for industrial control. This hardware will be further modified for the radiation environment of space. The use of such hardware has many future benefits for space applications:

- Off-the-shelf hardware eliminates a major design effort, uses the mass-market to lower costs, and allows fast component replacement if required.
- Ubiquitous architecture allows use of common and mature software tools and widely available expertise. Compatibility

allows development to occur on inexpensive desktop machines.

- PC software is compatible over a wide range of processors (8086 to "Pentium"), allowing hardware to be closely matched to software requirements.
- Systems designed for the industrial control marketplace are miniature, rugged, and have low power consumption.

2.4 POINT-TO-POINT PROTOCOL (PPP)

One of the design features of Citizen Explorer will be the use of off-the-shelf computer networking protocols to communicate with the spacecraft over the RF link. The protocols being considered are TCP/IP (Transmission Control Protocol / Internet Protocol) running over PPP (Point to Point Protocol). TCP/IP is the standard for network connections over the Internet, and PPP is a communications protocol which allows these connections to be conducted over a standard serial link. This set of protocols is commonly used terrestrially to connect remote computers to larger networks via modem.

These protocols will be used during normal operations, once the spacecraft has been stabilized and the communications system can accommodate the required bandwidth. (A much simpler "critical" protocol will be used to communicate with the spacecraft during modes when the main computer is turned off.)

TCP/IP and PPP are being considered for use by CX because they provide a number of "off the shelf" features which otherwise would have to be designed, written, and tested by the CX software team. The benefits of this approach are:

- It provides for the packetization and unpacketization of data.
- It can perform error detection to determine which packets arrived "bad", and can transparently request resends of bad packets.
- It can perform serialization so that packets received "out of order" (due to resends, etc.) are output in their original order.
- It allows multiple network connections to exist over a single serial communications link. The spacecraft can simultaneously download data, respond to commands, and upload new software.
- All of this happens transparently. The individual network sockets only see a clean connection with their counterpart on the other end of the link.
- It is a common set of protocols, and is a standard feature on both our flight (VxWorks) and ground (Linux) operating systems.
- Standard software tools exist to perform common functions via these protocols (Telnet for shell-level commanding, FTP for file transfer, Ping for link testing, etc.) These tools are also standard features of our operating systems.

TCP/IP and PPP were designed for use over wired connections, but balloon experimenters and amateur radio enthusiasts have been experimenting with their use over RF links. CX will piggyback the TCP/IP PPP packets onto standard amateur radio packets to change the asynchronous nature of PPP packets to the synchronous nature of packet radio.

2.5 EXTENDING THE NUMBER OF SPACE AMATEURS

The Citizen Explorer mission was created to further education in space, science, and technology. By taking a significant and active role in a real space project, students involved in the program will gain a better understanding of Earth's environment and become familiar with the latest space and radio communication technologies. The program provides radio amateurs, K-12 students, undergraduates, and graduate students with an array of opportunities to participate in a space project. Students participate at each project phase including: designing and constructing a spacecraft; building and operating a science instrument; implementing a ground station; measuring UV radiation from the ground; monitoring the spacecraft performance; and analyzing science and spacecraft performance.

The Internet will be used to further the educational and scientific impact of the project and to facilitate ground-based experiments, reporting, and sharing efforts. Through the use of the Internet, Citizen Explorer creates a powerful virtual community to encourage learning by uniting K-12 schools with university students, amateurs, faculty, parents, industry, government labs and agencies, and non-profit organizations in collaborative student/mentor partnerships. Students can combine data sets with other amateurs around the world to create regional and global measurements of the environment. The Internet will also be used for communication with the Mission Control Center, located at the University of Colorado and operated by students who have their amateur operator licenses.

A web site is being established to enable radio amateurs, students, and teachers to fully use this opportunity. The following information and software will be freely available to all potential users:

- Predicted orbit schedules to determine times of future satellite overpasses
- Formats of all satellite data
- The meaning and calibration of each telemetry channel
- Descriptions of the satellite and its payload
- Background information on the science areas addressed by the mission
- Software (PC-compatible) to enable users to decode, process, and manipulate satellite data
- Procedures for installing and maintaining ground equipment.

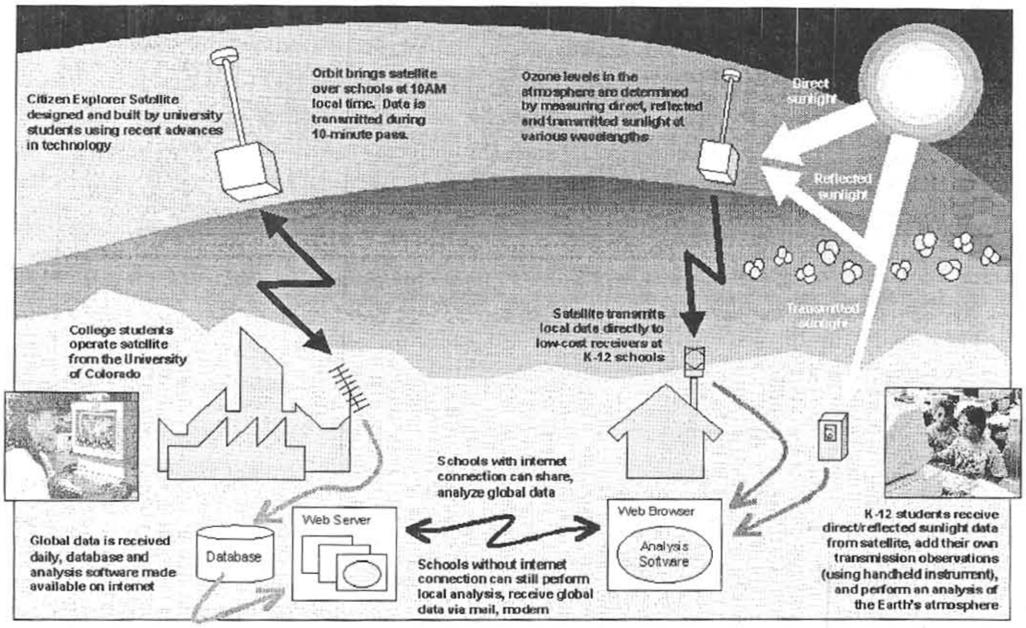


Figure 1: Citizen Explorer End-to-End Data Flow

2.5.1 HAM RADIO EDUCATION

The Citizen Explorer program promotes collaboration among a wide variety of educational institutions. Each of these participants joins the program as a part of the CX-I extended team, and is dedicated to the achievement of the Citizen Explorer mission objectives.

To better promote interest in radio communications technology, participating schools will be encouraged to have a licensed HAM operator to oversee the school ground stations. This operator will facilitate realtime receipt of CX-I spacecraft data, and will promote the interests of the amateur radio community throughout the mission. In a primary school, this operator will likely be a teacher who will teach the students about radio technology by example. At higher educational levels, the students themselves may be interested in becoming licensed operators, giving them a unique opportunity to participate in the CX-I mission at a more intimate level.

Each participant of the CX-I extended team will have the chance to communicate via radio with other members of that team. This exercise will unite the team with a technology that is new and interesting to students. These students will participate in amateur radio endeavors as skilled, excited members, not just spectators.

2.5.2 Educational Infrastructure

The Citizen Explorer educational network is an exceptional group of university faculty, industry partners, amateurs, K-12 school districts, and government supporters. This network will oversee and develop the educational segment for the Citizen Explorer mission.

The responsibilities of the educational network are vast, ranging from curriculum development to technical support to amateur radio licensing. Through the National Space Grant Program, college students in Colorado and across the nation will assist in training K-12 students and teachers in the use of the CX-I satellite to measure aspects of the Earth and its atmosphere from space. This training will be accomplished through workshops where classroom resources and lesson plans will be developed. The benefits of this interaction are far-reaching: teachers will receive science, advisory, and technology support; K-12 students will relate to university students and experts from industry and government; and an extended team will enable teachers to meet educational standards in fun, interactive, and dynamic ways. The Citizen Explorer Program has been developed with extensive input from teachers and educational professionals who have a first-hand understanding of the needs and problems of today's classrooms. As a result, strategies have been developed to support and ensure the effectiveness of the CX-I educational mission on a long-term basis.

2.5.3 Data Distribution

The Citizen Explorer data distribution scheme, illustrated in Figure 1, will transport data between its many distributed users, using RF links and the Internet. RF links will be used to:

- Downlink realtime data from the orbiting spacecraft to low cost receivers at participating K-12 schools, institutions, and amateurs.
- Uplink commands from the Mission Control Center at the University of Colorado (CU) to the orbiting spacecraft.
- Downlink both realtime and recorded data from the orbiting spacecraft to the Mission Control Center several times each day. These data will contain health and status information on the spacecraft, and measurements of the atmosphere in several UV wavelengths.

Communication among the Citizen Explorer ground users will take advantage of the Internet. Participating schools, citizens, and other users will share learning activities, raw and processed data, resources, and software with one another via the Internet. The Mission Control Center (MCC) will communicate with schools and user sites via the Internet. CU will maintain a mission database of satellite data, processed data, composite maps of the atmosphere built up from user contributions, ground measurements, software tools, educational resources, addresses of other users, and learning activities for the classroom. This information will be freely accessible to all world wide participants via a web server.

Users at participating schools and sites will provide data to the Central Web Server via the Internet. These data will be shared with other users and used in mission control. This user-provided data will consist of:

- User measurements made with hand held instruments of solar UV radiation and aerosol optical depth;
- Beacon messages from the spacecraft forwarded to the Mission Control Center;
- Telemetry data received from the orbiting spacecraft and relayed to the MCC; and

- Formatted and calibrated satellite data as maps and time series
- Data products generated by users to be shared with other users.

2.6 Science Mission

The Citizen Explorer Program will provide measurements of UV, ozone, and aerosol optical depth acquired by the satellite and a network of schools and user sites. This extensive coverage enables the study of large scale, global phenomena. CX-I observations will provide scientists and students with a unique opportunity to explore localized atmospheric trends vs. global scale variability, and to explore rural vs. urban atmospheric variations. This geographically broad network is invaluable for the study of the effects of these phenomena on global troposphere chemistry and the biosphere.

2.6.1 Ozone

CX-I will provide valuable observations of global total ozone to complement TOMS and similar data sets. These measurements are significant because:

- Ozone is responsible for shielding the Earth from excessive levels of ultraviolet radiation.
- Global ozone has been declining for many years.
- Ozone distribution is highly variable due to seasonal changes and atmospheric circulation.
- Regional polar ozone is being depleted in the Southern Hemisphere and has been observed at record low levels in the Northern Hemisphere.

2.6.2 Ultraviolet Radiation

CX-I will provide a unique network of monitoring sites with unprecedented spatial coverage that complements the new UV indices calculated from NASA TOMS data. These measurements are important because:

- UV is a driving force in photochemical oxidant formation and in photochemical formation of Aitken nuclei (sub-micron aerosols).
- UV is linked to skin carcinoma and melanoma, cataracts, plant damage, and net oceanic bioproductivity.
- UV plays a key role in the photodegredation of paints and polymers.
- Surface level UV radiation is difficult to accurately model due to aerosol variability.

2.6.3 Aerosols

The satellite will also provide valuable observations of aerosol optical depth that complement EOS-AM MODIS data and assist in modeling surface level UV flux. Aerosol optical depth measurements are significant because:

- Aerosol optical depth has a large effect on the global radiation budget.
- Aerosol optical depth strongly affects surface level UV radiation.
- Aerosol optical depth is highly variable and is influenced by photochemical activity, clouds, dust storms, relative humidity, volcanic activity, and biomass burning.

2.6.4 Instrumentation

Onboard the spacecraft, a 16-channel spectrophotometer (see Figure 2) uses a linear diode array to provide coverage from 290 to 360 nm. The spectrometer provides observations in 5 of the 6 channels used by TOMS. The channels between 290 and 340 nm will be used to monitor total column ozone. The 350 and 360 nm channels will measure albedo. Analysis of these data will be performed using wavelength-pairing techniques proven by TOMS and similar instruments.

On the ground, hand-held photometers employed by the network of student observers will measure broadband UVB radiance. Students will also monitor aerosol optical depth at 525 nm using the Mims Haze Network technique. Students will combine the spacecraft observations of backscattered UV with their own observations of surface UV and aerosol optical depth to create their own understanding of Earth's atmosphere and how it can be explored.

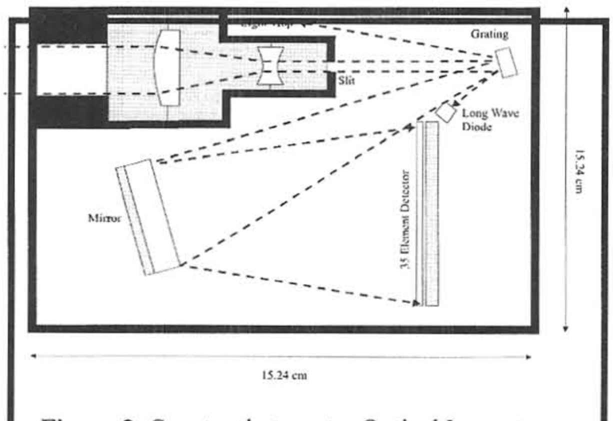


Figure 2: Spectrophotometer Optical Layout

3.0 MISSION IMPLEMENTATION

The Citizen Explorer mission uses a simple, robust spacecraft to meet the technological, scientific and educational requirements of the program. The spacecraft incorporates an inexpensive design to provide the necessary power, orientation, structure, thermal environment, and data handling for downlinking useful science measurements to amateur radio enthusiasts and to K-12 schools.

3.1 Mission Design

CX-I will launch as a secondary payload with the primary EO-1/SAC-C mission on a Delta II launch vehicle in October of 1999. The orbit geometry, dependent on the anticipated orbit of the primary payload, is a 10am/10pm, circular, sun-synchronous orbit at an altitude of 705 km. This orbit allows the spacecraft to achieve adequate solar-array pointing and ground links and ensures that atmospheric drag will be a minor factor over the one-year design lifetime of the mission.

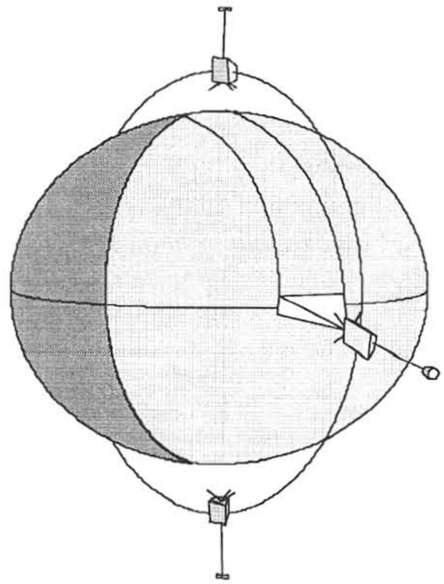


Figure 3: Citizen Explorer I Orbit Diagram

The CX-I spacecraft is gravity-gradient stabilized with additional control provided by three magnetic coils. The mission is designed to last one year, and all spacecraft components are chosen accordingly.

A sketch of CX-I is shown in Figure 5. With contingency, the total mass is 99 lbs. All instruments, engineering components, solar arrays, and launch vehicle adapters are supported by the CX-I mechanical structure. The structural design allows for maximum component accessibility.

The power system uses a Peak Power Tracking system to maximize solar panel efficiency, and to provide an on-orbit average of 27 W. A 2.3 Ahr, 12 V Nickel-Cadmium battery provides power storage during the mission.

The Command and Data Handling system uses commercial components to meet its schedule and budget requirements. This system interfaces to the other subsystems via a microprocessor network. C&DH stores digital and analog data onboard for later transmission to the ground.

Communications onboard CX-I occur at amateur radio frequencies. Commercial UHF components are modified to receive and transmit data at these frequencies. A transmit antenna, mounted on the nadir side of CX-I is used for data downlink. Two receive antennas, mounted orthogonal to the gravity-gradient boom, are used for all ground uplinks. Figure 4 shows a spacecraft functional block diagram.

3.2 Resource Budgets

Student projects require the inclusion of contingency and margin wherever possible. The approach taken for CX-I design was to include both contingency and margin in mass and power calculations.

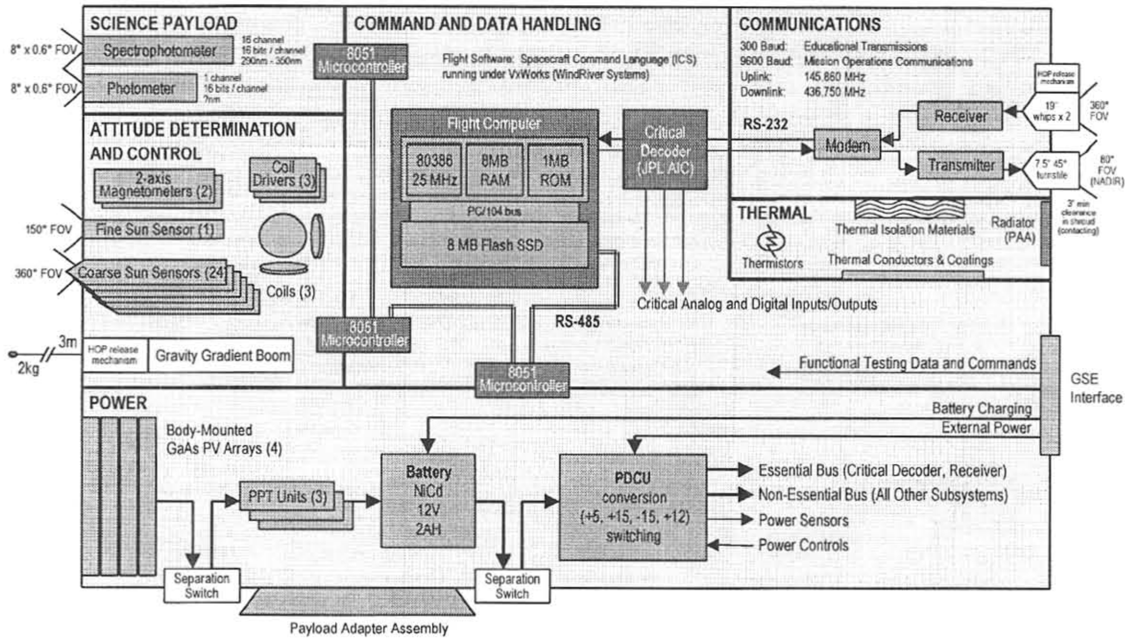


Figure 4: Spacecraft Functional Block Diagram

1.1

3.3 Structures and Mechanisms

The CX-I primary structure uses an aluminum plate construction to provide the structural integrity required to survive launch conditions while providing a stable platform for all instruments and components. The component configuration supports all subsystem thermal, volume, and field of view needs; minimizes wire lengths and losses; and promotes spacecraft modularization. To ensure that the structural design is adequate and capable of supporting all predicted launch loads, the structure is being evaluated using finite element analysis.

The satellite fits within the secondary payload shroud of the Delta II launch vehicle. The calculated mass for the entire satellite (including the structure, MLI, electronics, instrument and solar arrays) is less than 100 lbs. Figure 5 depicts the external structure of CX-I from several angles. Shown in this diagram are the communications antennas (both transmit and receive), the launch vehicle adapter ring, the solar panels, and the gravity-gradient boom.

3.4 Thermal

The thermal subsystem is required to maintain the components of the spacecraft and payload within their respective operating temperature ranges over the mission lifetime. The CX-I thermal subsystem relies entirely on the passive techniques of conduction and radiative heat transfer to provide the necessary thermal control at a low cost and with no power consumption. Surface coverings and component placement are the foundation of the CX-I passive thermal design. The component boxes and instrument surfaces are anodized to keep them within their desired operating temperature ranges. Components or subsystems are located within the spacecraft to suit their specific thermal needs. The CX-I passive thermal design will be verified with both computer analysis and detailed pre-flight thermal vacuum testing.

3.5 POWER

Spacecraft electrical power is supplied by a Peak Power Tracking distribution system. Gallium-Arsenide solar power generation with Nickel Cadmium battery storage provides the necessary peak and average power during all mission phases. Body mounted solar arrays on four sides of the spacecraft are sized to provide energy margin for all nominal mission phases at end-of-life. During eclipse, spacecraft power will be supplied by a 1.5A-hr battery stack. The batteries are capable of providing adequate power over the maximum eclipse time assuming a nominal loss factor in energy conversion. The distribution system consists of the Power Distribution and Conversion Unit (PDCU) and the wiring harness. In addition to the required distribution and switching, the PDCU provides voltage, current and temperature sensing.

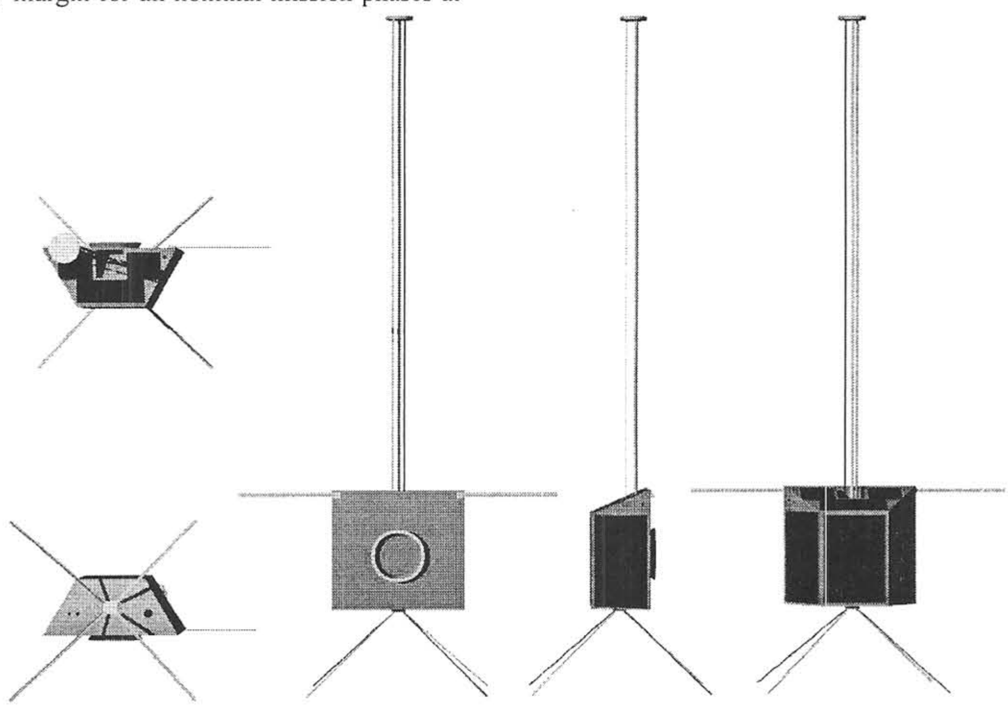


Figure 5: CX-I External Structure

3.6 COMMUNICATIONS

The CX-I spacecraft is equipped with two transmitters, a receiver, and a modulator/demodulator. These systems are designed to use AMSAT frequencies. Frequency selection (435-437 MHz downlink/2 meter uplink), two data rates (9600 baud and 300 baud), packetization of data, and radiated power levels are being selected to be compatible with AMSAT resources. Signals from the scientific instrument and spacecraft subsystems are acquired and stored by the C&DH system prior to storage and downlink transmission. On the ground, each participating school and user site will have a ground station capable of receiving data from the satellite. This data will be fed to a PC for storage, analysis, and collaborative sharing.

3.7 ATTITUDE DETERMINATION AND CONTROL

The spacecraft will be passively stabilized by a 3 meter deployable boom with a 2 kg tip mass. Additional yaw control, allowed by three magnetic coils mounted perpendicular to each other, will provide control authority to the spacecraft to offset disturbances and re-orient the spacecraft if necessary. The gravity gradient boom will be deployed in the anti-nadir direction by a one-time electrical switch via computer or ground command. During normal operations, two 2-axis magnetometers and a fine sun sensor will be used to determine the attitude and position of the spacecraft to the required accuracy. Additionally, a set of six coarse sun sensors mounted on all sides of the spacecraft will provide sun direction with full spatial coverage.

3.8 Command and Data Handling

The CX-I C&DH design is based on a standard PC/104 architecture that makes use of off-the-shelf, commercially proven products to meet the reliability and low cost requirements of the program. The C&DH flight computer, a 386-based processor, allows for an extremely small system (all cards are 4" x 4"), low power consumption (less than 1W per board), and use in a rugged environment (PC/104 has been designed for industrial control applications). The main processor is being further modified to mitigate radiation effects. A network of microprocessors will interface each subsystem to the flight computer. The C&DH flight software is responsible for all spacecraft and instrument control and spacecraft resource management during the mission. C&DH is responsible for command distribution and execution during nominal payload operations, gathering onboard science and engineering data, and storing this data for later transmission to the ground.

3.9 Software

Software for CX-I is based around the VxWorks embedded realtime operating system. The Spacecraft Command Language (SCL) is used for all high-level command and control functions. Furthermore, SCL is integrated with SELective MONitoring (SELMON) for enhanced fault-detection and reaction capabilities. SCL provides the limit-based fault-detection scheme, while SELMON provides additional trend analyses.

Custom device drivers for each interface to the C&DH system are being written in-house, and are currently under development. All flight software will be written in C and C++ to maximize the use of student experience. An evolutionary approach to software development will facilitate hardware/software integration and testing.

3.10 Integration and Testing

CX-I integration and test procedures will be performed at the CSGC and at Ball Aerospace in Boulder. Final integration of science instruments and subsystem components will be done in a clean room located at CSGC.

Each instrument and engineering component will undergo a comprehensive test program to ensure that all performance requirements are met throughout the expected range of environmental conditions. A standard battery of environmental tests, including thermal vacuum and EMI testing, will be performed at a systems level to ensure safe operations.

The CX-I integration and testing team will perform full-system tests to assess the readiness of the entire system. Non-destructive testing will allow the team to learn the state of the spacecraft without damaging flight components. Finally, full functional testing will be performed on all systems including the scientific payload.

3.11 Mission Operations

CX-I health and status information will be monitored at the Mission Control Center. Flight controllers will record all health and status gathered during downlink, analyze these data, and transmit commands to the spacecraft during overhead passes. Most of the activities during a pass will be managed with A Scheduling and Planning Environment (ASPEN), a software tool developed by the Jet Propulsion Laboratory (JPL). This tool will reduce the workload placed on the controllers. Prior to launch, the mission operations team will develop and test procedures for both nominal and anomalous operations of CX-I.

After a pass, all data will be processed and made available to the flight engineers who will monitor the long-term health of the satellite and its instruments. Any commands needed to update spacecraft operations will be prepared by the flight engineers for subsequent uplink. Specialists on the flight engineering team will perform orbit and attitude determination.

3.12 Ground Operations

The Citizen Explorer data distribution scheme will transport data between its many distributed users using RF links, Local-Area Networks (LANs), and the Internet. RF links will be used to:

- Downlink realtime data from the orbiting spacecraft to low cost receivers at participating user sites.
- Uplink commands from the Mission Control Center to the orbiting spacecraft.
- Downlink both realtime and recorded data from the orbiting spacecraft to the Control Center once each day. These data will contain health and status information on the spacecraft, and global measurements of the atmosphere in several UV wavelengths.

Communication among the Citizen Explorer ground users will take advantage of the Internet. Participating schools, citizens, and other users will share learning activities, raw and processed data, resources, and software with one another via the Internet. The Mission Control Center will communicate with these schools and user sites via the Internet. CU will maintain a web site of satellite data, processed data, composite maps of the atmosphere built up from user contributions, ground measurements, software tools, educational resources, addresses of other users, and learning activities for the classroom. This information will be accessible to student participants via a web server at CU.

Users at participating schools and sites will be able to share data with other users and to generate regional and global maps of the atmosphere and of UV radiation. Data will be shared with other users via the Internet. This user data set will consist of:

- User measurements made with hand held instruments of solar UV radiation reaching the ground user sites as measured;
- Beacon messages from the spacecraft
- Telemetry data received from CX-I a: the user sites; and
- Data products generated by users which can be shared with other users.

4.0 MANAGEMENT AND SCHEDULE

CSGC will provide the overall network organization for Citizen Explorer; facilitate student and user involvement; and enable the use of facilities and resources at CU and industry. The Citizen Explorer team organization is similar to a "traditional" project - with project management, subsystem leads, and subsystem teams (See Figure 6).

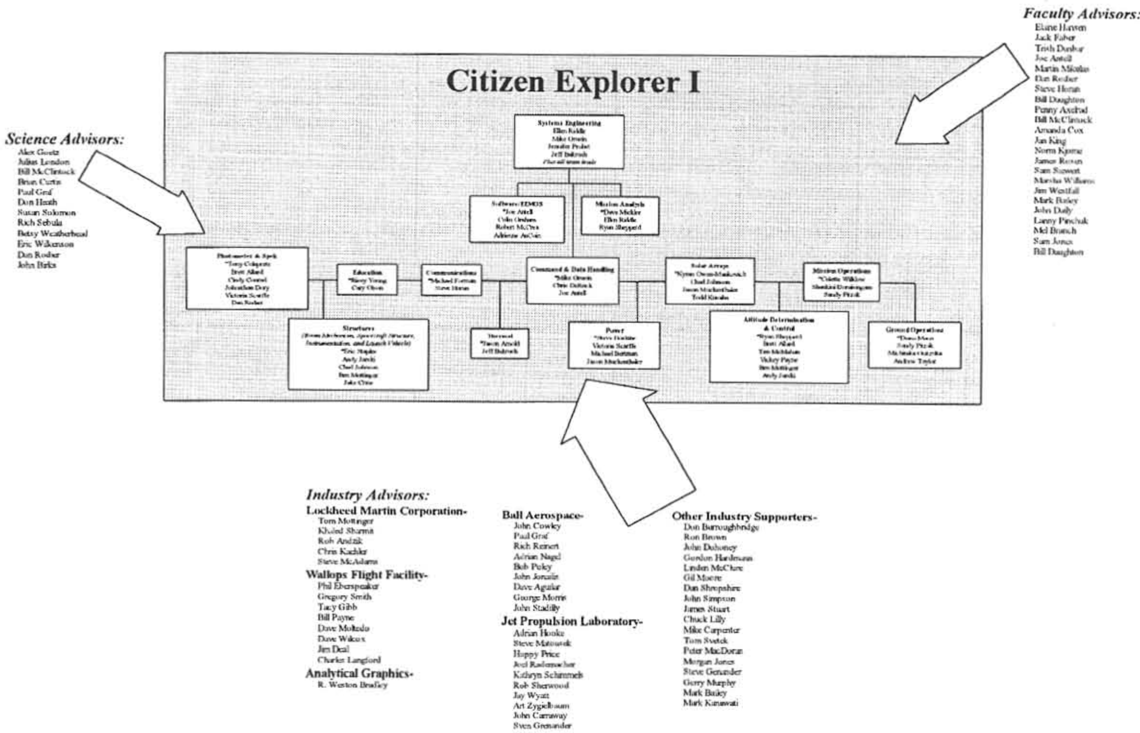


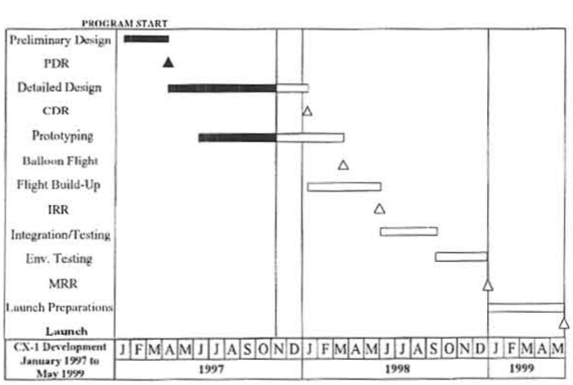
Figure 6: Citizen Explorer Organization Chart

This core student team is mentored by a dedicated and capable group of amateurs from the Radio Amateur Satellite Corporation (AMSAT) and experts from industry, universities, and government labs, who are committed to mission success. Through this teaming, the Citizen Explorer student team hopes to take advantage of the expertise and heritage these experts can bring.

4.1 Project Schedule

A project schedule summarizing mission phases and major milestones is shown in Figure 7.

Figure 7: Project Schedule



training includes the implementation of scientific and technical objectives, experimental design, payload development, integration, flight, mission operations, data analysis, scientific interpretation, and reporting - all within the short span of their undergraduate years.

6.0 REQUEST FROM AMSAT

To accomplish the goals of the Citizen Explorer mission, CSGC is requesting help from AMSAT in a number of different areas. The current team has been extended with advisors from AMSAT. Advice in the area of communication design and implementation has been especially useful. AMSAT has had a long and successful heritage in building low cost, reliable spacecraft. This experience within the AMSAT community has been extremely beneficial to the Citizen Explorer team. In addition to technical advice, the Citizen Explorer team would greatly benefit from any support that ham radio clubs could provide to help install small receivers at schools in their area as well as help with training K-12 teachers and students in the use of these receivers.

CSGC also is requesting guidance from AMSAT in the selection and allocation of uplink and downlink frequencies for use by CX-I. The Citizen Explorer proposes a downlink frequency of 436.750 MHz, and an uplink frequency at 2 meters. Recommendations on and adjustments to these frequency bands are appreciated to ensure that CX-I will not interfere with current or future satellites or ground repeaters. Finally, CSGC is requesting a letter of support of the use of these frequencies by the Citizen Explorer Mission.

The authors of this paper can be contacted at the following address: Colorado Space Grant Consortium, Campus Box 520, University of Colorado at Boulder, Boulder CO 80309

Please refer to the mission web site, located at http://citizen-explorer.colorado.edu, for the most up-to-date project information, including email addresses for the current project management.

SAPPHIRE – Stanford's First Amateur Satellite

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Abstract

Stanford's first student built microsatellite SAPPHIRE was be completed on July 10, 1998. The launch date is still undetermined, but now is the time to inform the amateur community of the capability of this satellite and how the amateur community can use it. SAPPHIRE operates in mode J and has the capability of operating with multiple users. Users can control its two main payloads. The primary payloads are a B/W digital camera and a voice synthesizer, similar to the Dove microsatellite.

The operating system is very user friendly in that it operates much like a bulletin board interface which allows the user easy access to commands with command listing and diagnostics on improper commands. The details of the satellite development is reviewed and followed by some details on the user communications interface.

Introduction and Motivation

The pioneering efforts of AMSAT-NA with Jan King –W3GEY, Tom Clark – W3IWI and many other satellite amateur radio enthusiasts have set a standard for a "non-traditional way" of designing, building and launching novel, inexpensive communications satellites.

Through association with AMSAT-NA, local hams and industry, Weber State University in Ogden, Utah set a course in 1982 to enhance education of engineering students with a project to build a microsatellite using the AMSAT-NA "non-traditional way". The first satellite from this program, NUSAT, was launched from the Get-Away-Special (GAS) canister on the NASA Space Shuttle Challenger in April 1985. NUSAT operated for twenty months, then reentered and burned up in December 1986. NUSAT did not even use the quality and engineering practices developed by AMSAT-NA for the "non-traditional way", yet the satellite performed in space for a significant period of time.

The development and operation of NUSAT turned out to be an excellent project for training undergraduate students. In 1988 AMSAT-NA started a project with Weber State University assisting in the development of the four microsatellites that were launched in 1990.

This "non-traditional way" used by AMSAT-NA engineering is to build microsatellites with the current commercial technology. Due to limited budgets, the "latest" space rated components were not used because they were extremely expensive and "old" technology. Good engineering practices were used with "commercial-off-the-shelf" (COTS) components to minimize the impact of operation in the space environment.

The accomplishments of AMSAT-NA and its success of using this "non-traditional way" of building microsatellites has, in some cases, been a real embarrassment to the aerospace industry and the government satellite builders. With smaller budgets the trend now seen at the annual AIAA/Utah State University Small Satellite Conference at Logan, Utah held in August and September of each year is to use this "non-traditional way" to build "small, cheaper, faster" satellites for commercial, military and science applications.

In 1993 the industry affiliates board established for the Department of Aeronautics and Astronautics at Stanford University to recommend improvements in the graduate program, directed the department to create a program that would give the graduate students systems engineering experience. In 1994 the department then selected the author, who was working on the Weber State University satellite program, to develop a similar program at Stanford. Since the author had been "schooled" in the AMSAT "non-traditional way" of building satellites at Weber State University, this same approach is being used for the Stanford program. The work on the microsatellites is directed through the Space Systems Development Laboratory at Stanford.

The first satellite developed in the Stanford program is SAPPHIRE; it will be described in detail in this paper.

SAPPHIRE Development

The initial assignment to the graduate students in the spacecraft design program at Stanford University was to design a microsatellite. They were given some basic physical parameters shown as the initial concept in Figure 1. This spacecraft would then be a student managed program for a student-designed, student-built spacecraft that is fully functional. Total costs for the spacecraft parts were to be less than $50,000.

The student selected the name SAPPHIRE that is the acronym for Stanford AudioPhonic PHotographic InfraRed Experiment. Those letters describe the three instrument-based missions of this project. The infrared detectors are a new-generation micromachined horizon detector, operating at room temperature and consuming about one watt. A voice synthesizer broadcasts an FM "computerized" voice. A commercial digital camera takes pictures of the Earth. In addition, several other missions advance basic research in spacecraft automation and operations. ***But the primary mission of this project is to train students in all aspects of spacecraft design, fabrication, testing and operations***.

This spacecraft emphasizes simple designs, reasonable objectives, short mission timelines and use of commercial parts and processes. The initial spacecraft structure was made out of plywood Figure 2. The final design would use honeycomb, but for prototyping purposes the plywood was a good simulation of the honeycomb and much easier to work with. This wooden structure was later covered with aluminum to simulate the final honeycomb flight structure.

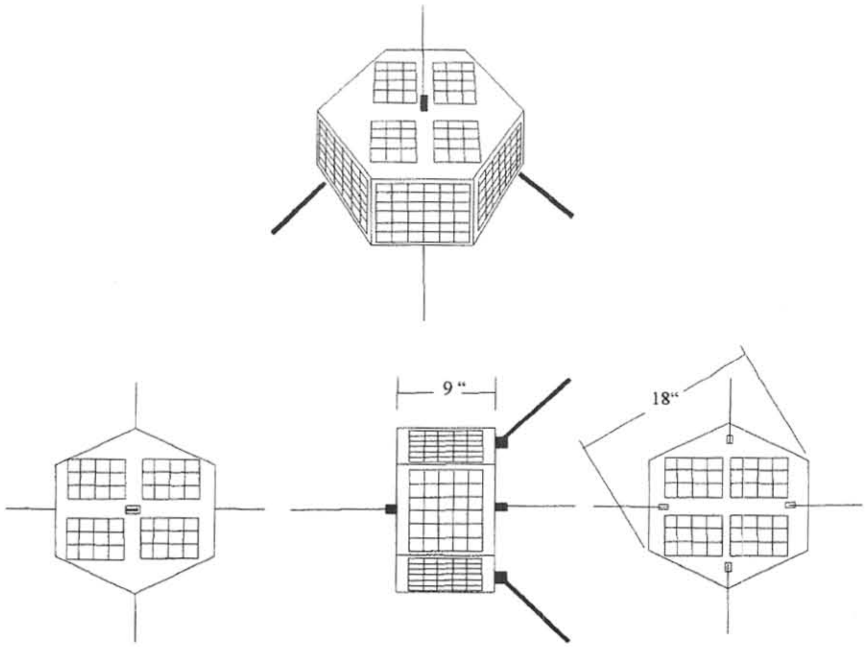
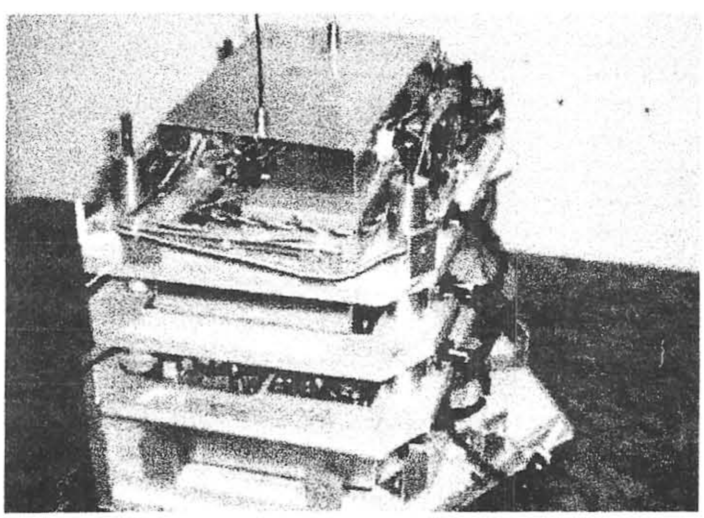


Figure 1 Initial SAPPHIE Concept

Thus with the combination of aluminum and wood the student now affectionately refer to the prototype as Al Wood shown in Figure 2.



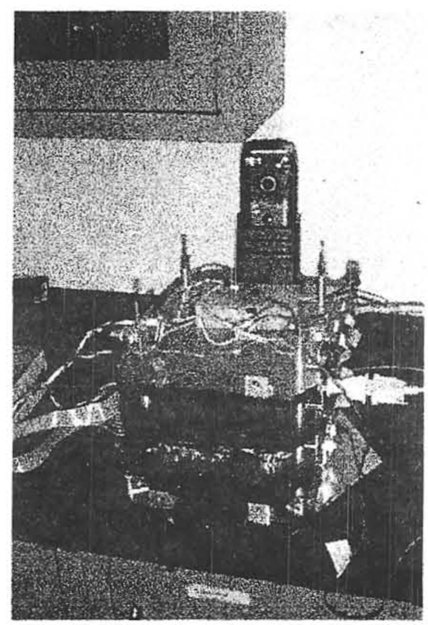


Figure 2 SAPPHIRE Plywood and Al Wood Prototype

The final design is a hexagonal cylinder made from aluminum honeycomb, 17" from tip to tip and 13" tall (including launch interface). It has a total launched mass of 20kg (44 pounds) as shown in Figure 3.

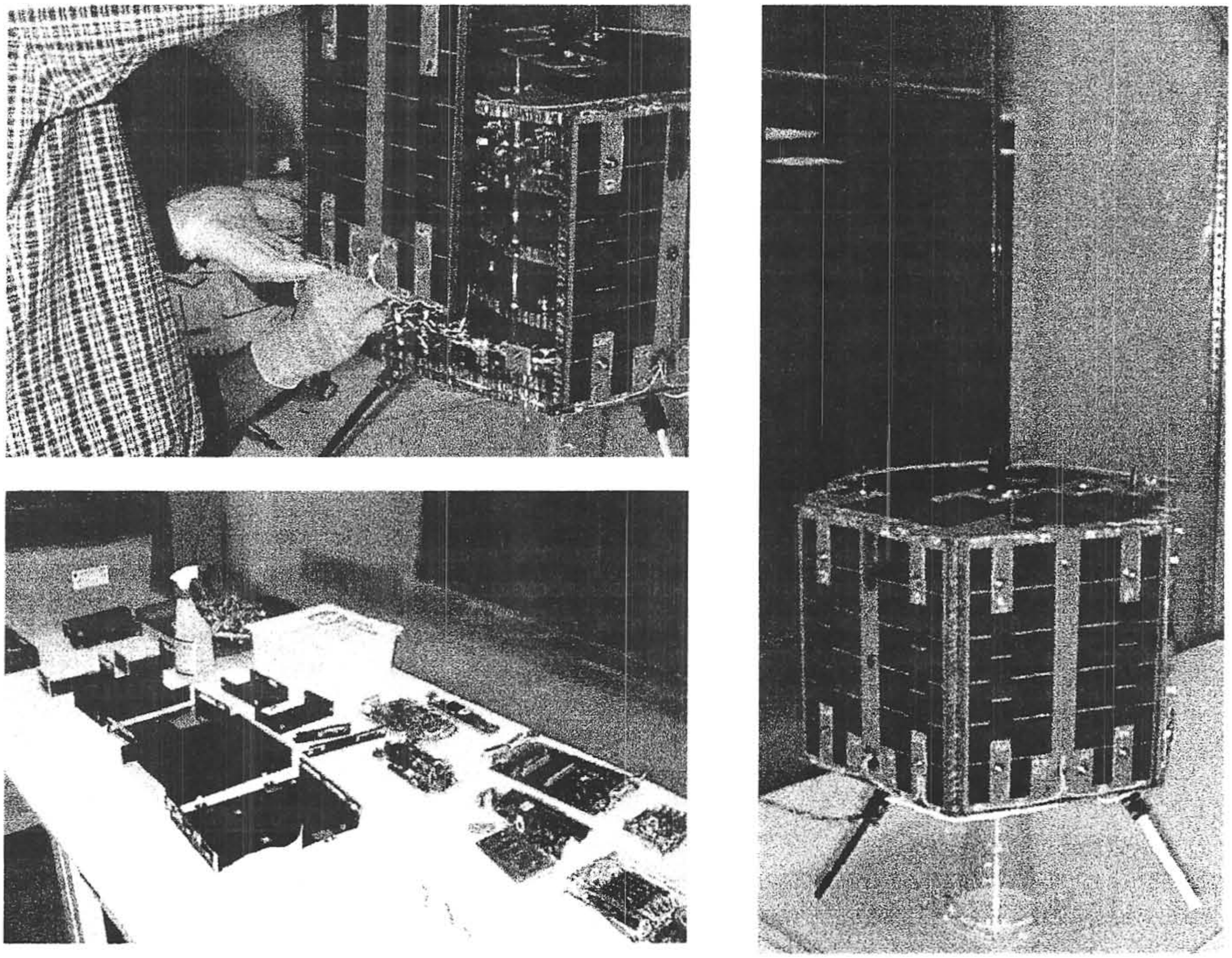


Figure 3 SAPPHIRE in Clean Room During Assembly and Final Operations Testing

Mission Statement & Design Drivers

The mission statement and design drivers for this satellite are shown in Table 1 & 2.

Laboratory Development	Identify, acquire, and maintain design, fabrication and testing equipment
	Develop contacts and recruit mentors from industry
	Identify sources for parts and facilities for long-term SQUIRT usage
	Develop the satellite-concept-to-orbit-operations process for the SQUIRT program
Education	Train students in the practices and importance of systems engineering.
	Train students in every aspect of a satellite project: Design, Modeling, Fabrication, Testing, Launch, and Operations.
	Encourage student research
Amateur Payloads	Take a picture of Northern Hemisphere and display it on the SSDL Web page
	Broadcast a digitalked message to a designated audience
Experiment Payloads	Operate the SAPPHIRE beacon notification system through the ASSET operations system
	Schedule data requests and deliver the data through the ASSET operations system

Table 1 SAPPHIRE Mission Goals

Driver	Motivation	Effect
Education	Novice students are to become systems engineers	Allow students to make big mistakes
Schedule	The project must be completed within the "lifetime" of the students involved, or risk losing key personnel	Simplify goals
		Emphasize base mission requirements
Lab Devel-opment	The project is to assist future SQUIRTs in development, speeding up the life cy-cle	Modular design
		All elements must be developed within laboratory when at all possible
Cost	The laboratory has very limited resources ($50,000)	Simple designs
		Commercial, off-the-shelf parts

Table 2 SAPPHIRE Design Drivers

Launch and Orbit Requirements

SAPPHIRE is intended to fly as a secondary payload on a wide range of expendable launch vehicles. It was designed to accommodate a wide range of orbits as well. The nominal design orbit was polar, with 500km altitude. Table 3 describes the general orbit requirements.

Requirement	Notes
Less than 1000km altitude	Signal strength for communications, magnetic field strength for attitude control, and radiation hardness all require low altitudes
Greater than 200km altitude	The payloads require about 30 days of operations, thus SAPPHIRE cannot reenter sooner than that
Two ground station passes/day	Originally, this meant that the orbit inclination had to be at least 37°- Stanford's latitude - but that requirement is loosening as other universities join the ASSET network. Granted, any orbit of less than 45° is going to significantly hamper picturetaking abilities, but picturetaking is a secondary mission requirement.

Table 3 SAPPHIRE Orbit Requirements

Project Timeline

Table 4 details the project milestones that have been accomplished. SAPPHIRE has been through operational verification and re-test of the solar panels. Operational verification consists of a one-month "locked operations" test; the spacecraft will be locked into the clean room and operated as if it were on-orbit. It was contacted during constrained time windows to simulate low-Earth orbits, and taken through the complete checkout, nominal operations, and contingency operations testing.

SAPPHIRE AND THE INTEGRATED OPERATIONS SYSTEM

As part of the graduate student research at SSDL, a program to experiment with new ways of spacecraft operations has been established. This new program is called ASSET for Automated Space Systems Experimental Testbed. Using the OSCAR type ground stations, ASSET is establishing a master control center, MMC, and a worldwide-interconnected ground network of satellite control and monitoring stations. A representation distribution of these stations is shown in Figure 4.

The main emphasis of the ASSET research is to reduce human intervention in the spacecraft operations, and reducing command and turn-around time to providing products such as photos, activation of a voice synthesizer, etc. The process is to automate the user interface for the customer needs as well as spacecraft health monitoring and maintenance. This architecture shown in Figure 5 allows the user to interact with the spacecraft through an internet, web browser interface and received returned products such as photos by the same means.

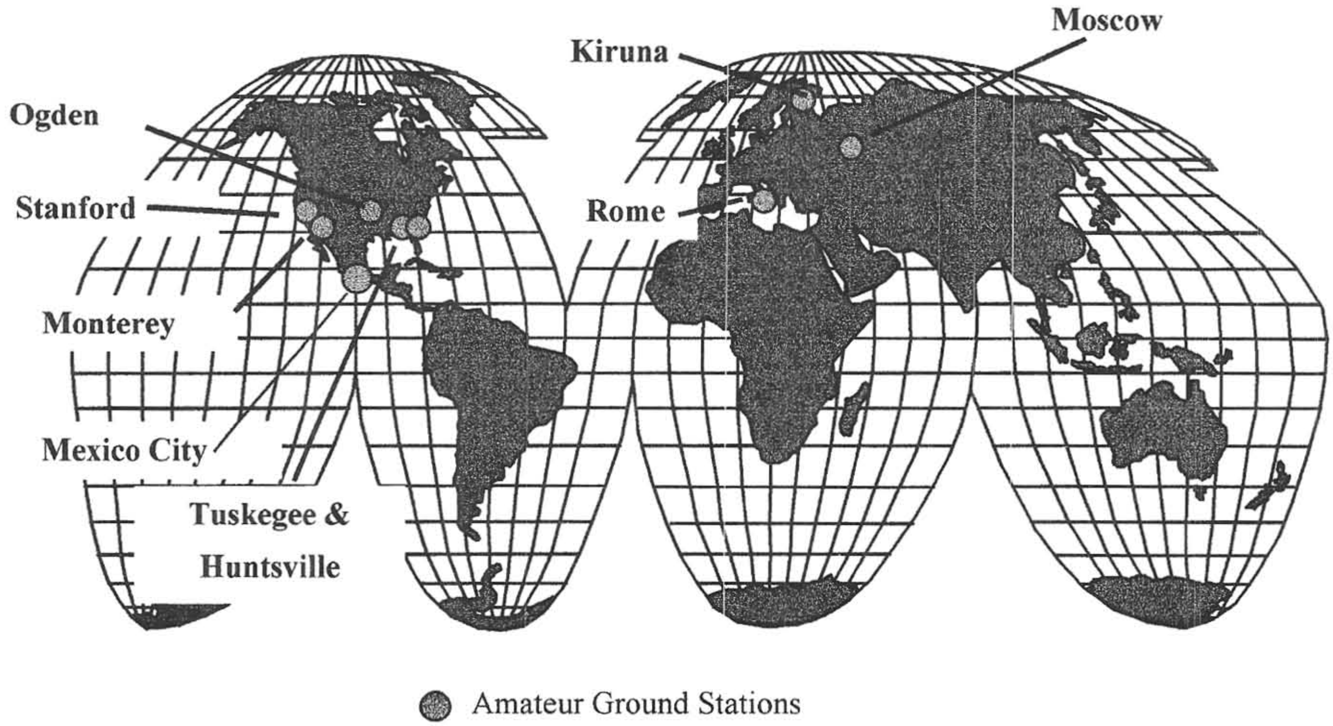


Figure 4 ASSET Control and Monitoring Station

The use of ASSET in the amateur radio community serves several important functions. 1) It provides training for a new group of well-educated, sophisticated users that will be a part of the amateur community and OSCAR operations --- a major goal of Ham radio. 2) It is greatly expanding the use and activity of the amateur frequency bands to assure these are reserved for future amateur use. 3) It provides experimentation and development of new communications technology. 4) It provides new ways for educational outreach to K-12 grades. 5) It promotes international cooperation through collaborative efforts using ground stations around the world. 6) It provides a testing that will have minimal negative impact to develop new operational paradigms. 7) This paradigm shift can reduce commercial and government space costs, improve new spacecraft utilization and generate new means of space use.

The use of SAPPHIRE in a closed room operational mode at Stanford University is already being used as a functional demonstration of ASSET

MISSION

Beyond the ongoing task of educating students, SAPPHIRE has two instrument-based amateur experiments (digital camera, and voice synthesizer). It also has student experiments for one telemetry experiment (virtual sun sensor), and two operations missions (beacon-based health monitoring and spacecraft operations). These are described, below.

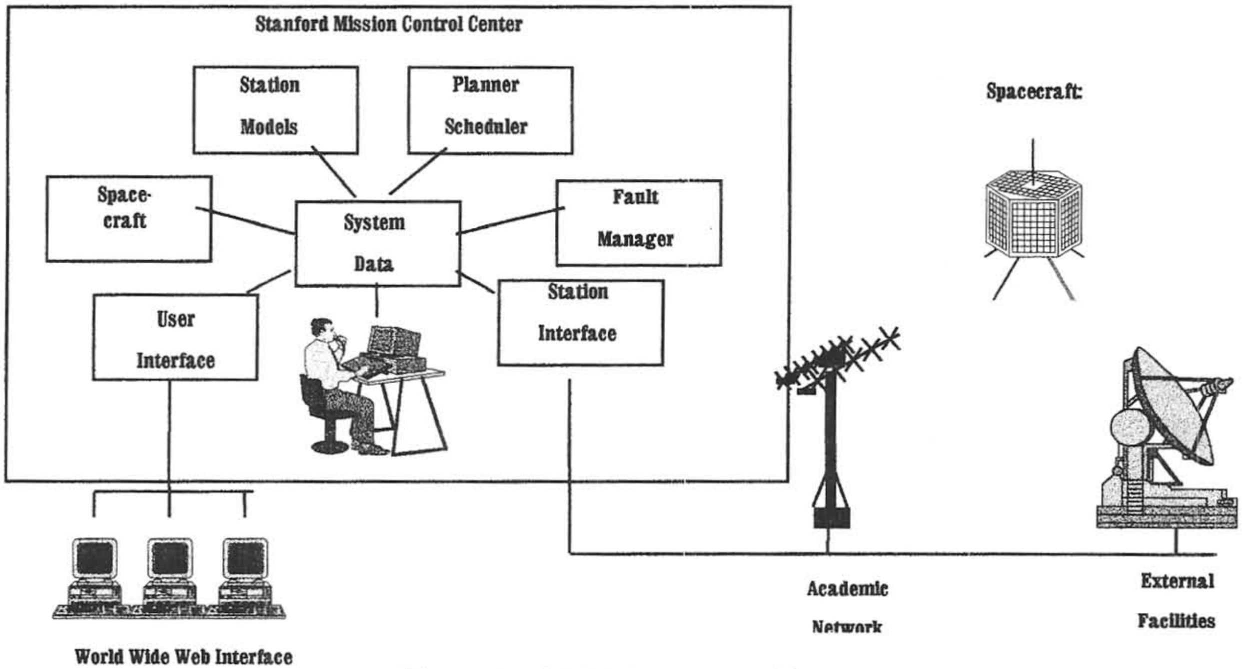


Figure 5 ASSET System Architecture

AMATEUR PAYLOAD MISSIONS

Digital Camera

Students were interested in taking pictures from space, since power, mass, computation and schedule margins existed, this experiment was added. The Logitech Fotoman Plus was chosen to provide this service due to its data handling ability, its convenient computer based operation, and the outstanding level of educational and technical support provided by Logitech engineers. As commanded by the spacecraft CPU, the Fotoman takes a picture and the image is stored in CPU memory. Expected resolution of the black-and-white camera is 1 km.

Camera requirements include the ability to view the Earth, power for the component, and interfaces with the CPU to handle data storage. The principal investigators for this mission are the SAPPHIRE team.

The Fotoman comes as a self-contained package, weighing about 450 grams and consuming 0.8 Watts on average. Flight modification required potting, coating, and repackaging the electronics, disabling the flash assembly, and adding a power switch. Software modifications permit reloading the Fotoman RAM code in case of radiation upset. The Fotoman takes 496x360 pixel images using 256 gray levels. JPEG compression is used to reduce each photo to about 23 Kbytes.

Voice Synthesizer

Voice synthesizers accept ASCII text strings, phonetically translate the strings, and generate an analog audio output equivalent to human speech. This is another student-motivated payload, and could provide interest to the Amateur Radio community as well. The RC Systems v8600 model was selected to provide this function due to its ease of use and interfacing, quality of voice output, and cost.

The voice synthesizer requires an interface to the CPU, power for the unit, and a means for an FM broadcast. It is intended, but not required, that voice broadcasts will be audible using a handheld radio. The principal investigators for this mission are the SAPPHIRE team.

Date	Event
April 1994	Project Start
December 1995	Operational vacuum testing
March 1996	Flight spacecraft vibration testing
May 1996	Flight software overhaul begins
June 1996	Development of tertiary missions
July 1997	Full component integration
	Engineering model upgrades
October 1997	Thermal design implementation
December 1997	Thermal vacuum test
April 1998	Flight software delivery
	Antenna test
May 1998	*Solar panel flash test*
	Final calibration
June 1998	*Operational verification*
July 10, 1998	*SAPPHIRE Delivery*

Table 4 SAPPHIRE Mission Timeline

Modifications consisted of structurally mounting the board in a shielding box and replacing and coating low confidence electronic components. Student designed reset circuitry simplified the board's interface with the bus computer. The flight unit weighs 220 grams and consumes less than 0.2 Watts.

STUDENT EXPERIMENT MISSIONS

Health Monitoring Beacon

One of the new approaches towards reducing spacecraft operations costs is to automate routine functions such as health monitoring. In this concept, the spacecraft is responsible for monitoring its own telemetry and making assessments as to its state of health. SSDL has initiated a new space system technology initiative in order to develop, demonstrate, and validate a beacon-based health monitoring system for spacecraft. This system consists of automated fault detection on board a spacecraft, a state of health beacon signal broadcast by the spacecraft, a ground based monitoring network, and a mission control center capable of efficiently integrating this health assessment strategy into its operating architecture.

SAPPHIRE will monitor its own telemetry sensors, comparing measured values with commandable entries in a state-dependent limit table. These modest steps provide SAPPHIRE with an anomaly detection system far more mature than most spacecraft. Depending on the seriousness of the limit violation, the spacecraft health is assessed to be one of four values. SAPPHIRE's main transmitter transmits the health beacon. SSDL has partnerships with universities in Alabama, Montana, and Sweden to develop a simple receive-only system for health monitoring. These stations will listen for SAPPHIRE beacon transmissions and notify mission control of the results by electronic mail. It is intended to put these stations at locations around the world, giving SAPPHIRE near-global coverage for health monitoring. The Signal flow diagram in Figure 6 illustrates the sequence of events that occur for the beacon health monitoring.

In this manner, all spacecraft sensor data is compacted into a few bits that tells an operator whether or not SAPPHIRE can continue to perform its mission. And while such information once had to be collected over time for eventual download and processing at mission control, spacecraft health is now continuously monitored and available anytime the spacecraft is within range of a low-cost receiving station. Once mission control receives a beacon monitoring update from a remote station, it logs this information and then takes appropriate action. Depending on the health assessment, there are varied responses, from storing the update in the system database to paging the operator on call and rescheduling the network to contact and recover a failed satellite.

Beacon monitoring will be a commandable function on board the spacecraft. SAPPHIRE will operate for a time with and without the beacon, keeping track of the amount of operator time required for health monitoring under each condition. It is expected that beacon monitoring will significantly reduce the man-hours of spacecraft operations.

Attitude Determination & Control (ADC) Subsystem

The primary ADC drivers are the general orientation of the camera to permit photos of Earth's Northern Hemisphere and the smoothing of the solar thermal load. After considering alternate configurations, passive magnetic stabilization was chosen. Magnetic control is achieved through the use of permanent magnets mounted to point the camera towards the Earth in the vicinity of the North Pole. Hysteresis rods are included to damp oscillations in this motion. This approach

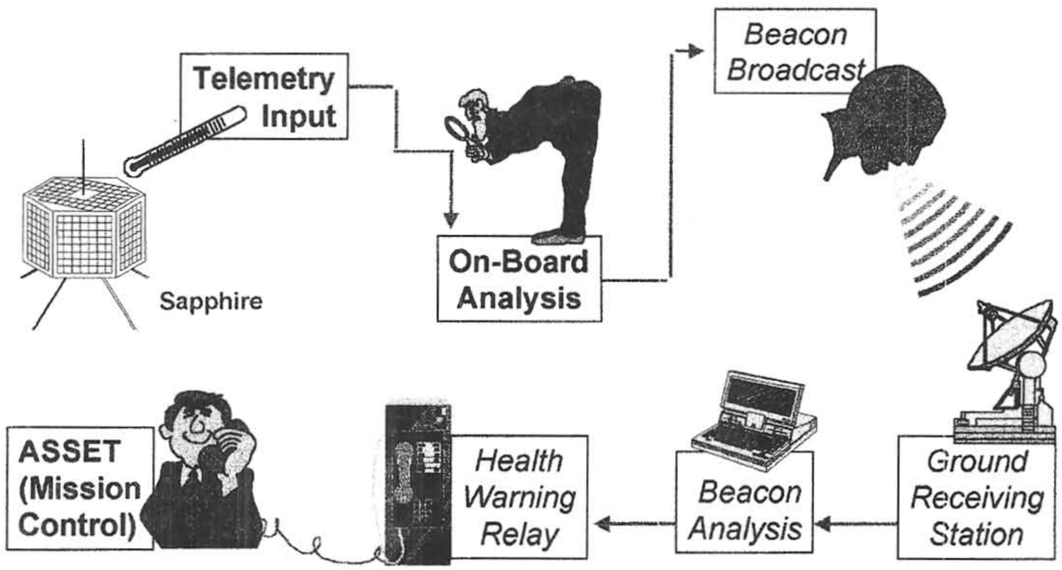


Figure 6 SAPPHIRE Health Beacon Signal Flow

provides what has been called the "controlled tumble", as shown in Figure 7. The spacecraft follows the magnetic field in a North-seeking orientation. The effect is for the Z (top) axis to be nadir pointing in the northern latitudes, zenith pointing in the Southern latitudes, and horizon-pointing in the middle latitudes. This allows camera operations over North America and Europe (the camera points out the top face).

The slow spin required by Thermal Subsystem is accomplished by a radiometer effect on the four transmit antennas; they are alternately coated white and black to be very reflective and very absorptive. Solar pressure creates a very small but constant torque. Attitude sensing is present primary as student interest and for use in future SQUIRTs

Four ALNICO-V bar magnets mounted on the external solar panels, and damping by six hysteresis rods on the CPU tray provide pointing. The slow spin comes from the painted antennas and is also damped by the rods. Additional mass was added to the side panels as ballast to ensure that the maximum moment of inertia was around the Z (spin) axis. Two infrared phototransistors form a simple wide-angle Earth sensor for possible use in determining when to take pictures. In order to assure steady pointing, a study of the magnitudes of the disturbance torques was conducted, summarized in Table 5. Since the orbit is undetermined, the study examines a number of candidate altitudes. Note that though the radiometer torque is extremely small, it has constant effects while in sunlight over time it becomes significant. Meanwhile, the magnet torques are orders of magnitude larger than all disturbances. Thus, SAPPHIRE will be very closely following the magnetic field.

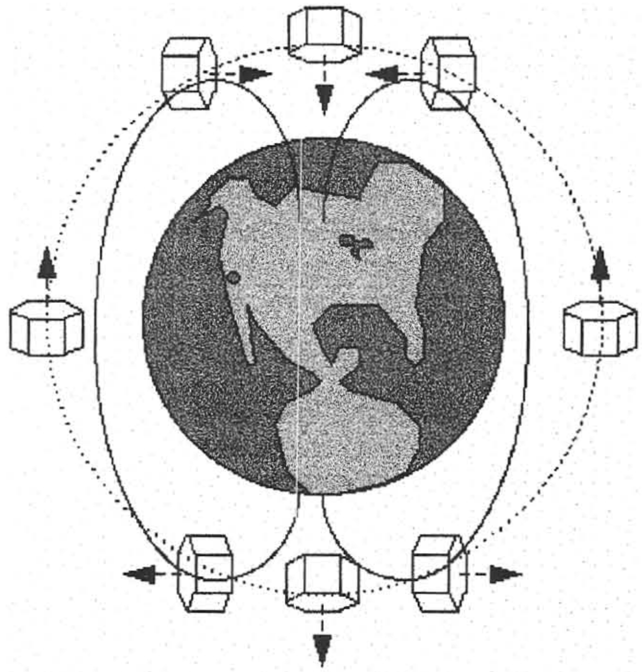


Figure 7 The Controlled Tumble

Altitude	200 km	300 km	400 km	600 km	800 km
Aerodynamic	418	52	13	1.07	0.11
Magnetic	1400	1340	1280	1120	1080
Radiometer	0.05	0.05	0.05	0.05	0.05
Gravity Gradient	0.32	0.30	0.28	0.26	0.24

Table 5 Maximum Magnitude of Expected Torque (dyne-cm)

According to Altitude and Type

All ADC components have been built and are part of the flight structure. The radiometer paints will be added when the thermal design is implemented.

OPERATIONS MISSION

The SAPPHIRE microsatellite is capable of performing three high level functions. These are to collect and filter sensor data, to provide space-based photographs, and to broadcast voice messages. Described below are the various aspects of operating the spacecraft.

Operations phases

Launch Phase - This phase includes all activities from when SAPPHIRE is delivered to the pad until it has ejected from the launch vehicle. Specific attention is given to procedures relating to pad assembly/testing/charging, launch adapter mating, and spacecraft ejection.

Checkout Phase - This phase includes all activities from when SAPPHIRE is ejected until the Mission Operations Team for normal mission activities has approved it.

Mission Operations Phase - This phase includes all activities from when SAPPHIRE is approved for normal mission activities until the Mission Directors decide to terminate normal operations or to transfer mission authority.

Exclusive Mission Operations - This first period of mission operations is controlled such that only SSDL operators and affiliates will have vehicle command capability. This will be done in order to ensure the timely completion of all mission objectives. Once these objectives have been suitably accomplished to the satisfaction of the Mission Directors, SAPPHIRE may enter its public period of mission operations.

Public Mission Operations - This second mission operations period enhances the provision of mission services by permitting properly equipped and certified public operators to directly communicate with SAPPHIRE.

End-of-Life Operations - This phase commences when the Mission Directors decide to terminate normal SSDL-controlled mission activities.

Complete termination of mission services will occur if SAPPHIRE is no longer functional. In this event, end-of-life operations may entail occasional health assessment contacts at the discretion of the Mission Directors. Mission transfer will occur if SAPPHIRE is functional but SSDL no longer desires to maintain the vehicle. Transfer will most likely be made to an SSDL affiliate such as AMSAT or a cooperating educational institution. In this event, SAPPHIRE payload operations may still be conducted as a standard SSDL groundstation activity.

Ground Stations

An OSCAR class amateur satellite ground station has been installed on the top floor of Stanford's Durand Building, the home of SSDL. The configuration of this station permits the operation of the SAPPHIRE spacecraft, future SQUIRT vehicles, and other SSDL and amateur satellites. The center is operated and managed by Stanford students and interested local high school pupils. This facility has already been used to contact orbiting Amateur spacecraft and to participate in SAPPHIRE operational testing. The ground station must operate in mode J, with AFSK modulation. The station uplink frequency is 145.945 MHz and the downlink frequency is 437.100 MHz.

User Operational Interface

Access Control : The SAPPHIRE operating system is a bulletin board system allowing multiple users to be logged in at a single time. Users logon to the spacecraft with a particular password in order to initiate a session. During a session, a user may execute any authorized command (controlled by the password used). Users "disconnect" upon completion of their session.

- To logon to the spacecraft, a connect command using SAPPHIRE's callsign(KE6QMD) is sent in order to establish a TNC link. The user's groundstation software should be properly configured such that his/her callsign or station callsign is included in broadcasts.
- Once connected, a password must be entered in order to initiate a session. Three password levels exist: *admin*, *school*, *guest*. Each password permits a different level of command authority for the vehicle.
  - The password for *admin* and *school* users is controlled through a special program with a controlled distribution. The program takes a passkey of varying length as a variable in order to produce the proper numerical password. The satellite upon connection broadcasts the passkey.
  - The password for *guest* users is "guest".
- Access control-related commands include listing all current users, broadcasting a message to all current users, disconnecting specific users, and setting/checking the total number of user permitted to be logged on at once. Setting/checking the total number of permitted users requires *admin* access). These commands are found in the <u>os users</u>... software subsystem (see http://aa.stanford.edu/~ssdl under SAPPHIRE satellite).
- It is interesting to note that the SAPPHIRE software system is always logged on to SAPPHIRE as a distinct, *admin* access user. This arrangement facilitates the programming approach as well as automated platform operation.
- SAPPHIRE is the first user to log onto the bulletin board system. If the total number of permitted users is limited to 2, then only a user with *admin* level access can log in as the second user. This facilitates operational control during anomalous vehicle conditions.
- When done, the user must enter a disconnect command in order to terminate the session. The disconnect command is <u>*disconnect*</u>. Alternatively, if the modem link is disrupted for more than 5 minutes, SAPPHIRE will automatically attempt to verify the link (by sending an "are you there" message ten times every 4 seconds); if the link is not reestablished, SAPPHIRE will terminate the session.
- When disconnecting from SAPPHIRE, the CPU sends a "**Goodbye**" message, and the TNC sends "*** **DISCONNECTE: KE6QMD**" message. Timing between these events is not controlled. If the TNC sends it's message and disconnects first, then the "**Goodbye**" message from the CPU will not be received by the ground operator. See the example login as a guest in Figure 8.

Summary

AMSAT-NA members pioneered a new way to use amateur radio communications through the OSCAR program. With the sift in economic need in industry and government to reduce costs of space access in the last ten years, the "AMSAT way" is now being adopted for space missions outside the amateur community.

Through AMSAT's association with and interest in education, the university community can use this space access as a valuable education tool. Stanford University joined this growing group of universities in the development of low-cost program to build and operate microsatellites in 1994 with the establishment of the Space Systems Development Laboratory – SSDL.

The first product of this program is the Stanford SAPPHIRE microsatellite that is ready for launch. Stanford expects to have a continual production of new microsatellites from SSDL to educate students and promote OSCAR activities and with ASSET a new means of operating these spacecraft.

AMSAT has been a leader in promoting communications in space education, now the educational community is helping promote AMSAT and its OSCAR activities.

```
cmd:c ke6qmd   <------  user typed in command
c ke6qmd       <------  command echo
*** CONNECTED to KE6QMD
Your passkey is 2938789.
Password:guest
guest
Welcome to Sapphire.
? for help.
sapphire>?
?
camera...
disconnect              list of user commands
os...
sensor...
sapphire>d     <------  d – abbreviation for disconnect
d
sapphire>Goodbye.
*** DISCONNECTED: KE6QMD
cmd:cmd:~exit
Connection closed by foreign host.
```

Figure 8 SAPPHIRE Command Example

References & Acknowledgements

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Garcia Sacristan, Michael Hicks – KE6QLG, Brian Engberg – KF6DSL, Bryan Palmintier – KF4YNP, Freddy Pranajaya, Jeff Chan, Kevin Stattenfield, Glen Sapilewski, Alison Nordt, Allison Floyd, Jong-Suh Park, Alex Luebke, Leo Liu, Will Kim, Patrick Hill, Dan Gilley, and those missed, but not forgotten. Also, special thanks also goes to our industry partners, who have aided us with advice and donations: Analog Devices, Dow Corning, Eagle Picher, Harris, ITT Cannon, Lockheed-Martin, Maxim, Motorola, National Semiconductor, PADS, Penstock, Raychem, Space Electronics, Shur-Lok, Space Systems/Loral, and the TiNi Alloy Company. Special thanks to the Jet Propulsion Laboratory for special assistance.

This paper is based on information taken from the SAPPHIRE web pages (http://aa.stanford.edu/projects/squirt1) and the following SSDL publications:

Kitts, Christopher A., and Robert J. Twiggs, "The Satellite Quick Research Testbed (SQUIRT) Program", May 21, 1994, Proceedings of the 8th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 29 - Sept. 1, 1994.

Kitts, Christopher A., and William H. Kim, "The Design and Construction of the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE) Satellite", May 25, 1994, Proceedings of the 8th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 29 - Sept. 1, 1994.

Swartwout, Michael A., Tanya A. Olsen, and Christopher A. Kitts, "The Omni-Directional Differential Sun Sensor", June 1, 1995, Proceedings of the 31st Annual International Telemetry Conference: Reengineering Telemetry, Las Vegas, NV, October 30-November 2, 1995.

Kitts, Christopher A., and Robert J. Twiggs, "Design Progress in the Satellite Quick Research Testbed (SQUIRT) Program", June 1, 1995, Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 19-22, 1995.

Lu, Richard A., Tanya A. Olsen, and Michael A. Swartwout, "Building 'Smaller, Cheaper, Faster' Satellites Within the Constraints of an Academic Environment", June 8, 1995, Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 19-22, 1995.

Nordt, Alison A., "The Design of the SAPPHIRE Separation System and Launch Vehicle Interface", June 8, 1995, Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 19-22, 1995

Kitts, Christopher A., "A Global Spacecraft Control Network for Spacecraft Autonomy Research", June 1, 1996, SpaceOps '96: Proceedings of the Fourth International Symposium on Space Mission Operations and Ground Data Systems, September 16-20, 1996.

Lu, Richard A., "Modifying Off-The-Shelf, Low Cost, Terrestrial Transceivers for Space Based Application", June 10, 1996, Proceedings of the Tenth Annual AIAA/USU Small Satellite Conference, September 16-19, 1996.

Swartwout, Michael A., and Christopher A. Kitts, "A Beacon Monitoring System for Automated Fault Management Operations", June 13, 1996, Proceedings of the Tenth Annual AIAA/USU Small Satellite Conference, September 16-19, 1996

The MOST Microsatellite Mission: Canada's First Space Telescope

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Abstract. The MOST (Microvariability and Oscillations of STars) astronomy mission has been chosen by the Canadian Space Agency's Small Payloads Program to be Canada's first space science microsatellite, and is currently planned for launch in late 2001. The MOST science team will use the MOST satellite to conduct long-duration stellar photometry observations in space. A major science goal is to set a lower limit on the age of several nearby "metal-poor sub-dwarf" stars, which may in turn allow a lower limit to be set on the age of the Universe. To make these measurements, MOST will incorporate a small (15 cm aperture), high-photometric-precision optical telescope to be developed by UBC.

The MOST bus and ground stations are being developed by Dynacon and the University of Toronto, in collaboration with AMSAT Canada. Several of the bus subsystems are based on similar designs that have been flown on past AMSAT microsatellites. However, the MOST attitude control system is unusual for a microsatellite, requiring highly-accurate (< 30 arc-seconds) three-axis inertially-fixed stabilization, far better than can be achieved using the gravity-gradient boom stabilization approach typical of many past microsatellites. Dynacon will provide the MOST ACS, based on its Miniature Reaction Wheel (MRW) and High Performance Attitude Control (HPAC) products. MOST's HPAC capability will enable it to be one of the first ***operational*** space science microsatellites.

Introduction

A paper on the MOST mission[1] was provided in the 11th AIAA/USU Small Satellites Conference (poster session). Since then:

- A Phase A study was carried out, during which the requirements and the design for the mission were defined in greater detail, and some elements of the design were changed.
- A proposal was made to the Canadian Space Agency for a team led by Dynacon to develop this mission.
- That proposal was accepted by the CSA, and mission development has been initiated.

This paper summarizes the current development status of the MOST mission.

MOST and the CSA Small Payloads Program

In 1996, the Space Science Branch of the Canadian Space Agency initiated the Small Payloads Program (SPP) with an Announcement of Opportunity[2]. The CSA has in the past supported missions employing balloon- and sounding-rocket-based science payloads, and the SPP extends this to include microsatellite-based missions. Based on its approved funding level, the SPP plans to launch one Canadian space science microsatellite mission every 3 years; these will be the first dedicated Canadian space science satellites since the Alouette and ISIS ionospheric topside sounding missions of the 1960s. The SPP will support missions within the three priority areas of the Canadian space science program:

- Space Astronomy
- Solar-Terrestrial Physics

- Atmospheric Studies

Early in 1998, the MOST mission was selected via a competitive process by the CSA to be the first microsatellite mission under the SPP. As part of that process, a Phase A study of MOST was carried out during 1997, during which requirements were defined in detail, and an initial preliminary design for the mission, the overall system, and each of the system's main components were developed. It is that design which is presented here.

Under the SPP, the CSA is procuring MOST as a complete *mission*. Dynacon and its team members will develop the mission's requirements, design and build the MOST satellite and its ground stations, support the launch of the satellite, and operate the satellite once it is in orbit. The CSA will provide the launch for the MOST satellite.

Note one of the most significant constraints of the SPP: the requirement that all missions be conducted at a very low cost, with a life-cycle cost cap of CDN$4M (at current exchange rates, under US$3M) for all activities to the end of the first year of operations. This will make MOST, and other SPP missions, among the lowest-cost space science missions ever attempted.

Mission Overview

Science Objectives

MOST is primarily a space astronomy mission. It employs a microsatellite platform to support a very small astronomical telescope. This will be used to collect light from nearby, bright target stars for measurement by a photometer, which will measure oscillations in brightness of the target stars. The frequencies of these oscillations can be used to infer fundamental properties of the stars, including their ages. This has already been done for the Sun, whose vibrations have been known since 1960. Extending this technique to other Sun-like stars will allow use to test theories of stellar structure and evolution, and offers an independent way to place a hard lower limit on the age of the Universe. This hasn't been possible before because the oscillation amplitudes observed in the Sun (a few parts per million in flux) are too small to be detected in other stars with ground-based telescopes.

Since the target stars are bright and provide high photon fluxes across wide bandpasses, a large telescope aperture isn't needed to ensure good signal-to-noise. The handicap has been noise due to atmospheric scintillation (what makes stars "twinkle"), so a small telescope in orbit can overcome this. Also, unlike instruments whose primary purpose is imaging, a photometer does not require a highly-focused image. The total light from a star can be integrated across the image profile on the detector, or reimaged by optics into a sharp image of the telescope pupil, whose total brightness is then measured. Finally, very weak oscillation signals can be extracted from long time series of data by Fourier analysis or similar techniques.

Therefore, it is possible to perform cutting-edge astrophysics with a small telescope on an orbiting platform with only moderate pointing accuracy. MOST has found a way to do this using a very small, inexpensive satellite.

Public Participation

The MOST team anticipates considerable public interest in this mission. The mission has been defined to include two explicit mechanisms to allow members of the public to become directly involved.

The first is an Amateur Observer's Contest. To be administered by the Royal Astronomical Society of Canada, this will provide an opportunity for members of that organization and students to submit proposals for observing specific stellar targets. The MOST science team, the RASC and the CSA will select winning proposals. A portion of the MOST observing schedule will be set aside to observe the selected targets, and the data collected will be provided to the proposers for analysis.

The second involves AMSAT Canada, which will be contributing to the MOST mission in several ways. One contribution will be in the form of an amateur radio payload, allowing AMSAT members to use MOST as a communications relay. (The target payload is currently defined as an L-band uplink, S-band downlink transceiver, to support digital store-and-forward packet communications using existing AMSAT protocols.)

The MOST Team

A team has been assembled that has the technical background necessary to develop the elements of the MOST mission, and to conduct the scientific research at the heart of the mission. The composition of the team reflects additional, programmatic objectives of the SPP, such as to develop a Canadian industrial ability to produce low-cost space science missions based on microsatellite buses, and to involve universities in the development process.

Science Team

The Mission Scientist for MOST is Professor Jaymie Matthews, of the Department of Physics and Astronomy at the University of British Columbia. Co-investigators include Slavek Rucinski (Canada-France-Hawaii Telescope), Professor Anthony Moffat (Université de Montréal), Dimitar Sasselov (Harvard-Smithsonian Center for

Astrophysics), and David Guenther (Saint Mary's University, Halifax). This science team is developing the mission's detailed science requirements, as well as new theoretical stellar models to exploit photometric data whose precision is two orders of magnitude better than what has been possible from the ground.

Instrument Team

Dr. Matthews is also the Principal Investigator for the MOST mission, responsible for the design and construction of the instrument. A team of optical, mechanical and electronics engineers has been assembled at UBC, who already have a strong track record in CCD instrumentation for many of the world's largest and most advanced ground-based telescopes. The UBC team will also benefit from the assistance of the Ontario Centre for Research in Earth and Space Technology (CRESTech), which has expertise in structural design and instrument testing.

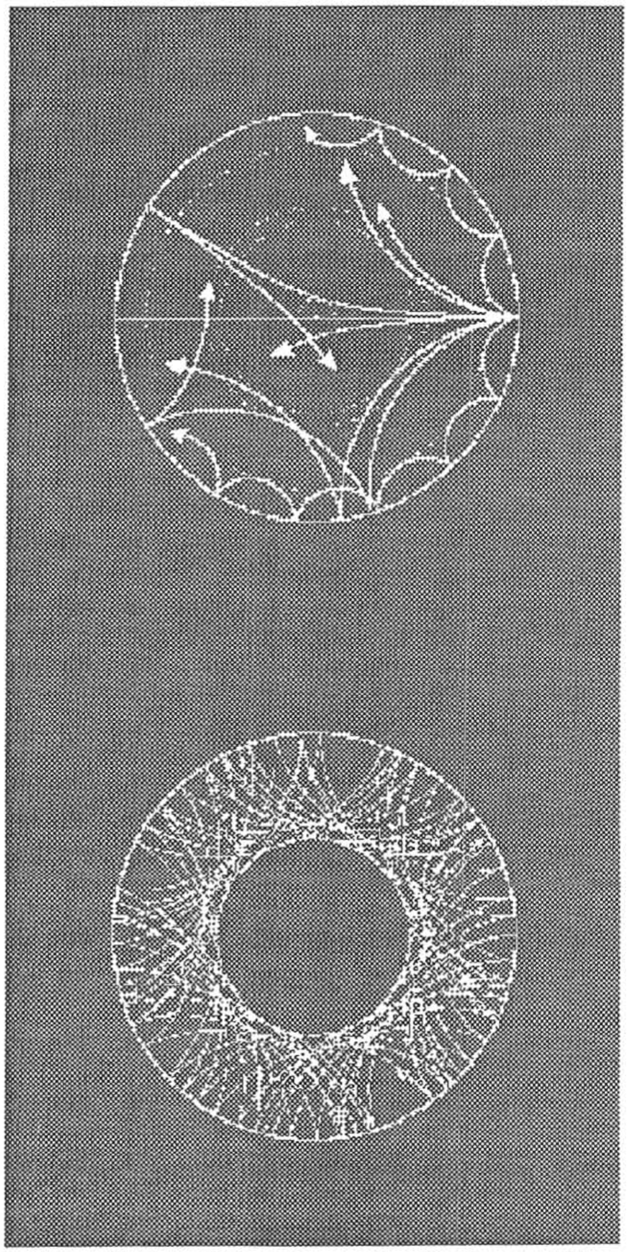


Figure 1: Sound Waves Propagating Within Acoustic Cavities In The Sun.

Industrial Team

Dynacon is prime contractor for MOST, and is responsible for overall project management as well as mission planning and system-level design. Dynacon will also develop the Attitude Control and Thermal Control subsystems for the MOST satellite bus. Dynacon's Project Manager for MOST is Kieran Carroll.

The remaining bus subsystems (structure, power, on-board computers and telemetry & telecommand), along with the ground stations, will be developed by the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS). The UTIAS/SFL team is led by Robert Zee. UTIAS/SFL will carry out development of these subsystems in collaboration with AMSAT Canada, with support from AeroAstro. In affiliation with AMSAT/NA, the designs used in AMSAT's Microsat series of satellites will be adapted for use by MOST.

Science Rationale and Objectives

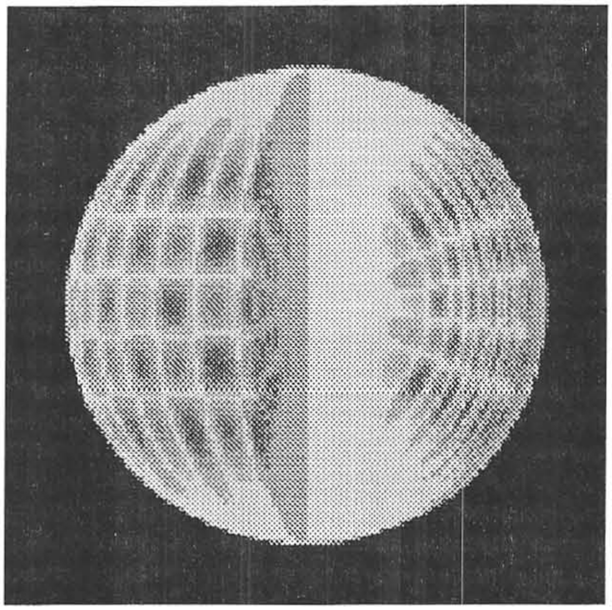
Dr. Matthews has written a review of the principles of stellar seismology from space, available on the World Wide Web[3]. The basic points and their relevance to the MOST mission are summarised below.

The Challenge

Analysis of subtle solar oscillations with periods near five minutes (caused by sound waves refracted through the solar interior by the varying sound speed of the gas, as illustrated in Figure 1) has opened a new window on the structure of our nearest star—the Sun. Using instruments such as spectrographs (which measure solar surface velocities along the Sun/Earth vector) and photometers (which measure variations of solar brightness), this young technique of ***helioseismology*** has confirmed the essential accuracy of the Standard Solar Model (by which we calibrate all other stellar models), and even shed light on the need for new high-energy neutrino physics. Due to the Sun's proximity to Earth, imaging versions of these instruments can resolve oscillation patterns across the Sun's surface.

Astronomers would like to extend this technique to other Sun-like stars but have failed to make any clear detections to date. The challenge is illustrated by the case of the Sun. If the Sun's light output is integrated across its entire surface (thus emulating the way that we see a distant unresolved star), the oscillation amplitudes are only a few

Figure 2: A Simulated Solar Oscillation Mode (Degree l=20, Azimuthal Order m=16, Radial Overtone n=14).



cm/s in radial velocity and a few micromagnitudes (on the order of 10^{-6}) in flux. In order to achieve such velocity precision using spectrographic techniques would, even for the brightest stars, require the largest telescopes and much more stable spectrographs than are currently available. In the case of photometry, photometric precision from Earth-based instruments is fundamentally limited by scintillation noise caused by our turbulent atmosphere. This can only be reduced from the ground by employing several telescopes of very large aperture over many months of time. A dedicated network of six ground-based 10-metre telescopes would be capable of seeing the five-minute oscillations in the brightest solar-type stars, but would have an estimated capital cost of US$745M and an annual operating cost of about US$90M.

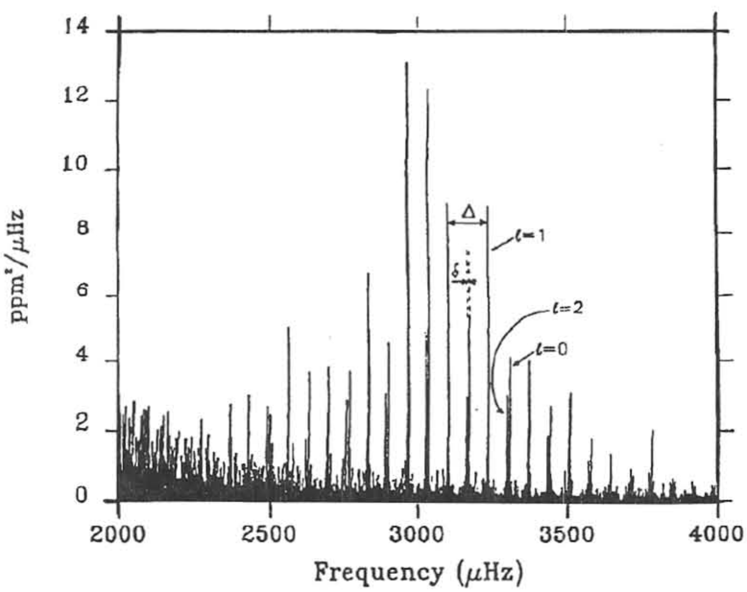


Figure 3: Fourier Power Spectrum of Solar Oscillations Observed Photometrically in Integrated Light with the IPHIR Photometer from Russian "Phobos" Mars Probe

The same goals are attainable with a single telescope of modest aperture (~15 cm) in orbit, above the scintillating atmosphere and monitoring stars in its Continuous Viewing Zone (CVZ—defined under "Mission Analysis", below) for weeks to months, at a fraction of the cost of a terrestrial network.

The Requirements

The sound waves propagating within the Sun set up acoustic oscillation modes at the surface corresponding to different eigenfrequencies and spherical harmonic patterns, as shown in Figure 2. In other stars, all but the simplest mode patterns would average out over the visible disk, but the remaining modes would appear as a "comb" of nearly equally spaced frequencies in a Fourier power spectrum, as shown in Figure 3. The spacing depends on the sound travel time across the star—giving us its radius—while small deviations from that spacing are sensitive to the composition of the stellar core. Since a main sequence star like the Sun is gradually converting its supply of hydrogen into helium to produce energy, the core composition is a "clock" which keeps track of the star's age.

In the solar eigenmode spectrum, adjacent frequencies are spaced by about 70 μHz; the fine structure can be as small as a few μHz. Frequency splitting due to the star's rotation can easily be as small as 0.5 μHz. Therefore, to obtain the best asteroseismic data, the necessary frequency resolution demands an observing time baseline of about 1/0.2 μHz, or about 2 months.

Gaps in the time series will introduce alias peaks and sidelobes in the Fourier spectrum, increasing the "noise floor" out of which the comb-like signal pattern emerges. Two main factors drive the magnitude of this "noise":

- The more photometrically precise the basic photometry data is, the lower will be the amplitude of the Fourier spectrum noise floor. Control of stray light in the instrument, and careful calibration of the instrument are them means for achieving this.
- The more nearly continuous the time coverage is, the lower the Fourier spectrum noise floor can be pushed; good observations must cover at least 90% of the duration of the data record of each observing run, in order to produce a final photometric precision in the Fourier spectrum at the level of a few parts per million.

The Science Plan

MOST can satisfy all the data requirements at a relatively low cost. In a one-year mission, it could monitor at least six target stars and return the following results:

- First confirmed detection of Sun-like oscillations in another star (still not achieved from Earth), and resolution of acoustic eigenmode frequency spectra for these, allowing their ages to be estimated.
- First detection of p-mode oscillations in a "metal-poor" (i.e., very old) sub-dwarf star, and resolution of eigenmode frequency spectrum to determine star's age. If the selected star is old enough, this could add new data to the current debate on the age of the Universe.
- Serendipitous detection of any Earth-sized planets whose orbits around the MOST target stars might cause eclipses and hence flux decreases on the order of 10 micromag.
- Accurate tracking of starspots carried around the stars' surfaces by rotation.
- Very precise eigenfrequency spectra of one or two magnetic pulsating stars (roAp stars) whose fine-splitting also contains information about internal magnetic field strength and geometry - insights which are impossible to obtain in any other way.

Mission Concept

Driving Requirements

The MOST mission entails placing a low-cost satellite equipped with a high photometric precision telescope into Earth orbit, and using it to conduct observations on a series of stellar targets. There are two mission requirements that strongly constrain the choice of orbit and launch vehicle for MOST:

Long-Duration Uninterrupted Stellar Observations

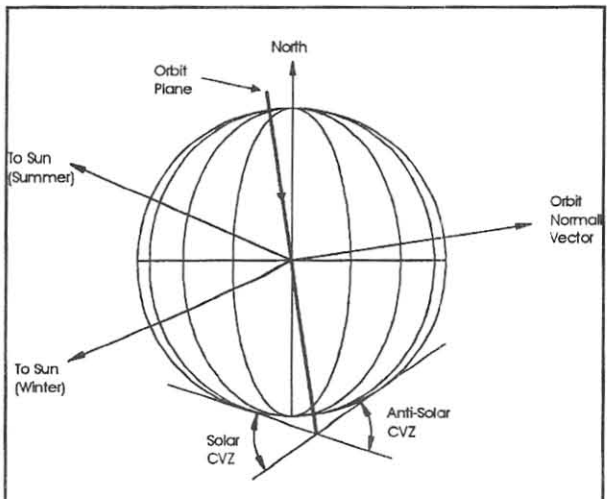


Figure 4: Continuous Viewing Zones for a Dawn/Dusk Sun-Synchronous Orbit

Low cost implies a small satellite, and given the resulting small telescope aperture, long (up to 7 weeks) duration observations are required in order to achieve an adequate signal/noise ratio following analysis of a star's photometry data. A nearly uninterrupted record of observations will improve the results of the analyses. The science team requires that no more than 10% of observations in a given period be missed.

Every Earth orbit has a Continuous Viewing Zone (CVZ) centered about each of the two orbit normal vectors; these are cones with half-angle equal to the declination of the Earth's horizon below the satellite's local "horizontal" plane, as illustrated in Figure 4. Stars located within the CVZ are visible from the satellite for the full duration of an orbit.

The science requirement implies that the CVZ "dwell" on each of the selected target stars for durations exceeding one month. This requirement is achievable only for near-polar and near-equatorial orbits.

Low Cost

The budget constraint for the project rules out all but the least expensive of launch opportunities. These include secondary payloads on launchers such as Delta and Ariane, and Get-Away Specials on a Space Shuttle. In each of these cases, the available mass and volume allocations are small, and the choice of orbit is dictated by the primary payload.

This requirement strongly favours orbits between about 600 and 900 km altitude. Above 900 km, high Van Allen belt radiation levels favour the use of expensive, rad-hardened electronic components over less-expensive, commercial-grade components. Below 600 km, the half-angle of the CVZ cone becomes so small that few stars are available for observations at any one time.

Baseline Orbit Selection

The orbit which has been chosen as the baseline for the MOST mission meets these requirements; it has the following characteristics:

Sun-Synchronous

The orbital plane, and hence the CVZs for this type of orbit precess about the celestial poles at a rate of about 1°/day (i.e., one scan around the celestial sphere per solar year), providing access to a large number of stellar targets, but with a slow enough scan rate to allow long-duration observations. The orientation of the orbit plane with respect to the Sun does not change for this type of orbit, simplifying the effects of solar aspect angle on the satellite's power, thermal and payload design. Also, many Earth-observation satellites are launched into this type of orbit as primary payloads, creating many possible secondary payload opportunities.

Baseline Altitude

An 785 km altitude circular orbit has been baselined, equal to the altitude of Canada's Radarsat I satellite (the corresponding inclination is 98.6°). This is high enough to have a large CVZ (26° half-angle), resulting in target star dwell times within the CVZ of up to 7 weeks; it is also high enough that atmospheric drag will not significantly degrade the orbit within the first year of operations. This orbit is low enough to avoid severe radiation effects from the Van Allen belts.

Ascending Node

A dawn/dusk sun-synchronous orbit, with an ascending node of either 6 P.M. (like Radarsat) or 6 A.M., has been selected as the baseline for MOST. This offers particular advantages to the satellite design:

- The Sun always lies within about 35° of the center of one of the CVZs, while the other CVZ always points in the anti-Sunwards direction; the MOST telescope will target stars in the latter CVZ, allowing the body of the satellite to shield the telescope's aperture from the Sun. This eliminates the need for the type of large external baffle that would be needed in most other types of orbit.
- At the baseline altitude, this type of orbit does not experience eclipses for most of the year, and the maximum-duration eclipse is less than 15 minutes long (out of a 100-minute orbital period). This offers the potential to design the satellite's power subsystem with relatively small batteries, and for a relatively large fraction of solar-array power production to be available for direct use rather than for battery charging.
- For the >9 eclipseless months of the year the satellite's thermal environment will be almost static, with one side always facing the Sun and the opposite side always facing deep space; this should simplify the thermal control system analysis and design task, helping to keep engineering costs to a minimum.

Baseline Launch Opportunity

The baseline orbit was not chosen casually. One of the greatest challenge faced by the developers of any secondary payload is the sourcing of a suitable launch opportunity. These are rarely known further than two years in advance of launch, and a primary payload with an orbit compatible with that needed by the secondary can be hard to find. MOST has the advantage that Canada's new Radarsat II satellite is being planned for launch into the same orbit as Radarsat I, an orbit which is ideal for MOST.

Radarsat II is currently planned for launch in November 2001 on a Boeing Delta II launcher, which has a well-established secondary payload capability. Discussions are proceeding with the Radarsat II Program at CSA, regarding the potential to fly MOST with Radarsat II. (Other launch possibilities are also being investigated by the CSA for MOST, in case the Radarsat II launch opportunity fails to become available.)

Operations Scenario

MOST mission operations are phased as follows:

- Following launch, the launch vehicle maneuvers to the desired orbit for MOST, and releases the satellite.
- The satellite then is detumbled, conceptually using the Earth's magnetic field and the Sun as attitude references, ending in a Sun-pointing attitude.
- The telescope's boresight is slewed towards the first selected target star.
- The attitude control system then operates to keep the telescope pointed towards the target star, with sufficient accuracy to allow the required science photometric precision to be achieved.
- The first target star will be tracked for a commanded duration, up to the time when it has drifted to near the boundary of the CVZ (up to 7 weeks). At the end of this period, the telescope's boresight will be slewed to the next target star.

The mission does not rely on continuous radio contact with the ground. Intermittent contact is planned for, with a pair of ground stations to be located in Toronto and Vancouver.

To achieve a reasonable level of robustness against unexpected anomalies, the mission requires that a "safe/hold" attitude control mode be developed to ensure continuity of power collection, along with a definition for the conditions under which the satellite would autonomously enter this mode, and the operations required to regain normal operations from this mode.

Mission Duration

It is anticipated that these operations will involve up to 7 weeks of observation of each target star in turn, for the duration of the useful life of the satellite. A useful lifetime of 5 years or more can be expected before the satellite's orbit drifts significantly away from the dawn/dusk condition due to atmospheric drag, Lunar/Solar gravitational perturbations, etc. The satellite has no consumables, and items of equipment that will degrade over time (e.g., solar arrays, batteries, reaction wheel bearings, digital electronics subjected to radiation) are expected to last for a similar period. The science team estimates that the main science objectives can be met within the first year of operations, but there are more than enough bright target stars accessible to MOST to keep it busy well after that.

System Design Concept

System Architecture

The equipment that will be developed to support the MOST mission comprises two major elements, the MOST Satellite and the MOST Ground Segment. The satellite is divided into a Bus and a Payload, and the Ground Segment into Ground Control Stations and GSE, which in turn are made up of Subsystems as shown in Table 1.

Table 1: System Architecture

Primary Element	Secondary Element	Subsystem
Satellite	*Bus*	Structure
		Thermal Control
		Power
		Attitude Control
		Telemetry & Telecommand
		On-Board Computers
	Payload	Instrument
		Payload Data Processors
Ground Segment	*Ground Control Stations*	Toronto GCS
		Vancouver GCS
	Ground Support Equipment	Development GSE
		Launch Support GSE

The guiding philosophy for design of this system is to employ proven microsatellite designs as a starting point, making minimal adaptations to these in order to enable the core science objectives of the mission to be met. The resulting system design allows the mission to be achieved while re-using structural, power, on-board computing, telemetry & telecommand and ground station subsystem design envelopes from previous successful microsatellite missions. A new instrument design was needed, and some new attitude control capabilities had to be developed to augment ACS designs used in past satellites.

Most of the inter-relations between subsystems are fairly standard, as illustrated in Figure 5. One somewhat unusual interface has been specified, between the science instrument and the attitude control subsystem. In addition to collecting science data, the instrument will be used to collect data measuring the pointing error between the instrument's boresight direction and the target star's direction. These data will be provided to the ACS, which will use them to control this pointing error towards zero.

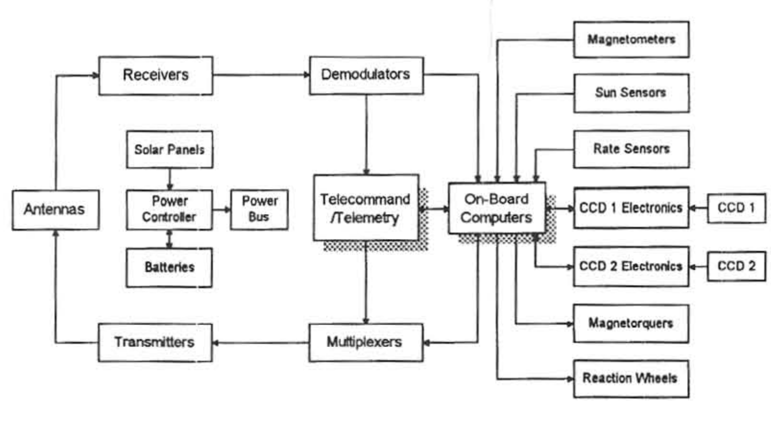


Figure 5: MOST Satellite Functional Architecture

Attitude Control Accuracy Trade-Off

With this system architecture, attitude control accuracy becomes a driving system parameter:

- An upper limit on acceptable pointing error can be determined by evaluating the effects of pointing error on instrument photometric precision. A narrow field of view is necessary to eliminate signals from background stars in the vicinity of the target star. Wandering of the target star's image within the instrument's field of view can also degrade photometric precision, depending on the level of calibration across the image plane that can be achieved.

- Achieving high-accuracy attitude control depends on achieving even higher-accuracy pointing error measurements from the instrument, at a sufficiently high measurement rate to be consistent with the attitude control subsystem's controller bandwidth. Below some level of pointing-error accuracy, this effect can lead to instrument requirements (e.g., in terms of resolution, and sample rate) that are more stringent than and incompatible with the science-related instrument requirements. This would lead to a more expensive instrument design than otherwise.

The attitude accuracy parameter thus can be used to trade instrument cost against photometric precision. For the current baseline instrument and ACS designs, a maximum instrument boresight pointing error of 25 arc-seconds has been selected. For reference, note that the typical level of pointing accuracy achieved by previous microsatellites has been about 1 degree (3600 arc-seconds); while larger satellites routinely achieve < 25 arc-sec accuracies, MOST demands an improvement in the microsatellite ACS state of the art.

Satellite Overview

Satellite Layout

The satellite's general layout is shown in Figure 6. It is driven by the secondary payload volume envelope provided by the Delta II launch vehicle. It incorporates a stacked set of Bus functional modules, with an adjacent Payload bay defined by a set of panels (including the solar array panels. The overall dimensions (including an allowance for the launch vehicle interface hardware, but excluding appendages for antennas and magnetometers) are 63 by 58 by 25 cm.

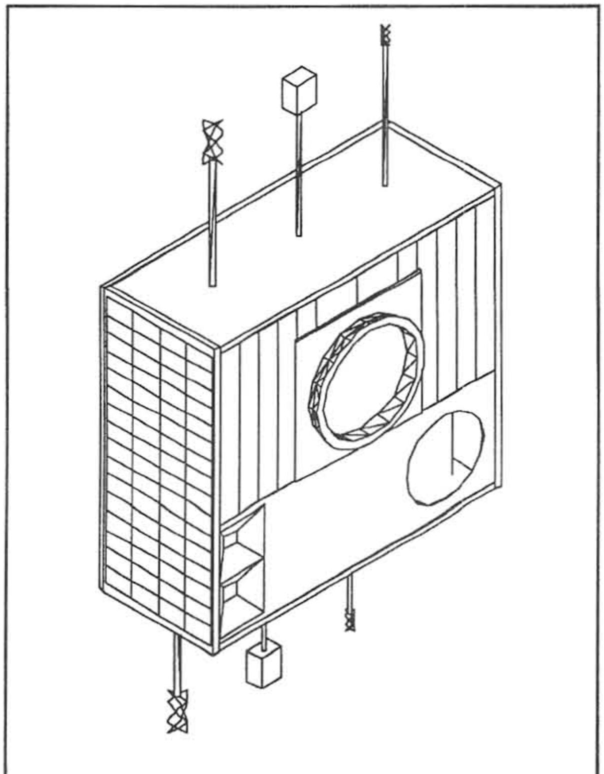


Figure 6: MOST Satellite Layout

Bus Overview

The main features of the MOST Bus design are:

- It is based on the stacked-tray modular concept that has been used successfully in the AMSAT Microsat series of satellites, as well as in the University of Surrey/SSTL UoSATs. The main functional elements of each subsystem (electronics boards, reaction wheels, batteries) will be housed within a set of trays of identical cross-section, which will be bolted together to form a "box-beam" structural back-bone for the satellite.
- On 5 sides, the stack of trays will be covered by a set of structural panels, on which will be mounted photovoltaic cells, and booms for antennas and magnetometers.
- On the remaining side of the tray stack will be mounted a standard Delta-II Payload Adapter Assembly (PAA): one-half of a Marmon-clamp ring plus supporting structure.
- The Power, Telemetry & Telecommand, and On-Board Computers subsystems are closely based on subsystem designs that have been flown on other microsatellites.
- The Attitude Control subsystem uses as its foundation a design that has been used successfully in other microsatellites: magnetometers and magnetorquers are used to provide a simple but low-accuracy basic attitude control capability, used for detumbling and safe/hold modes.
- To achieve the high-accuracy attitude control capability needed to achieve the science goals, a set of small reaction wheels will be used to provide 3-axis actuators. These will be actuated based on pointing error signals generated by the science instrument, when operating in fine-pointing mode.

Payload Overview

The MOST satellite's payload comprises the science instrument, along with the electronics required to operate it and interface it with the on-board computers. The main requirements on the instrument are:

- To collect science photometry data from the selected target star. This is required to be photometrically very precise in order to maximize the signal to noise ratio, to be photometrically stable over sample runs of several weeks duration when subject to up to 25 arc-seconds of instrument boresight wander, and to have a wide dynamic range in order to maximize the number of useable target stars.

- To collect star-field image data with which the ACS will measure the instrument's pointing error. The baseline requirement here is to produce star field image data once per second, using variable exposure times of as little as 1/10 of a second.

The main requirements on the payload data processing electronics are to operate the instrument's camera, to process photometry measurements from the target star using variable exposure durations between 1 and 100 seconds, and to process the star-field image data at a 1 Hz rate with a maximum latency time of one second to produce boresight pointing error measurements with an accuracy of 1 arc-second.

The science instrument features a CCD-based visible-light camera, which receives light through the largest optical telescope that can fit within the available volume and mass allocations. The baseline design has a 15-cm aperture, and is about 55 cm long. The CCD will be passively cooled, and its temperature actively controlled to maximize photometric precision.

System Resource Budgets

The current allocations of mass, orbit-average power and volume (in the form of tray-stack height) to each of the satellite subsystems are summarized in Table 2. The allocated values are estimates of the amount of each resource needed by each subsystem, based on preliminary designs of each subsystem. The "Satellite Total" represents the total secondary payload mass that the Delta-II launcher can support, the worst-case orbit-average power available from the baseline power subsystem design, and the total tray-stack height available in the baseline layout. The amount of system margin that remains available is fairly comfortable, for this stage of the design process.

Table 2: Satellite System-Level Budgets

Subsystem	Mass (kg)	Power (W)	Tray Height (mm)
Structure	13.9	0	0
Thermal Control	0.6	0	0
Power	6.8	0	35
Attitude Control	7.8	12.6	146
Telemetry & Telecommand	2.3	5	122
On-Board Computers	1.3	5	45
Instrument	7.4	3.4	26
Payload Data Processors	1.2	2.5	32
System Margin (%)	8.7 17%	13.5 32%	172 30%
Satellite Total	**50**	**42**	**578**

Ground Stations Overview

A large number of ground stations will be able to communicate with the MOST satellite. These can be grouped in two classes:

- A pair of ground control stations will be developed, that will be used to issue commands to operate the satellite's payload, attitude control subsystem, and other housekeeping functions. These will be located at the University of Toronto and the University of British Columbia.
- Amateur communications ground stations operated by AMSAT members will also have access to the satellite, through a communications payload to be provided by AMSAT. Tentatively, these will be used to provide a digital store-and-forward packet communications service.

Both types of ground stations will use a similar design: commercial UHF/VHF transceivers with programmable Doppler correction, L- and S-band up- and down-converters, and AMSAT-developed satellite tracking and radio-operation software running on commercial PC-class computers. These are inexpensive to develop and reliable in operation, and have the data throughput capacity needed to downlink the data generated by the satellite's payload.

Subsystem Summaries

Payload

The payload consists of a telescope which looks out the side of the bus via a "periscope" mirror and feeds a CCD camera (cooled by a passive thermal control system and radiators) whose electronics interface with the on-board computers. The current concept for this instrument is shown in Figure 7.

The instrument serves two roles:

1. An ultraprecise photometer for science measurements.
2. A star sensor providing data to the Attitude Control Subsystem (ACS).

The latter function requires a fairly large field, while the former requires a very clean "point spread function" (PSF) for star images and minimal scattered light. As a result, we have adopted a Maksutov optical design which provides an unvignetted field of about 2 x 2 degrees and has no support struts for the secondary mirror which would introduce diffraction spikes and additional scattering.

The size of the telescope is limited by the available volume in the bus. The 15-cm aperture is the smallest that still offers good photon-counting statistics for a reasonable selection of science targets.

To keep costs low and reliability high, the current design includes no moving parts. The truss-like mechanical structure is athermal, with components of various CTEs (Coefficients of Thermal Expansion) carefully chosen so the optics maintain the same focus across the full range of temperatures to be encountered by the payload (from the lab bench to orbit). There is only one broadband filter (since the primary science goals can be achieved without multicolour data) and hence, no motorised filter wheel.

The prime detector of the instrument is a large-format (~760 x 1152 pixel) CCD cooled to -50C and stable to 0.1C per hour to keep readout noise below the stringent photometric error budget. The device will be partitioned so that two regions can be read out independently at different clocking rates.

One portion of the CCD, with a field of about 0.5 x 0.75 degrees, will collect star-field image data (slightly defocused) with which the ACS will determine the instrument's pointing error. The baseline requirement here is to produce star-field images at least once per second, with exposure times as short as 0.1 sec. Signal-to-noise requirements are not stringent, and stars as faint as magnitude 10 - 11 will be suitable for guiding.

The other portion of the CCD will be dedicated to science data. The instrument must be capable of photometric precision of a few ppm even when the star images wander by up to 25 arcsec (the nominal performance of the ACS) in exposures of 1 - 60 sec. In-focus imaging photometry would require us to characterise the pixel-to-pixel sensitivity variations ("flat-fielding") of the detector on the ground and in orbit to precisions never before achieved. Instead, we direct the starlight onto a Fabry lens in the camera window, designed to produce an extended image (about 40 pixels in diameter) of the telescope pupil on the CCD which moves by less than 0.1 pixel even if the star beam wanders by as much as 25 arcsec. This makes the instrument very insensitive to detector sensitivity gradients.

(Note that while the instrument's requirements have not changed substantially from those presented at this conference last year, several important design changes have been made. In particular, the telescope optics have changed from Cassegrainian to Maksutov, the two CCD detectors for science and star-sensing data collection have been replaced with a single detector, and the beam-splitting mirrors have been deleted. These changes result in a large improvement in the instrument's photometric precision.)

Payload CCD thermal control involves two main components:

- A "cryocooler" module (developed by CRESTech under an earlier program) will be used to produce a low-temperature heat-sink, from which heat from the CCDs will flow. The cryocooler employs a set of second-surface mirrors and baffles to radiate heat from its mounting-point on the anti-Solar-CVZ-facing side of the satellite. It is sized to keep the CCDs at below -50 C.
- Heaters mounted by the CCDs will be actively controlled, based on measurements taken by temperature sensors, to maintain changes in the CCD temperatures to within 0.1 C per hour.

To minimize heat flow into the instrument from the satellite bus, insulating stand-offs and multi-layer insulation will be used to separate the two.

The payload data processing electronics must 1) operate the

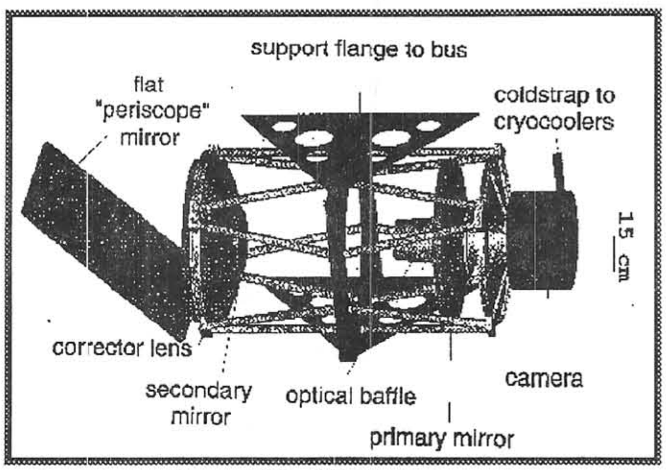


Figure 7: The MOST Instrument

CCD, 2) convert the raw CCD data to a form suitable to be stored and downlinked, 3) flag any deviations from nominal photometric performance and alert the ground station on the next pass, and 4) process the star-field image data to produce boresight pointing error measurements with an accuracy of at least 1 arcsec. The design for these electronics has heritage from designs developed at UBC for CCD cameras for use in terrestrial astronomical observatories, taking into account processors that have flight heritage; the baseline design uses ttwo digital signal processors (DSPs, baselined as TI TMS320C31): one to carry out star sensor software processing, and the other to carry out science data processing. Each DSP is allocated 1 MB of local RAM memory protected by hardware EDAC. The boot PROMs for the digital signal processors are built into the processor chips. They are to be programmed on the ground, so that if one of the DSPs is reset, it can recover back to an operational mode. Should one of the DSPs cease to function temporarily, a single DSP can satisfy basic data processing needs.

Structure

The MOST microsatellite is a rectangular box, 63× 58× 25 cm. The concept for the bus structure has three primary elements:

1. A set of stackable trays, into which electronics boards, batteries, reaction wheels, etc. can be mounted. The design details are driven by the volume and PAA location available in a Delta-II launcher for secondary payloads; unlike other satellites that have used the stacked-tray structure approach, for MOST the trays are oriented to "lie on their sides" during launch, with the PAA mounted to the side of the stack. To provide sufficient strength in this configuration, shear plates are inserted between each tray.
2. An instrument bay, which is an enclosure for the instrument, and also provides mounting points for solar panels. This is constructed from aluminum honeycomb panels.
3. A Payload Adapter Assembly (PAA), which bolts onto the side of the stack of trays, and is used to clamp the satellite to the launch vehicle (via a Marmon clamp arrangement). The NASA Delta II Secondary Payload Planner's Guide specifies the design of the interface ring for this PAA.

Reports from other developers indicate that the stacked-tray concept results in significant simplifications in the system development, integration and test process, which result in cost savings. The stacked tray assembly is held together by titanium tie rods.

The telescope "enclosure" consists of two honeycomb panels located at the bottom and bottom inboard sides of the satellite. Cutouts are provided for the telescope aperture and

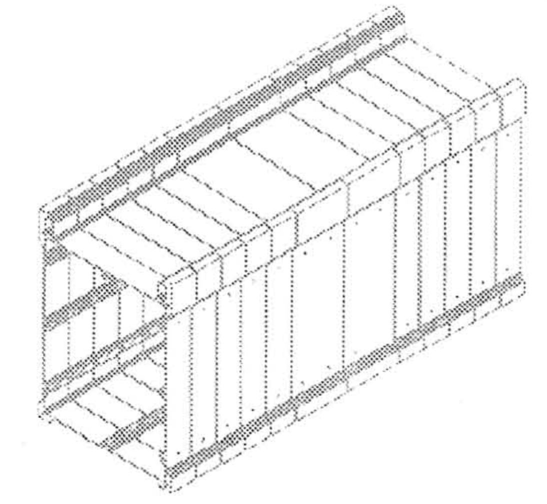


Figure 8: Stacked Tray Assembly

cryocoolers on the inboard panel (nominally facing away from the sun). Three solar arrays are to be fixed to the exterior of the bus structure via attachment bolts. Relative to the launch vehicle, they will be mounted on the outboard and side faces of the satellite. The solar panels complete the telescope enclosure. The payload adapter assembly is mounted against the electronics trays, on the inboard side.

The structure has been designed to accommodate conservative launch loads of 10G (specified by the Delta II launch vehicle guides) with an ultimate safety factor of two. Initial finite element analysis indicates that the structural design is more than adequate for the Delta II launch (the worst case loads occur during launch), with maximum deflections on the order of 0.1 mm.

The stacked tray assembly, as shown in Figure 8, consists of several electronics trays, the heights of which can be customized to the specific components that are housed. The two center trays behind the payload adapter assembly contain heavy components such as reaction wheels and batteries to place the satellite mass center as close to the launch vehicle attachment as possible. 2-mm-thick shear plates separate the electronics trays to strengthen the stack.

The electronics trays have nominal dimensions of 23× 31 cm and are made of 6061-T6 aluminum. A channel is provided for wiring harnesses at the top of each tray. The wiring channel is covered by a 1-cm thick aluminum honeycomb panel, with cutouts for the antenna and magnetometer standoffs mounted on the top face of the satellite.

The payload adapter assembly (PAA) for MOST consists of a square plate with the adapter ring protruding. The PAA is machined out of a single piece of aluminum, with the adapter ring designed to mate with the Delta II launch vehicle secondary payload attach fitting. The payload adapter assembly plate is removable to allow for mating checks with the launch vehicle payload attach fitting, and is machined from high-strength aluminum alloy.

Thermal Control

The baseline approach to thermal control for the MOST bus is to employ entirely passive means. (Thermal control for the payload is semi-active, as discussed above.) While a variety of thermal control situations can arise over the course of the mission (e.g., during tumbling after release from the launch vehicle), one of the most challenging is the one in which the satellite will spend most of its time. During fine-pointing mode:

- The telescope aperture face of the satellite (one of the two "large" faces) will be aimed towards science targets in the anti-Solar CVZ. This face will see a combination of deep space and the Earth's limb, the latter occupying at most ~40% of the face's FOV, usually somewhat less. This face will tend towards a low temperature.
- The opposite "large" face will thus point within the Solar CVZ, and will always see the Sun (except during eclipses, which occur only during <3 months of the year), with solar aspect angles ranging from straight-on to 57 degrees off perpendicular. This face will be covered with photovoltaic cells, which are highly absorptive; it will tend towards a high temperature.
- From a bus-fixed reference frame, the Earth will appear to rotate once per orbit about the axis through these two faces; the other 4 smaller faces will each be exposed in turn to the Earth's face and to deep space.
- As a result, a strong thermal gradient is prone to develop between the Sun-facing and anti-Solar faces.

Thermal control coatings will be applied to the 3 surfaces that aren't covered by photovoltaic cells. The design objective is to keep temperatures for temperature-sensitive components (e.g., batteries) within acceptable ranges for the full range of operational orientations. Initial analysis indicates that application of white paint to the anti-Solar face can keep bus temperatures between 7 and 23 degrees C, if the solar arrays are thermally coupled to the bus structure.

Power

The design concept for the power subsystem comprises the following components:

- A set of three solar arrays, mounted to the outboard and side faces of the MOST satellite, providing 14V.
- A rechargeable battery to provide power during eclipse, producing 12V during discharge. Analysis indicates that about 1 A-hr of energy is needed from the 12V battery.
- A battery charge controller circuit.
- Solar array peak-power tracking circuitry, for each solar array panel.
- A voltage regulator to provide some power at +/- 5V.
- A set of power-switching circuitry, to provide 12-14V and +/- 5V power through a number of computer-controlled switches, each equipped with a maximum-current shut-off capability. The switches are also commandable from the ground.

Table 3: Fine-Pointing Mode ACS Requirements

Telescope-Frame Axis	Pointing [deg]	Stability [deg/sec]
Roll Angle (Boresight)	1.0	1.2
Pitch Angle	0.008	0.010
Yaw Angle	0.008	0.010

Based on preliminary power analysis, silicon solar cells covering the entire outboard and side faces of the MOST satellite will produce at least 48 W of power when in sunlight, more than enough power to support all functions and battery charging requirements. No solar panels are required on the top and bottom faces of the satellite where the antennas and magnetometers are mounted. These calculations assume that the main solar array does not deviate by more than 57° from the sun line (for a dawn-dusk sun-synchronous orbit). In addition, it is expected that the side panels never get closer to the sun line than 33°.

The secondary power system for the MOST satellite consists of NiCd batteries. Batteries are intended to be used during eclipses, which are relatively short-lived (17 minutes maximum) for dawn-dusk sun-synchronous orbits. The current battery design consists of 10 cells in order to achieve a nominal bus voltage of 12 V.

The design concept for the power control unit, illustrated in Figure 9), is based on designs with heritage from numerous AMSAT satellites. When the solar panels are illuminated by the sun, they set the bus voltage. Power is also supplied to the Ni-Cd batteries during this period in order to charge them through the Battery Charge Regulator (BCR). Peak power tracking is included in this scheme. A

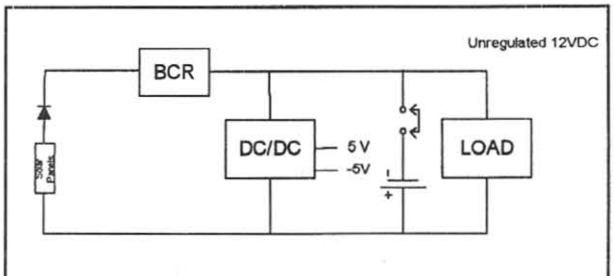


Figure 9: Power Control Unit

computer must operate in a loop with a DC to DC converter and controls the regulator in such a way as to manipulate the input voltage to the regulator.

Attitude Control

The requirements imposed by the mission on the MOST satellite's Attitude Control subsystem (ACS) are relatively demanding. While high-accuracy three-axis control is common among larger satellites, this type of design has almost never been used on microsatellites in the past (where "microsatellite" denotes a satellite of <100 kg, costing <$10M). This has been due to lack of availability of small and inexpensive star sensors and reaction wheels, key components for an ACS that aims for accuracies in the arc-second range. To overcome this problem, MOST will employ a new design for a small reaction wheel that is being developed by Dynacon, and will use the science instrument as the satellite's star sensor.

During stellar observation, telescope pointing must be regulated to maintain the image of the target object within a certain area of the CCD detector array—the area of the CCD that is covered by one of the camera's Fabry lenslets. These lenslets each cover a circular area of the CCD, whose diameter is equivalent to about 25 arc-seconds of telescope FOV angular extent; the pointing accuracy requirement corresponds to keeping the target star's image within the bounds of the selected lenslet.

(Note that these pointing accuracy requirements are considerably more stringent than the ~1 arc-minute cited in this conference last year. This is due to the changes in the telescope design, particularly the adoption of Fabry lenslets, which no longer permit the target-star's image to wander around the CCD's surface.)

In addition to these pointing dispersion limits, the instrument's use as a star sensor poses an angular rate (stability) limit on the pointing, determined by the finite exposure time required to acquire an image, coupled with the need to avoid smearing of star images. The resulting telescope pointing regulation requirements are summarized Table 3.

In addition to telescope pointing regulation, the ACS is required to support the general operation of the satellite as described by the following general functions:

- *Attitude Acquisition and Stabilization.* There will be times during the mission (including the post launch and separation condition) when the satellite must recover from a state of unknown attitude motion (tumbling) and achieve a state of stable attitude.
- *Target Slew.* The satellite must be able to re-orient itself from one stabilized attitude to another, such as when repositioning the telescope to a new target star.
- *Momentum Management.* The ACS must manage the disposition of satellite angular momentum throughout the mission.
- *Safe/Hold Provision.* The ACS must provide for protection of the science instrument from damaging solar exposure, as well as ensure adequate solar array exposure for power generation throughout the mission.

The general architecture of the ACS is shown in Figure 10. It includes the following main components:

- Actuator Hardware:
  Reaction Wheels (4, tetrahedral arrangement)
  Magnetorquers (3 axes, 2 of each)

- Sensor Hardware:
  Sun Sensors (2)
  Magnetometers (2 × 3-axis)
  Differential Star Sensor (1 × 3-axis)
  Inertial Rate Sensors (4)

- Major Software/Functions
  Orbit Model and Earth/Sun Ephemeris
  Earth Magnetic Field Model
  Inertial Attitude Estimator
  Relative Motion Estimator
  Coarse Detumbling B-Dot Law
  Fine Detumbling Control Law
  Fine Pointing Control Law
  Wheel Speed Management Law
  Safe/Hold Control Law

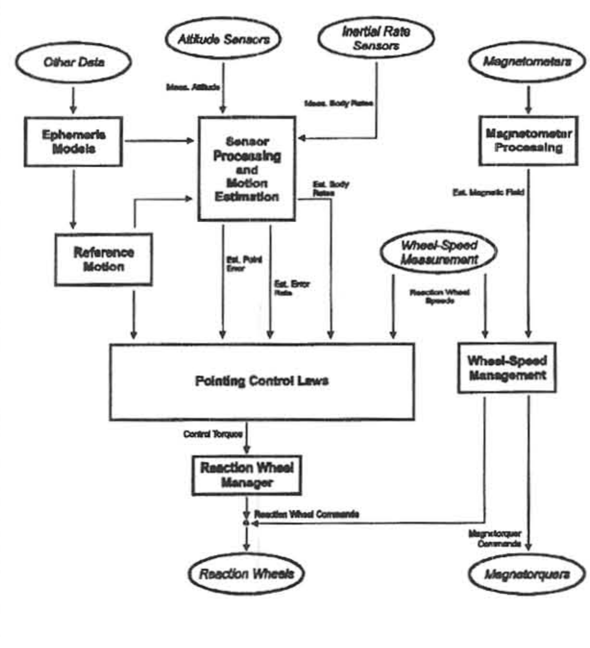


Figure 10: MOST ACS Architecture

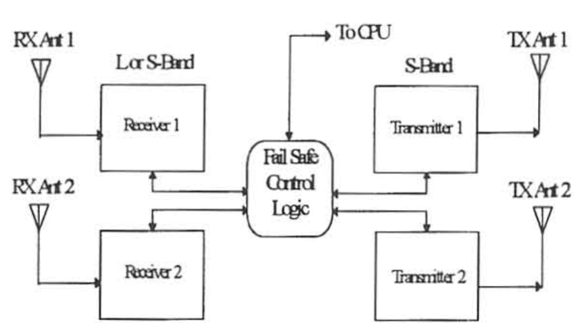


Figure 11: Transceiver

Magnetometers, magnetorquers and star sensors will be based on designs used on previous microsatellites developed by AMSAT and others. Detumbling and safe/hold ACS modes using this equipment will similarly be based on well-established microsatellite ACS design practices.

Dynacon will be providing a set of 4 of its commercial MRW (Mini-Reaction Wheel) modules for MOST. Each MRW incorporates a small (50 mN-m, 0.3 N-m-s) reaction wheel with a solid-state angular rate sensor, along with embedded sensor processing and local wheel speed control, into a single hardware module. With a mass of about 1 kg each, a size of 90×90×85 mm, and a power consumption of ~3.5 W, these MRW units are scaled to the very limited resources available within the MOST bus. The MRW design is at an advanced state of development; qualification-level testing on a flight-test unit is planned for late 1998.

Dynacon will also develop software algorithms (which will run on the Payload's DSP processors) to process star-field images to extract attitude information from them. These algorithms will carry out a *star-tracking* function, determining the satellite's yaw, pitch and roll angles with respect to an initial index image. (The *navigation* function, in which the index image is registered to absolute celestial coordinates, will be performed on the ground following downlinking of the index image.) Initial work on these algorithms suggests that attitude measurement accuracies of better than 1 arc-sec may be achievable.

The remainder of the ACS software, which will run on one of the OBC subsystem's two i386 computers, will be based on a Dynacon commercial product called HPAC (High Performance Attitude Control)—this is an add-on to existing microsat-class attitude control systems that adds fine-pointing capability. The software component of HPAC, which includes all of the functions listed, has been developed in prototype form, and tested via simulation against the expected environmental disturbance environment for MOST. With a 1 arc-sec accuracy star sensor being sampled once per second, and with an ACS controller frame rate of 10 Hz, the simulation predicts an attitude estimation accuracy of about 2 arc-sec, and attitude regulation to <10 arc-sec >99% of the time (< 7 arc-sec >90% of the time). Validation of these simulation results is now underway at Dynacon, using a hardware emulation of the MOST ACS that is supported by an air-bearing platform.

Telemetry & Telecommand

The main requirement on the TT&C subsystem is to provide reliable uplink and downlink communications between ground control stations and the satellite. The satellite will generate at least 2 MB of data per day, all of which will have to be downlinked.

The baseline sun-synchronous orbits has a near-polar inclinations. Rather than attempting to achieve full-time communications with the satellite, the telemetry and telecommand concept chosen assumes intermittent contact. The concept involves using the same type of packet-communications approach that is used in controlling numerous AMSAT satellites.

Two ground stations are to be installed, the primary at the University of Toronto Institute for Aerospace Studies (UTIAS), and a secondary at the University of British Columbia (UBC). Whenever the satellite is over one of these ground stations, contact may be initiated. For the baseline orbit this happens between four and six times per day per ground station, with two groups of passes per day. Each group is centered 12 hours after the previous group, with two or three passes centered about 6 A.M. and two or three more centered about 6 P.M.

The cumulative pass duration per day for each ground station is about 60 minutes. The design uplink data rate of 9600 baud will support uplink of about 3.3 MB of data per day; at a design rate of 56.4 kbaud, downlinking of about 19 MB of data per day should be possible, through each ground station.

A common AMSAT approach to packet communications is employed throughout. In this way, the same communications software (and some hardware) can be used to support both science and engineering command and telemetry, and AMSAT store-and-forward communications.

The telemetry and telecommand subsystem includes modems to support digital packet communications. Through this subsystem, it is possible to reset and manage the power for the main satellite elements during contingency situations, and provide a means of recovery if equipment like the on-board computer locks up.

The communications protocols and standards for the MOST mission closely follow those used in the amateur radio community, thereby drawing upon the experience available through AMSAT. The selected standards are as follows

- PACSAT File Protocol
- AX.25 Packet Data Protocol
- High-level Data Link Control (HDLC) Serial Communications Protocol
- Gaussian Minimum Shift Keying (GMSK) Modulation

The telemetry and telecommand subsystem includes two identical S-band transmitters and two identical L-band receivers for redundancy (Figure 11). Both receivers operate continuously, requiring about 2 W of power. Only one transmitter is on at any given time and draws about 3 W on average. The output power is selectable, should it need changing. Each transmitter and each receiver uses either an amateur-band radio frequency or a space science band frequency. Transmitters and receivers will be connected to the On-Board Computers via GMSK modems.

An important operational requirement of the MOST satellite is the capability of monitoring various parameters, such as temperatures and power levels while the satellite is in orbit. This will be done via a set of telemetry data collection boards, with one of each to be included in each tray where analog telemetry data must be collected. These boards will communicates their data to the On-Board Computers via the CAN data bus, reducing the amount of wiring needed between trays to just the CAN bus.

The antenna design for the MOST satellite consists of four quadrifilar helix antennas, two for reception and two for transmission. Circular polarization is used. Antennas are mounted on the top and bottom faces of the spacecraft (the long and narrow sides of the bus structure that do not have solar panels -- see Figure 12). On each side is mounted a receive/transmit antenna pair, spaced appropriately to avoid unwanted interference patterns between the antennas or between the antennas and the bus itself. The antenna patterns for the quadrifilar helices are hemispherical, providing excellent omni-directional characteristics.

Link budget calculations indicate that the parabolic dish antennas (L- or S-band) and loop yagis (L-band) selected for the ground stations (see below) can provide a 27.5 to 31.5 dB quotient of bit energy to noise power (uplink) despite losses in feed, propagation, and atmosphere, and polarization mismatch (linear polarization is used on the ground). These are excellent margins, considering that a 12 dB quotient corresponds to a 1×10^{-6} bit error rate. Larger quotients yield even lower bit error rates. For the downlink, the quotient is 24.5 dB.

On-Board Computers

The On-Board Computer subsystem receives commands from the ground stations, issues mode-change commands to the payload, processes and stores data collected by the payload, transmits that data to the ground when requested, and carries out computation and control functions relating to satellite bus functions (e.g., the Attitude Control subsystem).

The OBC subsystem design employs a pair of Intel 386-type processors, each with 2 MB of commercial-grade local memory protected by hardware error detection and correction (EDAC). One processor will carry out ACS functions while the other performs house-keeping, command and control functions. Two bootstrap PROMs are also included, one for each 386 processor. An Intel 387SX math coprocessor accompanies the 386 ACS processor, to increase the speed of attitude control computations.

The processors are cross connected to provide redundancy. In the event that one processor ceases to function properly, a single CPU would cover all basic satellite operations until the upset processor re-boots. (A permanent CPU latchup is considered unlikely in low-Earth orbit, as indicated by experience gained by AMSAT and others.)

In addition to the local memory provided to each CPU, 32 MB of static RAM is configured as a RAM disk for data storage. RAM devices are available that can provide a fast access, low power component that can operate effectively in extreme temperatures. Static RAM also has increased resistance to single event upsets over other types of RAM, and consume less power.

The RAM disk will be protected by EDAC software running on the main (housekeeping) 386. MOST is expected to collect approximately 2 MB of data per day.

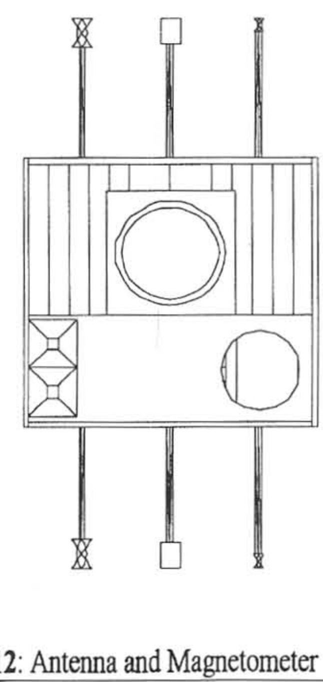


Figure 12: Antenna and Magnetometer Mounting

Assuming that in the worst case a maximum of seven days of storage without downloading data to the ground, 14 MB of memory is required for the mission. The software EDAC increases RAM requirements by 50%, adding an extra 7 MB. AMSAT is allocated an additional 11 MB to pursue their digital store-and-forward interests. Thus, in total 32 MB of RAM are required.

A Controller Area Network (CAN) bus connects all the processors, and the processors to most active elements in the satellite (e.g., the ACS components). The CAN bus has a 1 MB/s data capacity. Dual-redundant wiring is specified between CAN controller chips, to ensure that broken wires do not disable the bus. Separately from the CAN bus, command signal generator circuits will issue commands to open and close the power switches for all the on-board equipment.

The 386 processors have built-in watchdog timers. However, external watchdog timers are used to increase reliability in the case of single event upsets.

Software for the on-board computers include:

- The BekTek SpaceCraft Operating System (SCOS). This real-time, multi-tasking operating system has been used successfully on other microsats. In comes with PACSAT and AX.25 protocol software, and a package developed by Surrey Satellite Technology Limited that handles RAM-based file system management. BekTek SCOS also includes error detection and correction software to protect the main memory.
- Orbit propagator.
- Magnetic field model.
- Attitude estimation filter.
- Attitude feedback control calculations.
- Attitude control mode change decisions.
- Science instrument management software.
- Telemetry and telecommand subsystem management software.
- Watchdog software processes.
- Power control software.

The current concept is to include dedicated links between the 386 processors and the modems of the telemetry and telecommand subsystem, supplemented by a CAN-bus link. The approach to achieve reliability against computers entering an uncommandable state (from single event upsets, power transient effects or software errors) is for each of the 386s to keep watch on the other one, and to issue either a CPU reset signal or cycle the power if its partner fails to respond. In addition, the watchdog timer would reset both 386 computers if they both failed to respond after some longer period of time. As a final measure, computer reset commands can be uploaded directly via the telemetry and telecommand subsystem.

Ground Stations

The system concept includes two ground control stations, one located in Toronto at UTIAS, and the other in Vancouver at UBC. In addition, there are a large number of AMSAT stations that can access the digital store-and-forward function of the satellite, for amateur radio communications purposes. The two ground control stations are equipped to operate at both science-band and amateur-band frequencies -- the science frequencies are nominally used for all ground-control functions, and the AMSAT frequencies are used only for amateur operations.

The ground stations use equipment similar to that used by AMSAT members to contact other AMSAT satellites currently in operation. Both stations are identical. In addition, the Vancouver ground control station can be operated remotely from Toronto.

Ground station transmitters and receivers are responsible for Doppler correction (the satellite will not provide Doppler correction). High-gain tracking antennas are used for L-band uplink and S-band downlink, although loop yagis are an alternative for L-band operation. Linearly polarized ground station antennas communicate with the circularly polarized antennas on the satellite. This incurs a constant 3 dB signal strength loss due to polarization mismatch, but avoids deep nulls.

The ground control stations are equipped with computers to control the transmitters and receivers and antenna pointing gear, as well as send and receive communications packets, compensate for Doppler shift, form commands for the satellite, display and analyze engineering telemetry from the satellite, and perform some amount of limited display and checking of the science data downlinked from the satellite. The ground control stations are also equipped to archive engineering telemetry and science data, and to make the science data available to the missions scientists at remote sites (via the Internet).

A set of standard Pentium class computers will be used for the ground station control. A CD-ROM and tape backup drive serve as mass storage devices for archiving science data. With a download rate of 2 MB per day, a full year's operation requires only 730 MB of mass storage.

The ground station computer runs a program known as WiSP. WiSP is a fully-integrated program for operating digital satellites. It implements both the uplink and downlink protocols, manages all message files, updates the satellite schedule, and drives the antenna rotator hardware.

A commercially available piece of equipment known to AMSAT operators as a Kansas City Tracker (KCT) with Kansas City Tuner controls the pointing of the ground station antenna and the tuning of the transceiver. It is itself controlled by PC software which computes the orbital elements of the satellite. Based on these orbital elements, the KCT moves the antenna and sweeps the frequency of the tuner to account for doppler frequency shifts. The ground station antenna for each MOST ground station is a paraboloidal dish reflector (2 m diameter) for both L- and S-band communications; a two-axis gimbal will point the antenna with an accuracy of $\pm 1°$.

The Terminal Node Controller (TNC), a device in the ground station which is a combination modem and packet radio controller, interfaces between the computer and the RF radios in the ground station. One possible commercially available TNC is a Paccomm Spirit II which supports the AX.25 protocol, GMSK modulation and the maximum downlink data rate of 64 kbps.

The transceiver operates in the VHF and UHF frequency bands and, on one side, interfaces with the modem in the Terminal Node Controller at baseband. On the other side, it interfaces at either UHF or VHF to an S-band converter.

Microsatellites for Space Science Missions

Many types of space science missions carry imaging payloads, which require a satellite bus that can reliably point the payload towards the desired targets, and maintain stable pointing for the duration of imaging operations. As far as we are aware, MOST will be the first microsatellite to operationally conduct imaging space science. The factors that allow MOST to do this can also be used to enable other, similar missions. MOST may be the harbinger of many future microsatellite-based space science missions.

In the past, imaging-class science missions have always been placed on platforms somewhat larger than the MOST bus, costing very much more than the MOST bus. This is partly because of the size and cost of the science instruments themselves. However, miniaturization of detectors and electronics has enabled very powerful miniature instruments to be developed suitable for many useful space science applications. The impediment to placing these instruments on very small buses has its roots in the fact that achieving accurate attitude control requires a minimum complement of equipment on the satellite:

- Sensors capable of measuring attitude errors to an accuracy higher than the required pointing accuracy. For pointing accuracy requirements below 0.1 degree, the sensor of choice is a star sensor; Earth and Sun sensors cannot perform to accuracies significantly better than this, although they can serve useful auxiliary functions.
- Sensors capable rapidly sensing attitude motions, to enable implementation of high-bandwidth feedback control, which is needed to achieve high-accuracy pointing. The most common type of sensor used in this role is an absolute angular rate sensor, such as a rate gyro.
- Actuators capable of continuously generating torques about all three satellite axes. Reaction wheels, control moment gyros and thrusters all fall into this category, but magnetorquers do not; at any given time, one satellite axis is uncontrollable using these.
- Processing circuitry capable of implementing appropriate signal filtering and feedback command generation functions, in response to targeting commands. Often, this must also generate models of the satellite's orbit and target's relative location, as well as estimating external disturbances such as the Earth's magnetic field strength. In practice, this means a digital computer.

Equipment in each of these categories was, until recently, too large to fit on a microsatellite platform. However:

- Digital computers have miniaturized radically ever since the microprocessor was first developed, and this trend shows no sign of slowing down. While most high-budget missions have avoided using the latest in computing hardware (for reasons of engineering conservatism), some microsatellite-class missions have been willing to risk testing these in space, where they were found to perform quite well. MOST is employing flight-tested processors that are already becoming somewhat antiquated, but which nonetheless have the capacity to carry out the demanding functions needed by the ACS.
- Small star sensors have started to become available, at sizes and prices that are nearly within the budgets of microsatellites. MOST doesn't need a dedicated star sensor, because its science instrument is capable of producing exactly the type of data needed to fill that function. However, the technology will soon be available to enable other missions to achieve similar levels of attitude measurement accuracy.
- Old-style rate gyros were relatively large, heavy, complicated and expensive items of equipment, consuming large amounts of power and with limited operating lifetimes. Laser- and fiber-optic-based solid state replacements for these have been developed to relieve some of these problems, albeit at a price that is still relatively high. Silicon-based rate sensors are now available that are very much smaller, lower in mass and power consumption, and very much less expensive (with somewhat less bias drift stability). MOST uses several of these to achieve high-bandwidth attitude estimation; these are similarly appropriate to any other fine-pointing space science mission.
- Most satellite reaction wheels are far too large for use on a microsatellite. However, in the past 2 years a couple of suitably small commercial reaction wheels have become available, and Dynacon is adding another with its MRW product.

With these components all becoming available, the technological stage is now set for more missions like MOST. However, this does not mean that *every* space science mission objective can necessarily be met by using a microsatellite platform; far from it! A propitious set of circumstances combined in the case of MOST to allow it to be carried out using a microsatellite platform:

- There is a good match between the basic science data-collecting objectives of this mission, and the capabilities of existing microsat bus designs to support payloads of the size, mass and power consumption required. The field of asteroseismology has been hampered by the obscuring effects of scintillation in the Earth's atmosphere, which has kept even the most basic objective (detection of Solar-like oscillations in other stars) from being met using Earth-bound instruments. At this young stage of this branch of astronomy, even a tiny telescope is capable of making ground-breaking observations, if located above the atmosphere. The MOST science team carefully resisted the temptation to set mission requirements above the point where a microsat-sized telescope would be sufficient.
- There is also a good match between the type of orbit that MOST needs in order to carry out the necessary long-duration stellar observations, and the likely availability of secondary payload launch opportunities to these orbits. The proposed dawn/dusk sun-synchronous orbit not only provides a very suitable CVZ size and scan rate, it also provides a stable thermal environment and relatively high (in microsat terms) power-generation potential, reducing the difficulty of the engineering requirements on all satellite subsystems.
- MOST requires a level of attitude control system performance that is considerably better than has been demonstrated on previous microsat missions. Fortunately, Dynacon has a strong expertise in the ACS area, and (with support from the CSA) has developed subsystem and component designs and design tools that have allowed a High Performance Attitude Control system to be designed that meets the MOST requirements.
- The ACS performance goal is made easier to achieve because it is possible to make use of image data from the science telescope instrument, to provide attitude reference data whose quality is an ideal match to the attitude estimation process requirements for the mission.. (This is the ideal situation for a controls engineer: the quantity measured by the sensor corresponds directly to the quantity to be controlled.) Because the star sensor data is automatically registered to the science instrument's detector, this has the added benefit of virtually eliminating any sensitivity of star-tracking performance to instrument/bus alignment. Any misalignments that occur during launch (due to vibration loads) or on-orbit (say, due to thermal distortions of the bus), say between the telescope, the periscope mirror and the bus, will be automatically compensated for by the ACS's fine-pointing feedback controller. This greatly reduces design and testing costs associated with maintaining precise alignments.
- The University team members have expressed strong interest in the MOST mission, and their support brings access to the types of additional resources and areas of expertise that have characterized other successful, low-cost microsat missions in the past.

Designers of other space science missions who are contemplating the use of a microsatellite platform may want to compare the circumstances of their missions to these.

Acknowledgements

The MOST Phase A project was carried out under contract for the Canadian Space Agency's Space Science Branch, under the Small Payloads Program (SPP). The MOST team wishes to acknowledge the guidance and support provided by SPP Program Manager Glen Rumbold (who developed the Program Plan for the SPP, laying the groundwork for MOST and other future low-cost SPP microsatellite missions), as well as the CSA's Project Manager for MOST, Glen Campbell. Special thanks is also extended to the Ontario Research and Development Challenge Fund and the University of Toronto for supporting the Space Flight Laboratory. Dr. Peter C. Hughes continues to play a major role in securing funds for the MOST mission and in helping to organize the Space Flight Laboratory.

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Bios:

- Kieran A. Carroll graduated from the University of Toronto in 1982 with a B.A.Sc., in 1985 with a M.A.Sc. and in 1992 with a Ph.D., all in aerospace engineering, specializing in spacecraft dynamics and control. He co-founded, and served for 5 years as President of the Canadian Space Society, during which time he participated in the development of the Canadian Space Agency's long-term plans for technology development, microsatellites and planetary exploration. He has worked at Dynacon since 1986, and currently oversees all of Dynacon's space engineering activities.

- Robert E. Zee obtained his B.A.Sc. (1993) from the University of Waterloo Systems Design Engineering Department. As part of the cooperative education program there, Dr. Zee worked for IBM, Spar Aerospace Limited, and Allied Signal Aerospace. After being awarded the NSERC 1967 Science and Engineering Scholarship, he then obtained his M.A.Sc. (1994) and Ph.D. (1997) from the University of Toronto Institute for Aerospace Studies (UTIAS). Dr. Zee has been the UTIAS technical manager for DICE, a Space Shuttle Middeck experiment. He is currently leading microsatellite development efforts at UTIAS and is manager of the Space Flight Laboratory.

- Jaymie M. Matthews graduated from the University of Toronto in 1979 with a B.Sc., and from the University of Western Ontario with an M.Sc. (1982) and Ph.D. (1987), all in astronomy/astrophysics. He has been an Assistant Professor at UBC since 1992. Dr. Matthews' research centres on stellar pulsation and asteroseismology, performing rapid high-resolution spectroscopy and photometry with some of the largest telescopes in the world. He made the first detection of rapid surface motions in an oscillating magnetic star (confirming that this new class of variables was indeed pulsating) and pioneered a new technique to probe the atmospheric structure of stars via their pulsations at different wavelengths. He sits on the Canadian steering committees for the Gemini International Twin 8-metre Telescope Project and the Lyman/FUSE (Far Ultraviolet Spectroscopic Explorer) satellite, as well as the Commission on Variable Stars for the International Astronomical Union and the Board of Directors of the Pacific Space Centre. However, he's not quite as boring as this makes him seem.

Amateur Radio On-board the International Space Station

Frank Bauer, KA3HDO
and
Will Marchant, KC6ROL

Abstract

Amateur radio has had a substantial presence in human space flight since the mid-1980s. For over 15 years, amateur radio space enthusiasts in the U.S., Russia, and Germany have worked diligently to develop, deploy and coordinate operations of on-orbit amateur radio stations on the U.S. Space Shuttle and the Russian space station Mir. Human space flight is expected to change in the near future as the aerospace community rapidly evolves its focus towards operations on the International Space Station (ISS). The international amateur radio community is working with the aerospace community to make amateur radio a permanent fixture on ISS. This paper will summarize the status of the ISS program, the development of a transportable station for initial use on-board ISS, and the opportunities and plans for implementing a permanent amateur radio station on-board the ISS.

Ham Radio and the Human Space Flight Connection

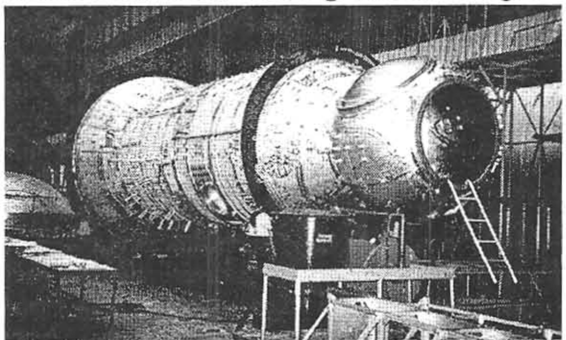
Amateur radio has had a significant human presence in space starting with a flight on board the space shuttle orbiter Columbia on the STS-9 mission late in 1983. At that time, astronaut Owen Garriott, W5LFL, provided an unprecedented level of excitement to the amateur community by talking to hams on the ground using a 2-meter FM transceiver. These modest beginnings 15 years ago have led to a significant, nearly continuous presence of ham radio in human-tended space vehicles today.

With twenty-four flights to date, the Space Amateur Radio Experiment (SAREX) has become the most flown payload on board the Space Shuttle. The primary goal of SAREX is to pique student's interest in science, technology and communications by allowing schools around the world to talk with the astronauts during Shuttle missions. The crew also uses the equipment for a limited number of personal chats with close friends or family members and to talk to hams on the ground during their break times. SAREX has accomplished a number of firsts in human space flight. SAREX was the first to demonstrate crew-tended 2 meter voice, packet radio from space, crew tended amateur television uplinks and Slow Scan TV uplinks and downlinks.

In 1988 a permanent amateur radio facility was placed on board the Russian space station Mir. Technical capabilities have steadily increased on Mir over time. Currently Mir provides capabilities for 2m voice, a packet bulletin board system, a 70cm repeater, and a digi-talker. This station, developed primarily by our German (SAFEX) and Russian (MAREX) colleagues, provides an important spontaneous link for the astronauts and cosmonauts. While it isn't officially a backup communications source for Mir, ham radio has served as a secondary psychological ice-breaker; for the Mir crew, particularly after events such as the political and economic reorganizations in Russia and the 1997 Mir/Progress accident.

The Mir space station amateur radio facilities have provided a critical capability for the crew. As stays in space get longer and longer the psychological impacts of isolation become more severe. Amateur radio allows the crew to interact with friends and loved ones as well as serving educational needs with school contacts. The ability to perform random QSOs provides a vital psychological break for a crewmember that may have been stuck "in a tin can" with their crewmates for months at a time.

The world's space flight community is now concentrating a significant amount of their resources on the development and implementation of an International Space Station (ISS.) The ISS has gone through a number of name and configuration changes



Functional Cargo Block readied for Flight
Figure 1

since its first inception in 1985. The current design calls for modular components from a number of countries to be lofted on board Russian expendable rockets and the United States Space Shuttle. Construction is planned to begin in 1998 with permanent human residence to start in 2002.

With ISS hardware design and development underway, preliminary planning for ISS on-orbit operations took place through joint experiments and U.S. astronaut visits on board the Russian space station Mir. This joint U.S.-Russian activity was called ISS "Phase 1." U.S. astronauts learned valuable lessons on Mir during their 4-6 month stays. Astronauts were transported up to Mir using NASA's Space Shuttle. Supporting experiments, hardware and materials were carried on the shuttle or on the Russian Progress resupply ships. This effort had refocused nearly all the Space Shuttle missions to become Mir/Shuttle docking flights. Since these missions were typically fairly short and exceedingly busy, the SAREX team had curtailed its activity on those Shuttle missions. During the construction of ISS, the U.S. space shuttle will become a primary carrier of ISS hardware, materials, and crew. Thus, these flights will also be too busy for SAREX activities. Over the past two years, the SAREX team reduced its activity on the shuttle and concentrated on astronaut amateur radio operations on Mir. In parallel, the SAREX team in the USA worked with its international partners to make the ISS a permanent base for amateur radio operations. The amateur radio facility on ISS is expected be used by the visiting shuttle crews, if they have time, and will serve as an educational outreach and recreation tool for the crews stationed on the ISS.

In November of 1996 a meeting was held at Johnson Space Center in Houston, Texas with representatives from national amateur radio organizations of eight countries. This meeting served to initiate the dialog on the development of a permanent amateur radio station on ISS. The outcome of the meeting was a Memorandum Of Understanding (MOU) that states that the groups would work together to coordinate the development of one amateur radio plan for the ISS. This coordinated international station would be called ARISS for Amateur Radio on the International Space Station. Since NASA is the coordinating agency for ISS, it was decided to have the SAREX Working Group coordinate requests and plans with the ISS project management. This included seeking official sanction and allocation of space for amateur radio equipment.

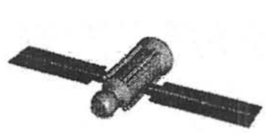
In July of 1998 a follow up meeting was held in Surrey, England to better define the hardware complement to be flown for ARISS. An international "hardware committee" has been established which will define the permanent ham station for ISS, given the space and power resources obtained from the ISS project. On-board space for the permanent ISS facility is expected to become available late in the ISS construction project (around 2002). In the interim, the international hardware committee has been charged with implementing a series of "transportable stations" which can be launched in late 1998 and 1999.

ISS Development Status

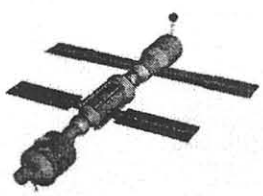
Preparations of flight hardware for the ISS are progressing fairly well. The first component of the ISS is the Russian Functional Cargo Block (FGB). See figure 1. Currently the first ISS elements are scheduled for launch in late 1998 on board a Russian Proton rocket. This

Russian built Functional Cargo Block provides initial propulsive capability through the early life of ISS. The first USA built "node" will be launched on a space shuttle a month later. The nodes provide six connection ports that will allow different modules to be docked, providing a way to build the ISS out of separate modules. The Russian built service module is to be launched in the middle of 1999. It will provide propulsive, attitude control, and life support systems for the ISS.

In December of 1998 a shuttle flight to ISS, called the "2A.1 Logistics flight," will carry supplies to ISS. The SAREX working group has arranged for the launch of an initial "transportable station," very similar to the



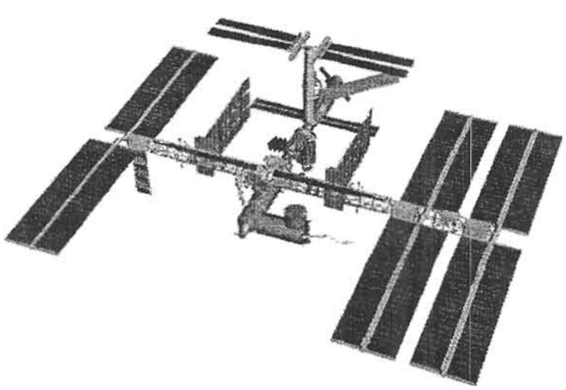
Functional Cargo Block (FCB) on-orbit configuration late 1998



2A.1 Logistics Flight December 1998

current SAREX equipment, on that flight. This will provide a temporary ham radio capability on board the ISS.

Several years later on flight UF-4, (figure 2) currently scheduled for January 2002, the



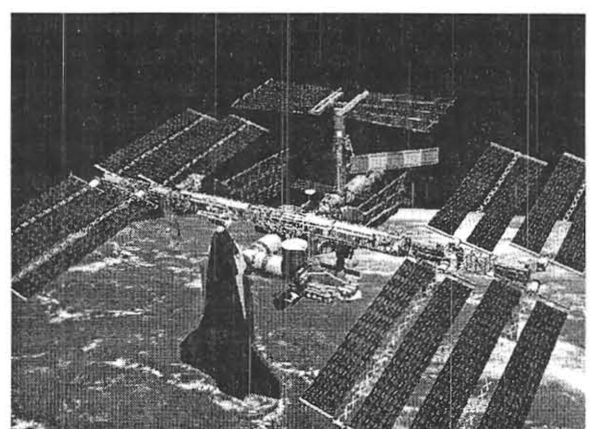
International Space Station
UF-4 January 2002
Figure 2

working group has arranged for space on board an "EXPRESS Pallet." EXPRESS Pallets are mounted external to the station, and it is expected that there will be room for a fairly sophisticated "OSCAR like" payload. A request is in progress for permanent rack space in the "habitation module" which is to be launched on flight 16A no later than December of 2002. See figure 3. The request includes access to external antennas and access to the ISS computer systems for status information.

Transportable Station Plans

The SAREX team had been working on an upgrade to the SAREX hardware for quite some time, and it was decided at the 1997 AMSAT-NA meeting in Toronto that this set of upgrades would provide the most efficient mechanism for putting an "interim" amateur radio capability on the ISS.

The initial plan for a transportable station uses intrinsically safe commercial 2m and 70cm hand held radios from Ericsson. These radios are extremely rugged and will not pose a hazard on the Space Shuttle or ISS. The radios are very simple to operate, with text displays for frequency configurations. They can be reprogrammed on orbit with software compatible with the laptop computers planned for use on board the ISS. Initially, these radios will be used with externally mounted



International Space Station
On-Orbit Configuration, Late 2002
Figure 3

antennas to provide a low power voice communication capability.

The packet bulletin board system on Mir has proven to be incredibly valuable for educational and recreational activities. The primary problems observed with the Mir packet system is the limited memory space for messages and the fact that only a single connection can be made at a time. Hams unfamiliar with Mir packet operating practices have been known to lock up the system over an entire pass because the single connection does not time out for approximately 5 minutes. The Terminal Node Controller (TNC) that is being qualified for the ISS transportable station is the PicoPacket TNC from PacComm corporation. PacComm TNCs are also used on board Mir so the user interface for the Mir and ISS systems will be close if not identical. The transportable station on ISS is expected to include 1 megabyte of memory to alleviate the current memory problems. The PicoPacket will also support multiple connections so this should ease some of the problems that have been seen when connecting to Mir. All these components are to be delivered to the ISS on 2A.1 logistics flight (STS-88) in December of 1998. Our Russian colleagues are working hard to assure that feedthroughs for external antennas are available early in the ISS assembly process.

A 70 centimeter Ericsson handheld, SAFEX supplied digitalker module, and a cable for dual band operations will be launched on STS-96 in May of 1999.

In late 1999, on either STS-98 or STS-99, there exists an opportunity to place an upgraded transportable station on ISS. This will likely consist of a SAFEX supplied dual band transceiver, digitalker, and packet unit will provide a more robust dual band capability to support operations until the permanent station can be implemented.

A Permanent Amateur Radio Station on the ISS

Plans for the development of a permanent amateur radio station located in the habitation module have also begun. A set of derived requirements were generated for the permanent station. These are shown below.

Permanent station derived requirements:

- Eight minute contact with well equipped ground station
- Computer to computer radio links
- Thirty second contact with a minimal ground station
- Autonomous beaconing of status in digital form
- Still picture transmit & receive
- Video transmit & receive
- Support continuous contacts (for at least thirty minutes)
- Support multiple concurrent operations
- Space-to-space as well as space-to-ground operations

Based on these requirements, the NASA ISS management were briefed on specific interfaces for the ham station. The briefing suggested 30 kg of hardware in a standard 19 inch wide rack. The rack-mounted system would be 24 inches high and would draw 200 Watts of power. The station includes external antennas, and connections to the ISS audio, video, and computer networks. ISS management thought these requests were quite reasonable. A summary of the hardware described included:

- Multi-band radio support: 10m, 2m, 70cm, & up
- External Omni antennas for voice and low rate data: nadir and zenith
- 5-25 Watts transmit power; 100 Watt for ATV
- Flexible TNCs (probably DSP based)
- Multiple transceiver systems to support concurrent operations
- PC interface to the ISS flight computer systems
- Video processing capability (to support SSTV and ATV)
- Gained antennas for high data rates
- Active station control through the ground
- Pass planning and scheduling software.
- Expandability for experimentation.

The briefing also suggested external allocations for four "microsat class" payloads that could be changed out. This would allow schools and universities to develop stand alone payloads and not have to worry about attitude control, or power concerns. This allocation has been made on an EXPRESS Pallet scheduled for a flight in 2002. It will be incumbent upon the hardware committee to rapidly formulate plans to effectively utilize this space before it gets reallocated to another project.

Plans for utilizing the externally mounted payload opportunities of the EXPRESS Pallet still need to be generated. The initial EXPRESS Pallet is on the bottom of the ISS so it provides an ideal Earth view for amateur radio operations. Each Pallet can hold six experiment adapters, and ARISS has been allocated half of one of those, to be shared with a Jet Propulsion Laboratory optical communications experiment. Each adapter has a cubic meter of usable volume and a kilowatt of power.

Plans for utilizing these resources come in the form of proposals to the international hardware committee. It will be the responsibility of the international hardware committee to evaluate the technical merit and feasibility of the proposals and generate a final integrated plan for the ISS. Those wishing to review the status of the various ISS hardware proposals are welcome to peruse the world-wide-web site:
http://garc.gsfc.nasa.gov/~ariss/ariss.html

Launch windows and configurations of the final permanent station are still being evaluated. Designs will be modular to allow easy replacement of failed components and to allow for upgrades and experimentation. Command station operations will be supported from the ground so that crews will not have to spend valuable time reconfiguring the station.

Conclusions

The historic use of amateur radio on the Space Shuttle and Mir to support educational outreach, crew personal contacts and interaction with terrestrial-based hams will become even more important when the international aerospace community migrates to the International Space Station. The ARISS international partners are working hard to transform the dream of a permanent amateur radio station on the international space station into a reality.

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The P3D Spacecraft Thermal Design

By
Dick Jansson
With the assistance of Keith Baker

Abstract:

When creating a new device, such as a new automobile or a satellite, many different engineering technologies must be considered to be successful. Certainly the needs for high quality Mechanical and Structural Design are clearly understood, as are the needs for meaningful Electronic and Electrical Designs. One technology that is necessary for the satellite, and not usually needed for an automobile, is that of Thermal Design. Thermal Design engineering deals with the interrelationships of heat and temperatures, and is significantly different from the field of Thermodynamics, which deals with the interrelationships of heat and work.

The need for a careful thermal design of a satellite becomes more apparent because there are no gentle air breezes around the satellite to carry off the heat absorbed from the Sun and that generated by the internal equipment. In fact, the cooling effects on the satellite can be profound, as the "space heat sink" is considered to be some 4 Kelvin, or -269°C (-452°F), ***far*** colder than even the coldest day at the South Pole on Earth. Further, the heating effects of the Sun are about ***twice*** that received by the family automobile parked at the beach, even on the hottest of summer days. This is because there is no atmospheric attenuation of the heat generated by solar radiation for a satellite flying in space.

This then highlights the fact that without this gaseous exchange provided by our atmosphere, there would be no convective heat transfer from onboard devices in a satellite. Heat can only be transferred by conduction across solid bodies and by radiative (electromagnetic) exchange, which, in turn, makes balancing the heating and cooling of the spacecraft an infinitely more complex task.

This paper will illustrate the activities conducted on the P3D Project to create a proper Thermal Design for the satellite. For this project, already complex Thermal Design activities were made even more complex because of the size of the satellite and because it has several different operating configurations, or modes, whose thermal effects are not necessarily in concert with each other. Creating a proper Thermal Design for P3D has been like threading the eye of one very small needle ... and we've gotten "stuck" by the needle a number of times in the process!

Introduction:

Communicating through the use of a Ham Radio satellite can be thought of as a relatively simple process. You transmit an uplink signal to the "bird" and listen on a correct frequency for the downlink signal. This process involves, of course, a receiver and transmitter on the candidate satellite, and as you and I are using such equipment in our shack, the technology of this equipment is reasonably well understood.

Also understood is that the candidate satellite containing the receiver and transmitter is a piece of mechanical hardware. It must withstand the rigors of being placed on the top of a "controlled explosion" rocket-propelled launch vehicle that will be used to place this electronic equipment into an orbit around Earth. Implicitly then, this mechanical assembly needs to be reasonably lightweight and rather robust to withstand the rigors of the rocket ride.

So what else?

That "what else" is a matter of heat and cold. A philosopher of some 500 years ago was thought to have pondered and put forth the following:

"Heat and cold are Nature's two hands, whereby She chiefly worketh."

And so we come to the heart of this discussion, the matter of placing and keeping the satellite and its electronic contents in a temperature domain in which all will not only be able to operate, but to operate "happily" for rather long periods of unattended time. This involves an engineering technology called by its practitioners "Thermal Design".

I have had the pleasure of practicing Thermal Design engineering for essentially all of my professional career, having been introduced to this field in one of my first jobs, after high school and before taking time off to attend a university and thereby sanction my goals with a proper degree. This exploration into matters of heat and cold quickly took me into the arena of missiles, then into spacecraft and space instruments. Along the way in these fields, one learns about diverse technologies such as mechanics, cryogenics, optics and electronics. The secret to success here is to be able to understand enough of all of these technologies to allow the thermal design of the final device to satisfy ***all*** of their requirements. One such technological pinnacle was the design of a "cold optics" telescope integrated into a space lunch probe. Such optics need to operate in the very cold temperature domain of liquid hydrogen, about 15 Kelvin (15°C above absolute zero).

Thermal Design engineering deals with the interrelationships of heat and temperatures, and is significantly different from the field of Thermodynamics, which deals with the interrelationships of heat and work. Indeed, heat is involved in both cases, but "what comes out the pipe" is different.

As most of our Ham Radio electronics require the same kind of temperatures as do our bodies, the radios in my shack are treated rather well, as otherwise I would not be in the shack to use them. And this is true for most consumer electronics. So neither your shack, nor mine, need the services of a thermal designer. Place those electronics into space and we have a totally different matter.

The need for a careful thermal design of a satellite becomes more apparent because there are no gentle air breezes around the satellite to carry off the heat absorbed from the Sun as well as that generated by the internal equipment. In fact, the cooling effects on the satellite can be profound, as the "space heat sink" is considered to be some 4 Kelvin, or -269°C (-452°F), ***far*** colder than even the coldest day at the South Pole on Earth. Further, the heating effects of the Sun are about ***twice*** that received by the family automobile parked at the beach, even on the hottest of summer days. This is because there is no atmospheric attenuation of the heat generated by solar radiation for a satellite flying in space.

This, then, highlights the fact that without this gaseous exchange provided by our atmosphere, there could be no convective heat transfer from onboard devices in a satellite. Heat can only be transferred by conduction across solid bodies and by radiative (electromagnetic) exchange, which, in turn, makes balancing the heating and cooling of the spacecraft an infinitely more complex task.

P3D - Early Efforts:

In May of 1990, the first "Experimenter's Meeting" for the P3D project was held in Marburg, Germany. At that meeting, I was "asked" by Dr. Karl Meinzer (in his own inimitable way) to handle the thermal design and the (preliminary) mechanical design of the P3D spacecraft. None of us at that time had any concept that only eight very long years later we would finally be preparing the spacecraft for a launch. This assignment was appropriate. I had similarly supported the earlier Phase 3 and Microsat spacecraft with my thermal design efforts. In the case of P3D, I would also be able to insure that the mechanical design incorporated suitable provisions to permit the thermal design to be properly incorporated into the structure.

No one suspected at that time that we would need to conceive a dozen different basic spacecraft configurations and carry three of them into some serious design levels. Every one of these configurations was subjected to basic thermal modeling and computer analyses to insure their initial suitability as an AMSAT spacecraft. Karl and I were about to initiate the fabrication of a spaceframe at Weber State (WSU) University, Ogden, UT, when the launch authority, the European Space Agency, ESA, informed us that a launcher interface that they had offered to us would no longer be available. That announcement tossed over a year of design work in the trash bin!

So I went back to the "drawing board" (in these days the CAD computer), and a bunch more potential configurations. Out of all of that scribbling came a spacecraft configuration that both Karl and I liked very much, the hexagonal prism design that is now the P3D characteristic. Along the way, we had to convince ESA that having to take our launcher adaptor (now called the SBS) to separation and orbit with the payload was not to ***their*** advantage. Eight months after ESA's announcement, a group of three of us (Ralph Butler and Jaim Parsons, both of WSU, and myself) were back in Marburg constructing the prototype spaceframe.

In all of this mechanical design turmoil, the spacecraft thermal design concepts evolved to a level of maturity and understanding that was substantially greater than in earlier P3 spacecraft. Patently this was needed, as P3D is much larger than the earlier spacecraft and that the thermal behavior is different and needed to be well understood ***before*** we cut metal.

P3D - Internal Thermal Design:

Several key factors have determined the path that the P3D thermal design should follow. These are:

- P3D is not a small satellite, and "small" thinking could not be allowed.
- P3D is a three-axis stabilized spacecraft, not a spinner, and "spinning" thinking could not be allowed.
- P3D will have much higher-powered transmitters that, even though efficient, requires the high power dissipation from the output stage transistors to be safely accommodated.

AMSAT has previously constructed only small to medium sized, spin-stabilized satellites with relatively low power output transmitters. We collectively could not allow this experience to dictate our thinking for P3D.

This then points to the evolution of the P3D thermal design. Owing to its size, the thermal "events" happening on one side of the spacecraft would not significantly affect any other side. With the stabilized, "pointing mode" orientation, one side would continuously face the Sun, while the opposite side would never see any sunshine, Fig.1. We could expect that the Sun side would become quite warm, and the backside to get dreadfully cold. All of this even though the structure is of aluminum, which is thought of as a pretty good conductor. In these dimensions, sheet aluminum structures the size of P3D are incapable of moving enough thermal energy to make a difference in this matter.

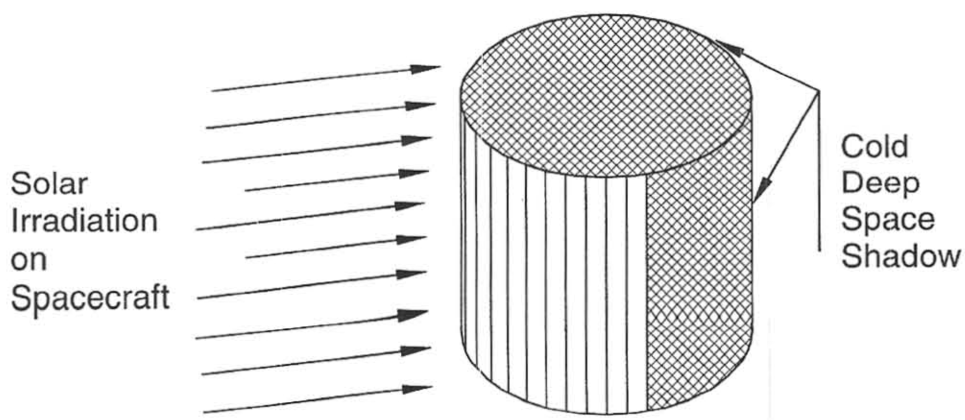

Fig.1 Sunshine and Shadow on a Satellite

The potential transmitters to be installed in P3D were planned to be up to 300 W PEP, with average power dissipation levels planned to be in the 25-75 W category. This meant that there would be one, or more, power transistors (MOSFET devices actually) with quite small mounting surfaces trying to get rid of tens-of-Watts of power. Numerically, heat fluxes of up to 30 W/cm^2 could be expected at any single transistor. To give you a feeling for this type of heat flux, the sunshine that you get at the beach on a clear summer day is in the order of 60 mW/cm^2, or $1/500^{th}$ of the flux at the mounting face of these transistors! To further heighten this problem of cooling of high-powered solid-state electronics, the semiconductor junction inside these devices should not be allowed to become any warmer than about 125°C. These devices cannot be allowed to glow red like the handy radiant heater in your house.

The solution to all of these basic thermal problems on P3D was to employ the use of heat pipes inside the spacecraft. This arrangement is shown in Fig.2, which illustrates the basic six-sided prismatic structure of P3D. The six Equipment Panels are mounted about 220mm (≈8.7in.) below the exterior Side Panels. The key to this design is that the Equipment Panels are in contact with the four Heat Pipes and that the Heat Pipes are not connected directly to any external panel. The basic tenant here is that the "waste" heat removed from one part of the spacecraft is used to keep the cooler parts suitably warm, a thermal redistribution system, if you will. This thermal design concept provides for heat rejection from

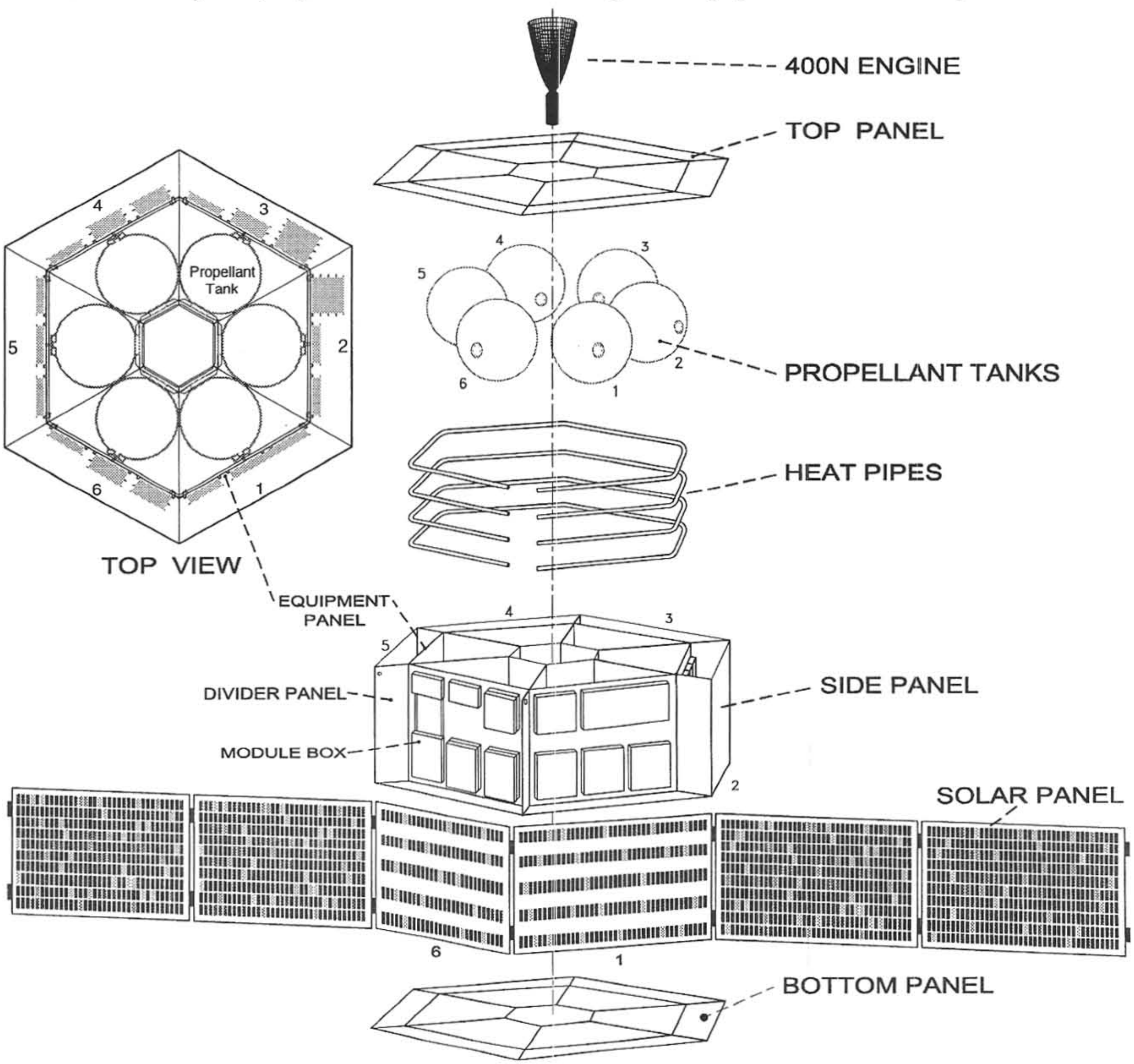

Fig.2 P3D Basic Thermal Structure, Exploded View.

the spacecraft by radiant exchange between the Equipment Panels and the Side Panels, which can, and will get very cold, as intended. As can also be seen, all of the basic electronic modules are mounted to the same Equipment Panels. We do not know of other satellite designs that have used this principle.

Heat pipes have been previously described,[1] see Fig.3, and I will quote that information here: "Design reference literature provides some useful descriptions of a heat pipe.[2] 'The heat pipe is a thermal linkage of very high thermal conductivity. It is a closed, evacuated chamber lined with a wick. Heat is transported by evaporation of a volatile fluid, which is condensed at the cold end of the pipe and returned by capillary action to the hot end. The vapor passes through the cavity. Heat pipes consist of three zones or sections: the evaporator, the condenser and an adiabatic section connecting the two. In some designs the adiabatic section may be very short. This device offers a number or important properties useful in electronic equipment cooling systems. It has many times the heat transfer capacity of the best heat-conducting materials while maintaining an essentially uniform temperature and transporting heat over distances of several feet. It requires no power and operates satisfactorily in a zero gravity environment.' "

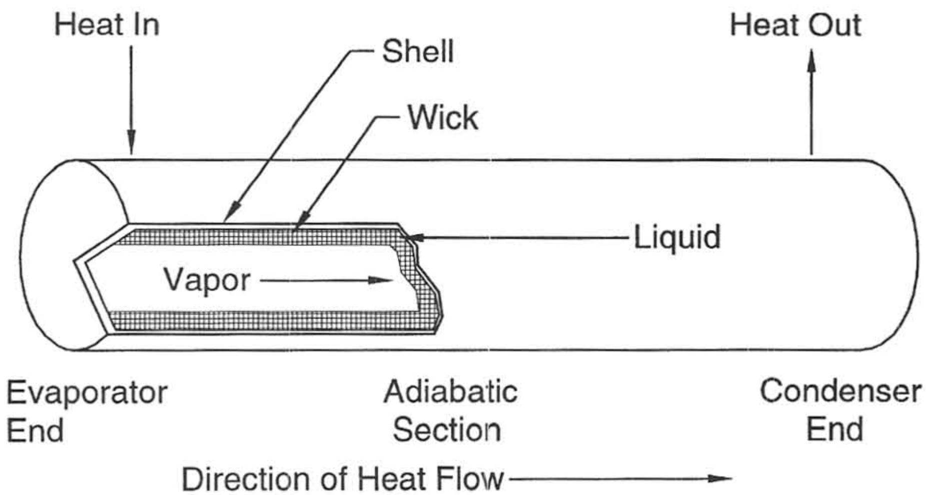

Fig.3 Heat Pipe Basics

In the real-life of P3D, the Heat Pipe is a very sophisticated aluminum extrusion. These were available in 16-ft. sections, just long enough to be formed into a nearly complete hexagon on the inside of the Equipment Panels. Working with this particular heat pipe extrusion has been a continuation of efforts started with the (late, lamented) Phase IV program. It was usefully assimilated into the P3D spacecraft. An enlarged view of this extrusion is shown in Fig.4. As can be seen, the "wick" is really a group of 27 closely spaced channels in the wall of the extrusion. The geometry of these channels allows a very substantial flow of liquid returning from the "condenser section" to the "evaporator section", thus providing for an equally substantial thermal transfer rating for the heat pipe. In P3D use, there is no clear geometric definition for these evaporator and condenser sections, as the pipes are exchanging thermal energy with the spacecraft in many locations.

While the bonding of the heat pipes to the Equipment Panels was sufficient for the panels, such methods would be insufficient for the high-powered transmitter modules. Coupling high power transistors to this heat pipe system therefore required some additional measures to be taken. Fig. 5 shows a cross-sectional view of this arrangement. At the high heat fluxes presented by these transmitters, coupling to just one side of the heat pipe is not adequate. Therefore a specially machined aluminum "Heat Pipe Clamp" was made of high purity aluminum (for maximum thermal properties) and carefully bonded to the heat pipe using a special fixture. These Heat Pipe Clamps were, in turn, bonded to the Equipment Panels at the same time as the heat pipes. On the other side of this thermal path, the

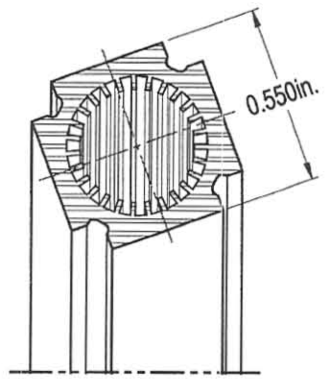

Fig.4 P3D Heat Pipe Extrusion

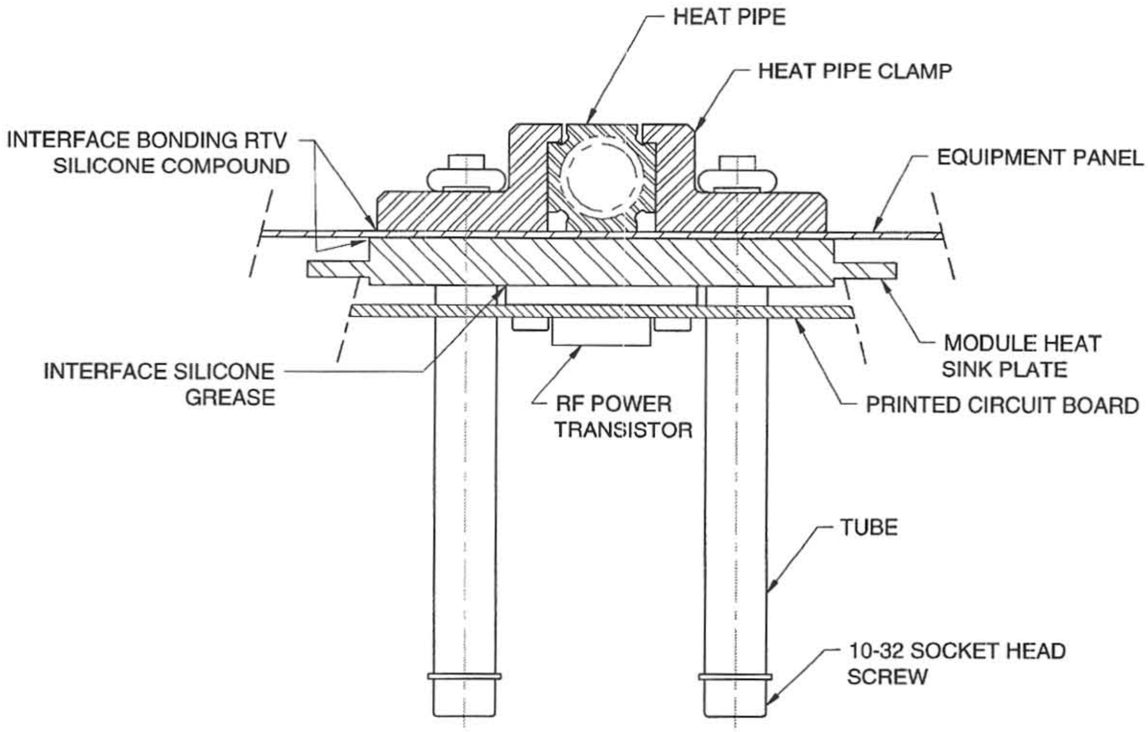

Fig.5 P3D Heat Pipe Clamp & Module Heat Sink Cross Section View

transmitter modules are equipped with two high-purity aluminum Heat Sink plates for the mounting of the power transistors. These modules will also be bonded to the Equipment Panels as well as bolted through to their respective Heat Pipe Clamp. The final step, shown in Fig.5, is to mount the power transistor to the Heat Sink, using space-rated silicone grease. All of these bonding and bolting steps are necessary to insure a very high quality thermal path from the transistor to the heat pipe fluid (anhydrous ammonia, NH_3). Figs.6 & 7 are photo illustrations of these Heat Pipe Clamps as a separate assembly and as installed in the spacecraft.

The thermal performance of this complete high-power coupling of transmitter transistors to the heat pipe system was the subject of fairly extensive thermal analysis and a specially constructed physical thermal model, including a short section of active heat pipe. The need for such elaborate evaluation is that in the vacuum of space, the satellite does not have that air between parts, and nearly none of the parts will be in perfect contact. These "interstitial" spaces must be filled with a compliant material to permit the thermally conductive joining of the parts. The analyses and testing checked out the use of

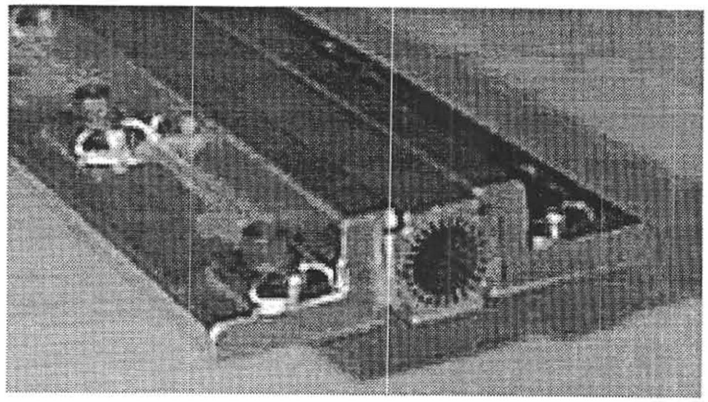

Fig.6 Heat Pipe & Heat Pipe Clamp Assembly.

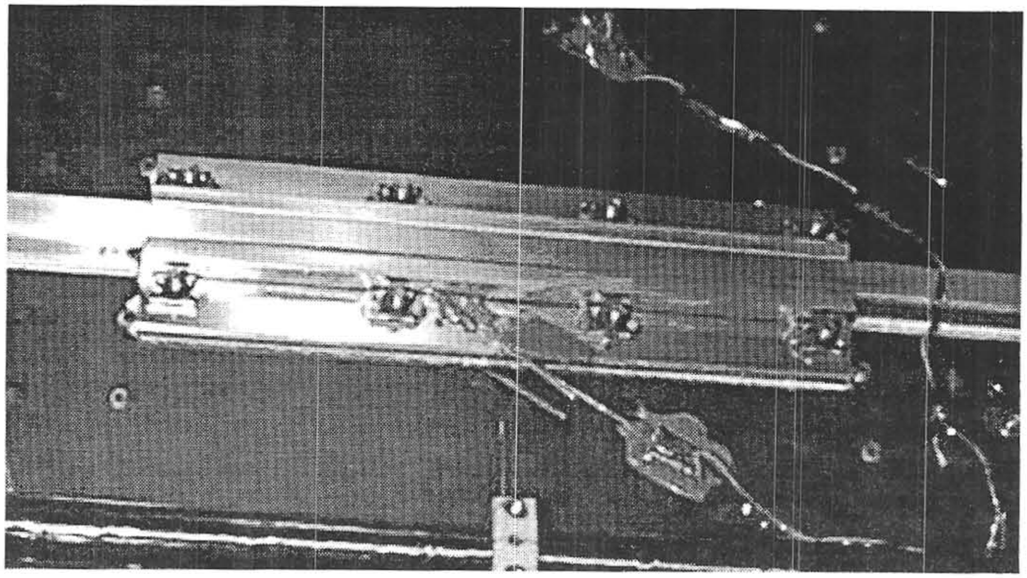

Fig.7 Heat Pipe & Heat Pipe Clamp Assembly Mounted in Spacecraft.

these various materials and I made trade-off evaluations as a result. All of this work was done three to four years ago, but the "bottom line" of this effort is a transistor thermal mounting with an effective thermal resistance, $\theta_{sf} = 0.27°C/W$, that is quite low, even lower than that of the transistor junction to its case. The results of this effort were very gratifying, as the initial concerns that it wouldn't work had been great.

Using the heat pipes in the spacecraft is not the whole story for the internal design. From the onset, Karl and I agreed that certain design features that I created for the earlier P3 spacecraft, starting with P3A, which was lost in a launcher failure in May 1980, would not be changed. We applied the "if it aint broke, don't fix it" principle. This approach provided a deliberate thermal isolation of certain low-power electronic modules from the spacecraft. In space, sometimes there are pretty dramatic thermal events happening. One of these events is that of eclipse of the Sun, with the spacecraft going into the Earth's shadow. Spacecraft temperatures can (and do) drop precipitously over possible eclipse periods of up to three hours. The need to keep certain critical command receivers and the IHU at reasonable temperatures during such events (so that they do not loose their electronic functionality!) is important. The approach that we took for P3A, and for P3D, was to fabricate module mounting rails from a poor thermal conductor ... fiberglass epoxy composite. These critical modules also experience rather low power dissipation so that their exterior surfaces can be made of polished aluminum, reducing their radiated thermal coupling to the spacecraft. Even with these precautions, the modules do not run too warm in normal orbital situations. This has been discussed previously for the earlier P3 spacecraft.[3 4] Temperature telemetry data from both OSCAR 10 & 13 very closely tracked the 1979 thermal analytic predictions in these eclipse situations.

For P3D, we did, however, do one thing new in this area of module thermal isolation. Following some of the difficulties of the earlier P3 spacecraft, I made a new design for the fiberglass-epoxy mounting rail. The new design is taller, providing some more room for the captive screw hardware. Fig.8 is a photo of one of these rails with a part of a module mounted in place.

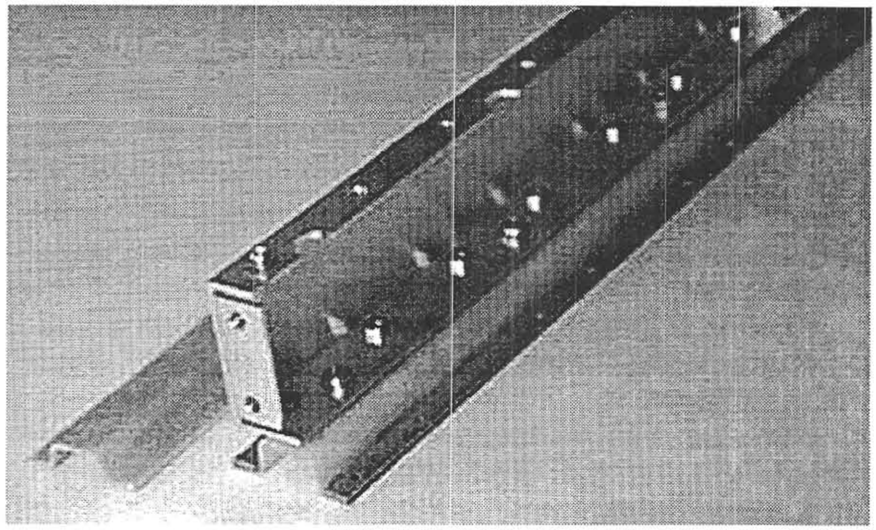

Fig.8 P3D Module Mounting Rail with Module Side Attached (Right), P3B/C Fiberglass-Epoxy Casting for Module Mounting Rail (Left).

Some medium-power modules have required additional treatment. All such modules, along with the high-power units have been painted black to maximize the radiant heat transfer from their cases. In some situations, the fiberglass mounting rails have been replaced with aluminum units to promote reasonable thermal conduction from the module to the Equipment Panel.

P3D - External Thermal Design:

All of these internal thermal design concepts are totally useless if the satellite outer shell is not in the correct temperature range. In recent times, this has been a very substantial concern. At the same time, some errors of omission on my part created a delusionary situation. I shall explain.

P3D must be able to function in two very different operating situations. The first operating mode is that following launch, where the spacecraft is spinning for stability, and the Solar Panels are still latched to the sides of the spacecraft. The second operating mode is in the final orbit with the spacecraft in its three-axis stabilized orientation with Solar Panels 2 through 5 deployed in their "wings". When the Solar Panels deploy, the spacecraft Side Panels are uncovered on sides 2 through 5, permitting these panels to radiate a lot more thermal energy, and they get quite cold. While the solar power generation capability in the stabilized mode is up to ≈620 W, the power generation capability in the spinning mode is exactly $1/\pi$ (31.8%) of that of the stable mode, <200W. Accordingly, the satellite power dissipation must be significantly lower, and this is somewhat helped by the Solar Panels covering the Side Panels.

The next caveat is that for our previous P3 spacecraft, we needed and had to fabricate space-rated thermal insulation blankets to reduce the heat needed to keep the spacecraft warm enough. These are highly sophisticated multiple layers of very thin aluminized Mylar®, and are called "multi-layer insulation", or simply MLI. Having personally fabricated the MLI blankets for two of the three previous P3 spacecraft, I found the process to be "painful", and would do almost anything to avoid their need for

P3D. To this end, I created a thermal coating plan for P3D for the stabilized mode of operation without employing MLI blankets. At that time preliminary studies indicated that achieving a suitable thermal design for the spinning mode of spacecraft operation would be relatively easy. So much for preconceptions. Reality set in by mid-1997 when I constructed a detailed spinning thermal analysis model, to go along with the stable mode model. Using the previous (no MLI design) in the spinning mode analysis made for a dreadfully cold spacecraft, in the range of -30°C to -40°C for some parts of the orbit. I had to "bite-the-bullet" and concede that the use of some form of insulation for the spacecraft appeared to be unavoidable. Many thermal analyses later, Karl and I now believe that we have a viable thermal plan that will satisfy both operating modes.

The use of MLI blankets is significantly complicated by the "antenna farm" located on the top of the spacecraft. This is a busy area. To give you a further understanding, the thermal performance of a MLI blanket is seriously degraded at each and every cut, or penetration of the blanket. There are ≈30 different items located on the top of the spacecraft. For these, we need to have ≈43 penetrations of the MLI blankets, the blanket thermal performance suffering accordingly.

A second factor also reared its ugly head regarding the use of MLI blankets. As we are depending upon the top of the spacecraft to act as a RF reflective surface, the presence of the MLI degrades that property. It turns out that the thickness of the metal in the aluminized layers of the MLI is much too thin, in terms of the needed RF skin thickness. As a result, the MLI becomes a rather lossy participant in the RF fields on the top of the spacecraft. Not swift! We found that we needed to include a good RF-conductive layer as a part of the exterior surface of the MLI blankets. An aluminum foil layer (0.001in. thick) was found to be the solution. This is the very same kind of foil used in "heavy duty" household kitchen service, only wider, and it has ample thickness for the RF situation. But there is a catch. To give the proper RF performance, this RF layer has to be thoroughly connected to the top surface of the spacecraft to insure a contiguous RF surface. Any, and all, such connections represent a thermal short (circuit) across the very thing that we want to use as a thermal insulation. Not good! To mitigate this thermal short situation, when we constructed the outer RF layer with stainless steel foil strips (0.001in. thick) were bonded the aluminum foil edges for the grounding connection. While the stainless steel strips are metal, their thermal conductivity is 1/10th that of aluminum, reducing the thermal conduction term. The most that we can do is to try to make the best of the thermally difficult situation.

The MLI blanket was designed to cover only ≈58% of each of the top and bottom surfaces of the spacecraft. The central zone of the top needed to still remain clear of MLI to allow the U Band antennas to continue to use the spacecraft top surface as their reflector plane. Getting the right amount of MLI coverage has been much like designing through the "eye of the needle". If we have too much MLI, the allowable power dissipation of the satellite will be too limited, while too little MLI will create excessively cold conditions in some orientations.

The exposed surfaces of the top and bottom of the spacecraft are basically that of the natural bare aluminum. The thermal radiative properties of aluminum lend themselves well to these needs, provided that the insulation is used to assist. However, there are some non-ignorable (effectively) black surfaces that have a significant impact on the low-value thermal radiative properties created by the insulation and the bare aluminum. These "black" surfaces are the lenses of the SCOPE cameras, Sun Sensors, Earth Sensors and horn antennas. Despite some fine finishes on these parts, their "blackness" is a thermal problem. A solution, suggested by Karl, is achieved by capping the horn antenna openings with a thick foam plug, providing a very poor thermal conductor in this area, and eliminating the black cavity effect of these antennas.

Even with all of the aforementioned restrictions and difficulties, we do have several thermal control variables available to trim the spacecraft temperature situation. These are: 1) use IHU controlled electrical resistor heaters on the ends of propellant tanks; 2) vary the thermal coating properties of the body-mounted Solar Panels 1 & 6; and 3) vary the thermal coating properties of the Side Panels 2 through 5 (exposed to space when the Solar Panels are deployed). As this paper is being written (shortly before the spacecraft is delivered for an anticipated launch) the final options for some of the coating trims will be taken only at the launch site. Such coatings are quite delicate and are best left to such last-minute application to avoid damage.

The thermal analytic work has highlighted the fact that, in some of the low-power situations in the early spin-mode operation, the spacecraft equipment, operating in a reduced-mode, will not dissipate enough heat to keep the spacecraft warm enough. The key here is that the nitrogen tetroxide, N_2O_4, the oxidizer for the 400N motor, freezes at ≈-12°C. Allowing the N_2O_4 to freeze is obviously unacceptable. At that point, a safety measure was taken to give us some direct heat into the N_2O_4 and NH_3 tanks, by mounting redundant power resistor heaters onto the ends of those four tanks. These heaters will also assist the overall spacecraft temperature situation under these operating circumstances.

Another thermal control coating factor (Nr.2 above) is that the body mounted Solar Panels do not have their full compliment of Solar Cells. This was a design decision taken a number of years ago, as the "solar panel facts-of-life" clearly show that if the heat transfer from the backside of a fully populated panel is not permitted to radiate to space, that panel will get quite hot, ≈90°C ... obviously unacceptable. We made the conscious decision to partially compromise the solar power generator to avoid that situation, by populating these panels with only 50% of the cells of a full panel. The spaces between the rows of solar cells are populated with a space-rated glass that has a silvered coating on its backside. This material is known as "optical solar reflector", or OSR. The material emittance, ε_{IR}, is quite high, as with all glass materials, while the solar absorptance, α_S, is very low due to the reflectivity of the second surface silver coating. Thus, the area not occupied by solar cells provides the needed cooling into space for the remaining cells.

In the spin-mode of spacecraft operation, it has been found that these body mounted Solar Panels run a little too cool, with consequent results on the spacecraft temperatures. Karl suggested that some solar absorbing coating (tape) could be partially applied to these panels to help this situation. In the thermal radiative world, gold surfaces are the warmest thing going when in sunlight. Thermal control tapes have pressure-sensitive-adhesives, PSA, on their backside, and desired vapor-deposited-coatings on their front side. Thus a gold-coated tape is known as "vapor deposited gold", or just VDG, while aluminum coated tapes are close behind the gold tapes. The aluminum tapes are known as "vapor deposited aluminum", VDA. In Karl's plan the body mounted Solar Panels would have ≈10% VDG added to them, and the analyses reflect this tape use. Similar results would be achieved with ≈10% VDA tape.

The last potential control parameter is that of the thermal emittance, ε_{IR}, of the Side Panels on sides 2-5. When the final orbit is achieved and the spacecraft is de-spun and placed under three-axis positional control, the Solar Panels on these sides will be released and deployed for full power generation. This step will also increase the power dissipation capability of the spacecraft, because of the exposed Side Panels. Most analyses have been conducted with about the highest emittance that can be achieved with a thermal coating, ε_{IR}=0.91. The panels are actually painted white, but in the far infrared spectrum, they are just as "black" as if they had the best black paint on them. If it is determined during final analyses that these panels are radiating too much heat, VDA tape can be used to partially lower the panel emittance, and raise the spacecraft temperature.

Computer thermal analysis is an extremely powerful tool these days. In the last 35 years, this tool has advanced our abilities from providing educated guesses of thermal performance to a rather precise engineering technology. Also achieved in this same time period is the capability to do these analyses more accurately on a desktop computer. When this technology was started we needed mainframe computer that filled a room. I shall not get into the gory computer details of these particular analytic efforts, save to note that over the span of this program effort, there have been some very remarkable advances in both the hardware and software capabilities of computer thermal analysis. Thermal model computation times have gone from 20+ hours each to about 2 hours each ... very remarkable.

For the curious, the "complex model" analysis is some 440kB of ASCII data, about 530 Nodes (measurement points) and more than 4500 Conductors (linkages between the nodes). And while this may seem like an extremely complex model, it sometimes seems to be too greatly simplified. The P3D analytic effort has two such complex models. One is configured for the spinning mode, and the other for stabilized mode operations. In addition, several "simplified models" have been constructed to evaluate the effects of basic parameters, without the extensive effort required for running the complex models. The data reported in this paper is derived solely from the complex models.

The two illustrations that follow, Figs.9 & 10, provide a snapshot view of the spacecraft thermal performance for both the spin and stable modes and for a single set of thermal coatings. These coatings are for the "10% VDG" on the body-mounted Solar Panels and with no lowering of the emittance of the Side Panels. In both models, "active" power control of the equipment is used, so that neither model will use more electrical power than is possible to generate in those orientations. I need also to explain that as the P3D orbit is so high, even at perigee, the Earth heating effects are negligible, especially at apogee. As a result, the computations have been conducted as a series of steady-state runs for eleven different solar orientation angles, β, where $\beta=0°$ is the Sun shinning directly on the Solar Panels and none on the top or bottom of the spacecraft. Orientations out to $\beta\pm50°$ are computed in 10° increments. The data is consequently spreadsheet plotted as temperature vs. β angle.

Notable in these data plots is the "gull wing" characteristic of the temperature curves. This is an artifact of the basic geometry of the spacecraft surface area presented to the Sun to be heated. As $\beta\neq0°$ the top and bottom of the spacecraft become very quickly exposed to solar heating. With the aid of the insulation blankets, the temperature changes from $\beta=0°$ to $\beta\pm40°$ have been held to less than 15° C, which is relatively modest compared to some of the earlier analytic results. The power numbers noted with each of these plots is that of dissipation, not consumption. The difference between these two numbers account for the RF power that is "pushed" out of the antennas. From these analyses, it should also be quite clear that the spacecraft cannot safely employ the full capability of the solar power generator ($\approx$600W), certainly not in communication service, as the spacecraft would become excessively warm. Similarly, the dissipation lower value should not be allowed to be less than about 175W, else excessively cool conditions would prevail. This restriction is not all that bad, as the solar power generator will only be able to produce some 350W at the end-of-life of that generator, thus the dissipation and generation capabilities will be fairly matched. In the spinning mode a similar situation exists, only lower ranges of power are involved, $\approx$50W to $\approx$150W.

Conclusions:

Designing suitable thermal conditions for the equipment on the P3D spacecraft has provided an interesting diversion for a number of years. Hopefully these efforts will prove fruitful for the life span of an active P3D mission. It is very clear from these studies that the command stations will have an added parameter to consider in their controlling of P3D ... that of power dissipation for proper operating temperatures.

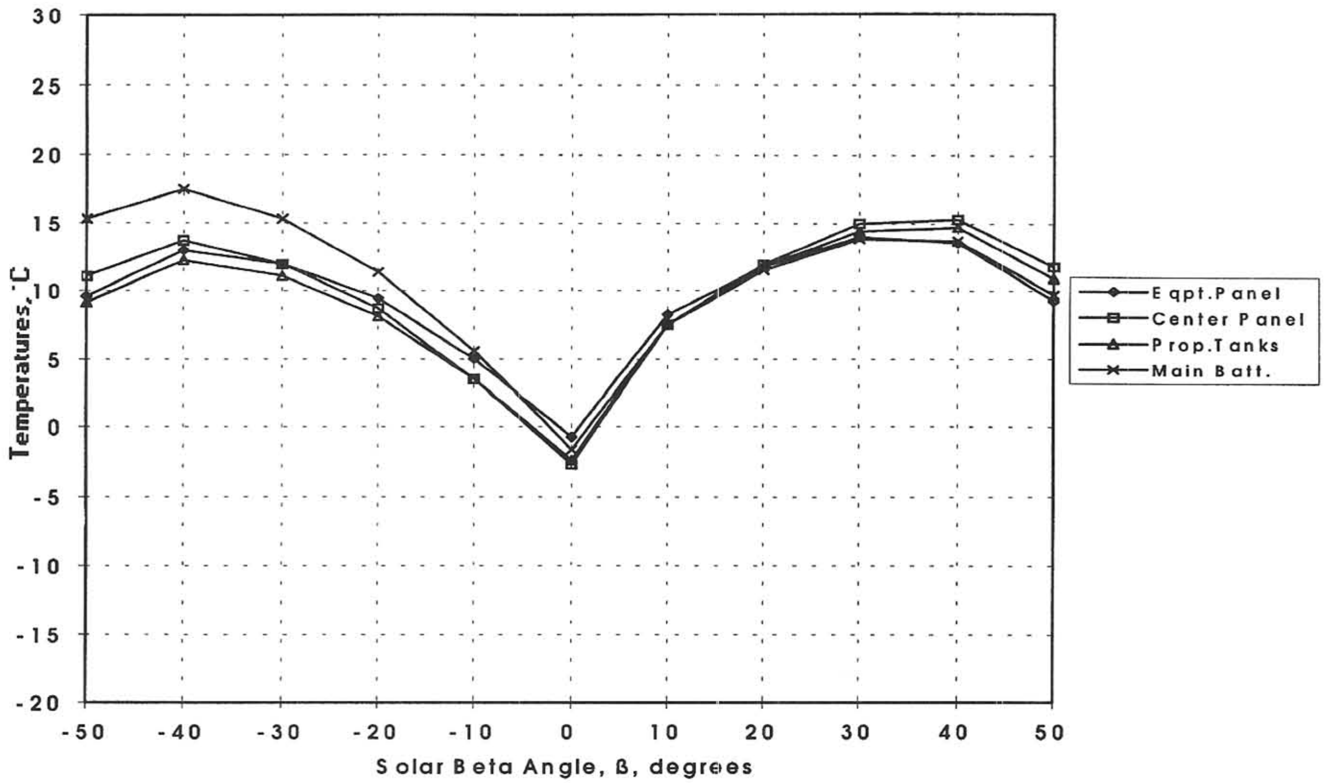

Fig.9 P3D Spacecraft Analytic Temperatures, Spin Mode, 120W Power, 10% VGD on Body Solar Panels, ε=0.91 Side Panels, 57.9% MLI

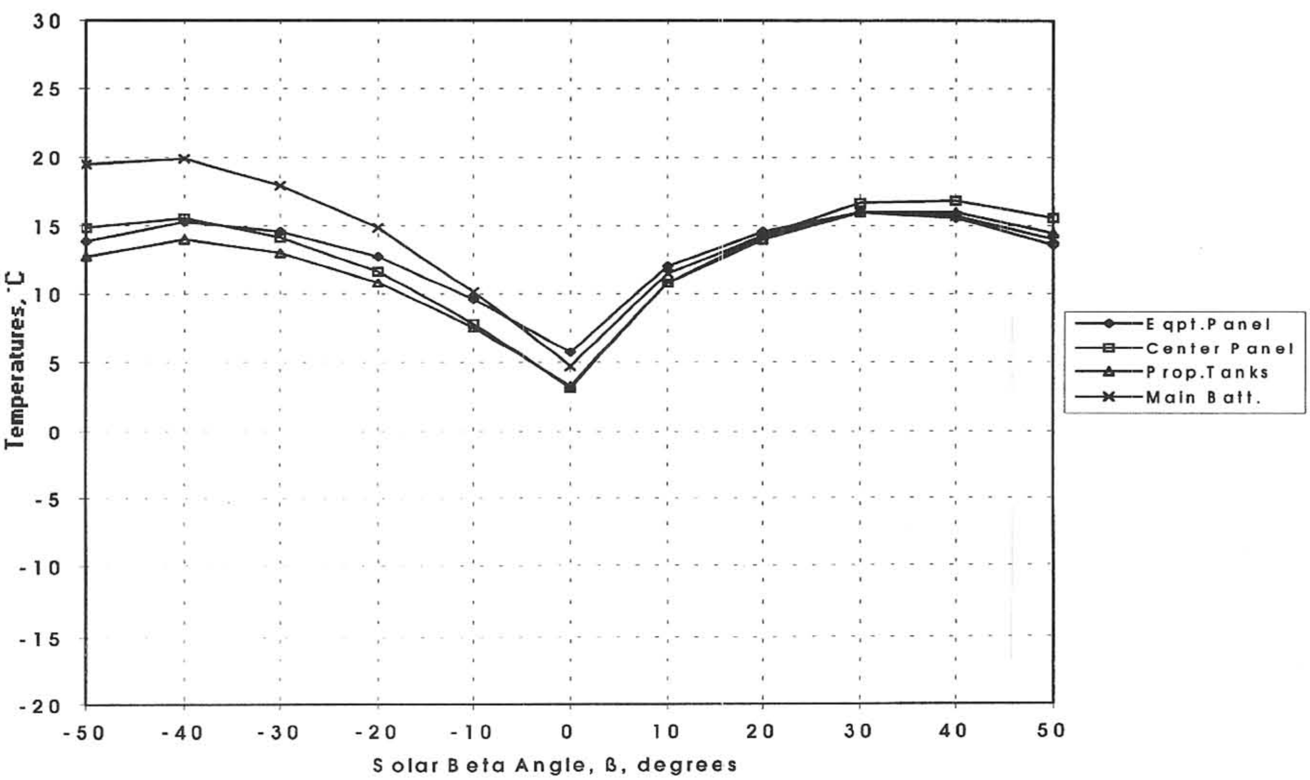

Fig.10 P3D Spacecraft Analytic Temperatures, Stable Mode, 300W Power, 10% VDG on Body Solar Panels, ε=0.91 Side Panels, 57.9% MLI.

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The Experimental IHU-2 Aboard P3D

Chuck Green, Peter Gülzow
Lyle Johnson, Karl Meinzer, James Miller

Abstract

IHU-2 is intended to act as a future replacement for the current COSMAC-1802-based flight computer (IHU) that has flown on all previous P3 missions and indeed controls the AMSAT P3D satellite. The IHU-2 is aboard P3D as a proof-of-technology experiment. Although in contact with other P3D sub-systems, it will not manage anything mission critical. These notes document the design from inspiration in September 1997 to running hardware/software, April 1998.

INTRODUCTION

IHU-2 is an experiment to use currently available, standard process technology components to implement a higher-performance IHU, and running an enhanced version of IPS to enable software re-use. It provides a test-bed for a one-wire-per-module control/status system, implements a CMOS imager for navigation testing, and is very power efficient. Finally, it includes a DSP-style, up to 20 kilobit/sec radio modem experiment to better balance memory capacity to uplink/downlink data rates.

Background [LJ]

In late 1997, Peter Gülzow circulated a note about a CMOS image sensor based on photon rate rather than charge accumulation and suggested its characteristics might make it a good candidate for starfield navigation experiments as well as capturing images of the first moments of life of P3D. At about the same time, Digital Semiconductor (since partly absorbed into Intel) announced a highly integrated version of their StrongARM processor, the SA-1100. Karl Meinzer had just obtained a desktop PC based on Digital's StrongARM technology. James Miller had been using such a computer for years for developing AO-13 spacecraft management software and, along with the P3 command team, managing that spacecraft. Lyle Johnson had just made a decision to use the SA-1100 in a major product development at his work. P3D had missed the AR-502 launch. There were discussions on AMSAT-bb and elsewhere about missions beyond P3D. Chuck Green had finished building a lot of flight boards for P3D and seemed to have some bandwidth available. Lyle was headed for 3 weeks vacation in New Zealand.

As so often happens, these seemingly unrelated events were the mutual catalysts that led to a small group of us discussing, designing, building and debugging a major new spacecraft computer for inclusion on P3D!

Why an IHU-2?

The IHU flown on previous P3 missions, and which will fly on P3D, is based on the COSMAC CDP-1802 processor. UoSAT-1 and UoSAT-2 also used the 1802. Originally developed by RCA in the mid 1970s, this processor is currently made by Harris. Sandia National Laboratories (US) spun a radiation-hardened version circa 1980, and AMSAT has had the good fortune to obtain a small number of them for the P3 program. In 1994, as we worked on the P3D IHU, it became clear that these processors were long obsolete, and the rad-hard versions would no longer be obtainable. Indeed, the CPU chip in the P3D IHU was fabricated in 1983!

Immediately after the P3D IHU was brought to life in 1995, the I/O multiplexer was designed. While various proposals had been made, none seemed acceptable to reliably replace the parallel wiring that controls the various modules on P3D and provides status. The wiring bundles in P3D are extensive, massive and complex. More than 200 wires fan out from the multiplexer to destinations all over the spacecraft.

The CAN bus implemented on P3D offers some promise of relieving wiring complexity. In fact, many experiments on P3D are tied together by the CAN bus, and some of them rely solely on it. But the CAN protocols require a processor and the simplest systems continuously draw over 100 mW of spacecraft power. However, this situation is improving with the growing popularity of the CAN standard.

Current rad-hard processors are extremely expensive, or use a lot of power, or both.

Early discussions

As the need for a new IHU became clear, discussions were held over the Internet as well as one-on-one, about the processor technology, memory complement and feature set that would make the unit viable. Key to these discussions was the processor choice. Step back, for a moment, a couple of decades.

An eerily AMSAT-like sequence of events in the mid 1980s led to the development of the Acorn RISC Machine (ARM). This was a 32-bit RISC processor developed by a team of four people at Acorn Computers, Ltd. [1] Acorn at the time was the leading UK manufacturer of small computers for education and home use. Goals of the processor design included simplicity, low-power operation, and moderate performance at low cost. First silicon appeared in 1985 and the first desktop computer using the ARM-2 in 1987.

In 1990, Apple, Acorn and VLSI Technology co-founded Advanced RISC Machines to exploit the ARM architecture. This was to be a fabless company, and was an early embodiment of the now-popular intellectual property (IP) semiconductor business paradigm.

The ARM processor has evolved over the ensuing years. In 1994, Digital Semiconductor licensed the ARM technology with an agreement to dramatically increase its performance. It resulted in the StrongARM processor in 1996, which Acorn themselves immediately incorporated into their flagship product, the Acorn RISC PC.

The StrongARM is a 32-bit RISC processor with on-chip instruction and data cache, a memory management unit (MMU), and the ability to deliver over 200 MIPS sustained performance while consuming about 0.5 watt. This compares to, for example, a "mobile Pentium" which delivers similar performance but uses nearly 8 watts.

In September 1997, Digital announced the SA-1100 StrongARM chip. This includes the StrongARM SA-1 core, but adds on-chip memory interfaces, interrupt controllers, timers, serial ports and numerous other auxiliary and peripheral functions. In spite of the increased functionality, it still offers over 200 MIPS of processing power, and at a lower 0.2 watt power consumption. It is a fully static part [10.5]. See figure 1.

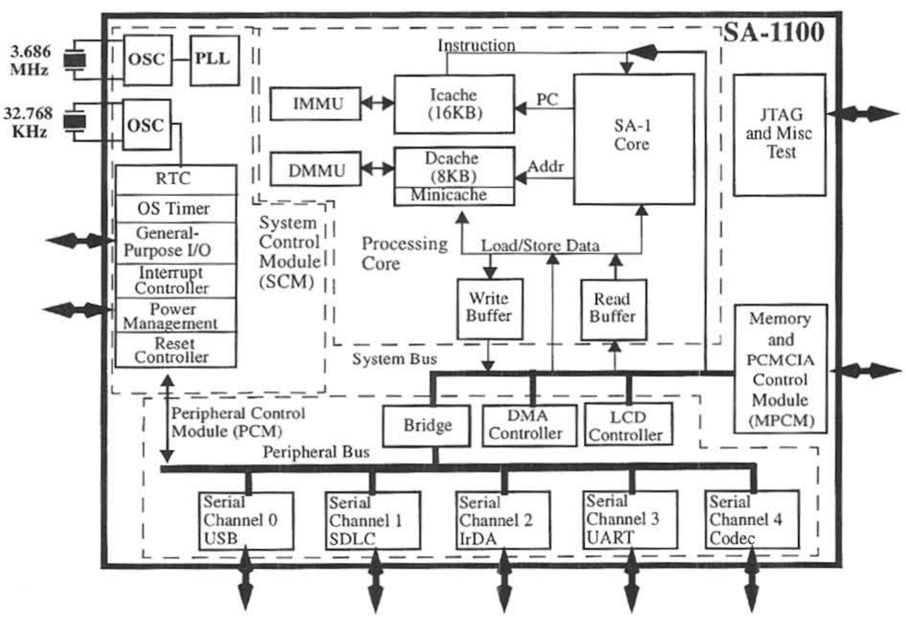

Figure 1. SA-1100 Block Diagram. The StrongARM SA-1100 implements most of a computer system on one chip! Capable of up to 200M instructions/s yet consuming only 200 mW, which reduces pro-rata with clock speed down to 0 Hz. The IHU-2 uses all the elements shown except RTC, DMA, LCD and Serial 0,1,2. All input/ output is via the GPIO system at the left, and Memory Control on the right. Serial 3 is used for ground test at 115,200 baud; Serial 4 is used as a one-wire bus system.
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After consideration of various processors, the group decided to explore a design based on the SA-1100. Once that decision was taken, the memory size and technology were discussed.

For optimum operation of the StrongARM, a 32-bit wide memory system was indicated. Experience with RUDAK suggested that a large, protected memory space is counter-productive for power consumption. The MicroSat model of a smaller hardware-protected memory space for program execution, coupled with a software-protected larger memory space for data storage, was followed instead. The MicroSat computers are comparative power misers, and the design philosophy has proven to be scaleable with, for example, AO-27.

Using IPS, with roots in Forth, meant that a relatively small memory size would suffice. For example, AO-13 had 32K bytes of memory but never required more than half of this amount in spite of the complex operations it performed operating the spacecraft.

The memory size decided upon was 128K x 32-bit of hardware protected memory (EDAC) and 8 megabytes (2M x 32-bit) of software protected data storage.

Other early decisions included the use of a 400 bit/sec DPSK uplink and downlink for compatibility with the AMSAT community's existing command and telemetry hardware [9], CAN bus support, monitoring of the IHU on-board engineering beacon data stream, the use of programmable gate arrays to implement most of the hardware logic functions, and RAM-only memory system (no boot PROM).

Meeting

An on-going meeting has been held on the Internet since September 1997 and continues as of this writing.

The Design Review was held at the facilities of the Philipps University of Marburg, Germany, 1997 December 12-15. This was the only time the team was physically together. During these intense four days, the initial design was reviewed and substantially altered. It was at this meeting that the IQ modem was added, the single-wire expansion interface conceptually designed, and a FLASH memory chip included.

Hardware Development

The initial hardware design was accomplished during a 3-week holiday in New Zealand! In fact, in order to meet the aggressive development schedule, this respite from normal work duties was necessary. The design was done on a laptop computer using the OrCAD Capture tools. Programmable logic was done on the same laptop using the QuickLogic tool chain [10.6] (and drew a lot of stares from other patrons at the downtown branch of the Christchurch Public Library!).

During the design process, the Internet proved to be invaluable in fetching the latest data sheets and specification of the parts to be used, and sorting through candidate parts in the search for the best available components.

Hardware Description

The block diagram figure 2 shows the overall hardware architecture of the IHU-2. The following narrative describes the function of each block in limited detail, and their interactions. Internet site references for the principal ICs are given at the end of this paper.

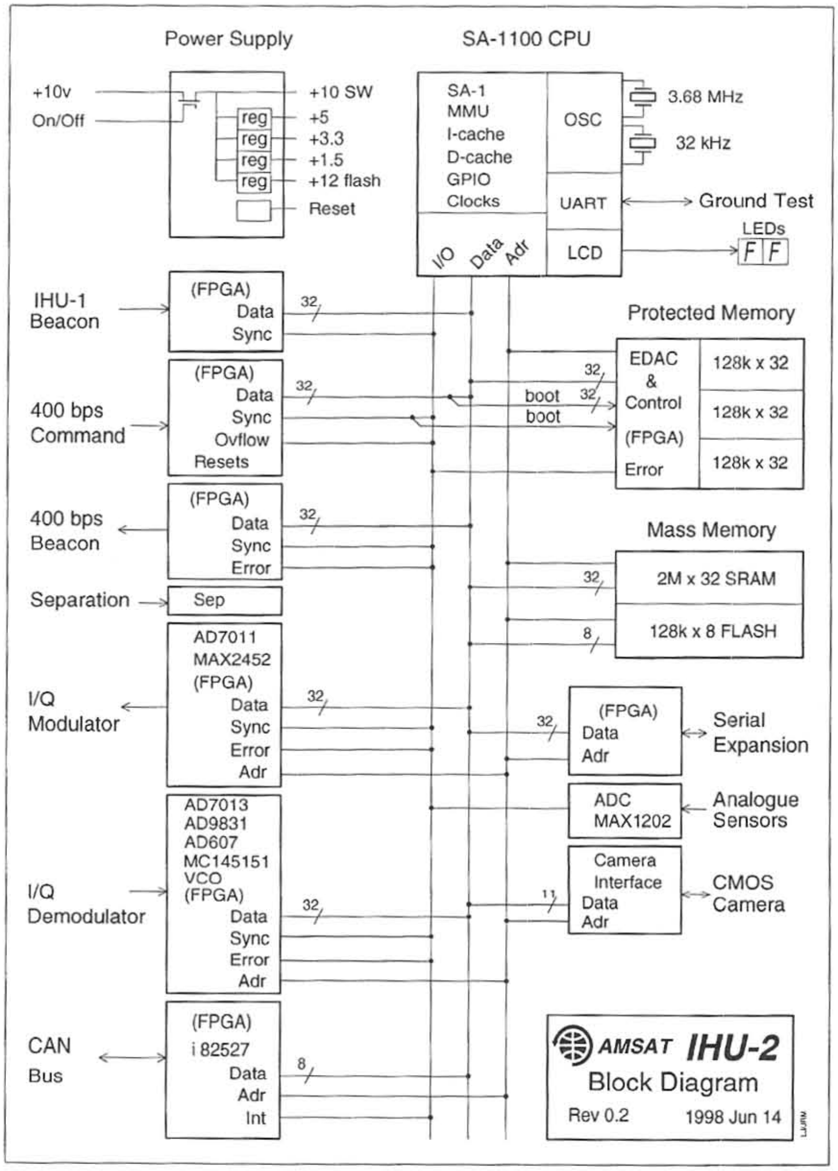

Figure 2. IHU-2 Block Diagram. Almost all "glue" logic is subsumed into three QuickLogic 2005 gate arrays, saving space and substantially reducing development time. Complex signal processing ICs are used as indicated. Most blocks are managed via interrupts (15 sources) marked Sync, Error, Ovflow and Int. The IHU-2 consumes just 1.2 watts at 10 volts.

The *Power Supply* operates from the spacecraft +10V buses. After combining, the merged +10V is run through a FET power switch under direct control of the P3D IHU. When commanded on, independent switching power supplies provide the necessary +5V, +3.3V and +1.5V outputs needed by IHU-2. There is also a low duty-cycle +12V supply activated only when erasing and programming the FLASH memory.

The *CPU* consists of the SA-1100 chip and associated crystals. The part is so highly integrated that little else is needed.

The *Protected Memory* is composed of three (3) physical banks of 128K x 32-bit fast static RAM with error detection and correction (EDAC) logic implemented in a pair of QuickLogic field programmable gate arrays (FPGAs). A 2-out-of-3 majority vote system is employed, so that a bit may be corrupted in every memory bit location and the processor will still get accurate data. When an error is detected, the output from each memory bank is saved (96 bits total) as well as the address at which the error occurred. The processor may fetch this record for analysis or downlinking. In addition, the familiar 8-bit error counter is incremented, so that error rates as well as locations may be easily detected. Including correction delays, the memory system is designed for a nominal 70 ns access time.

Mass Memory consists of 8 megabytes of SRAM organized as 2M x 32-bit. This uses standard 4-megabit (512K x 8-bit) SRAM chips. Finally, there is a 128K x 8-bit Flash memory device using a 12-volt external power supply for erase and write. This type of memory was selected to avoid on-chip charge pumps, which are notoriously easily damaged by radiation.

Engineering Beacon data (for monitoring) passed from the IHU-1 is translated to 3.3V logic levels and passed into the FPGAs. Here, the sync vector is recognized, clock extracted, and differential decoding accomplished. The resulting data is presented to the CPU as 32-bit words, interrupt driven.

Uplink 400 bit/sec data is isolated by an op-amp, then sliced. The slicer output is fed into the FPGAs, where a digital phase-locked-loop (DPLL) recovers the clock. The recovered clock then operates an integrate-and-dump filter, and the output from this is passed back into the FPGAs for extraction of the data stream, differential decoding of the same, and block sync detection. A lock detector is also incorporated.

If the unit has just been powered up or commanded to "reset and load" then the recovered data is passed through the FPGAs directly to the protected memory array. After the uploading of the requisite number of words, the CPU is given access to the memory and begins executing instructions. If the CPU is already running, the FPGAs then assemble each 32-bit word and interrupt the CPU so that it can fetch the word and process it.

Downlink 400 bit/sec data is presented to the FPGAs as 32-bit words. The FPGAs convert the data to serial format, differentially encode it, multiply it by the 400 Hz clock, and shift the data out. This data is then changed to 10-volt logic levels for use by P3D. The FPGAs pace the data from the processor by means of interrupts. If data is not presented by the processor, the output of the uplink lock detector is used to change the downlink from a nominal 400 Hz square wave (unlocked) to a 200 Hz square wave (locked). This helps the command stations assure that the IHU-2 has acquired their command signal prior to commencement of uploading.

The *CAN Interface* uses the same Intel 82527 CAN controller and peripheral components that are used in RUDAK, the IHU and other CAN-equipped P3D systems.

A *Ground Serial Port*, modeled after the system developed for RUDAK, is provided for engineering unit development and testing. It is not powered or otherwise enabled in the flight unit. Likewise, a pair of HP 5082-7340 hex numeric LEDs are socketed on the board for debug purposes. These indicators are not fitted to the flight unit since they consume more power than the entire IHU-2, and no-one would see them anyway. They proved to be indispensable during testing.

The *Camera Interface* comprises 3V/5V CMOS translating buffers and a simple power switch. This allows the camera(s) to be switched on or off, and provides all needed signaling to control them and retrieve the image data.

An output from the *Separation* circuitry is scaled and fed to the processor so that it can determine if P3D is still attached to the launcher.

An IQ (In-phase and Quadrature) modem operates at the spacecraft IF of 11 MHz. The *IQ Downlink* uses an Analog Devices AD7011 IQ modulator operated in analog mode and fed a quadrature signal sample under interrupt control by the SA-1100. The SA-1100 parallel bus to AD7011 serial bus transformation and pacing logic is implemented in an FPGA. The output signal is filtered and scaled, then presented to a MAX2452 IQ modulator chip, driven by an external oscillator. The MAX2452 provides over 40 dB of carrier suppression, and the whole system draws only a few milliwatts. Output from the modulator is amplified by an AD8031 op-amp, filtered and matched to 50 ohms at an output level of -20 dBm. The downlink frequency is fixed.

The *IQ Uplink* signal is presented to a 50 ohm matched load, filtered, and amplified by an AD607 IQ receiver chip. The IQ output is filtered and matched to an AD7013 IQ demodulator, whose samples are de-serialized and synchronized, then presented to the SA-1100 as 32-bit words, interrupt driven. A DAC output from the AD7013 is used to provide gain control for the AD607 under control of the SA-1100. The chip lineup used is designed for low power portable devices such as cell-phones and draws little power.

The local oscillator for the uplink needs to be variable and controlled by the SA-1100. The means to do this in a low power fashion is to use an AD9831 direct digital synthesizer (DDS) chip driving the reference input of an MC145151-2 PLL. A VCO made from discrete components is used as the variable oscillator. The SA-1100 can command the DDS chip over a wide range of frequencies with very good resolution. In this way, the SA-1100 can compensate for doppler shift variations on the uplink as well as any other reasonable frequency drift, and close the loop for proper demodulation of the uplink signal using DSP techniques.

The IHU-2 includes an 8-channel, 12-bit *A/D Converter*. It is wired to monitor the +5, +3.3 and +1.5 volt power supplies as well as three temperature sensors (CPU, EDAC memory and unprotected memory). Additional inputs are provided to allow monitoring off-module parameters, none of which are currently defined for this mission.

Lastly, the one-wire *Serial Expansion Interface* is implemented in an FPGA with external level shifting. The external interface is designed as an open-collector of fairly low impedance to allow for a fairly fast transfer rate (4 µs/bit). Even with low impedance, because the duty cycle is very low, power dissipation is only a few milliwatts.

It is interesting to note that IHU-2 uses about half the number of ICs as the P3D IHU, has 130 times the memory capacity, operates 1,500 times faster, uses the same physical PCB size (200mm x 270mm), and consumes half the power - 1.5 watts!

Comparison with IHU

The following table compares and contrasts the old IHU and new IHU-2 system:

	IHU	IHU-2
CPU	CDP1802	SA-1100-AA
Buswidth	8 bits	32 bits
Native MIPS	0.1	133 max
Protected Mem	64K bytes	512K bytes
EDAC *	1-bit	32-bit
Unprotect Memory	none	8M bytes
Nonvolatile Memory	none	128K bytes
A/D	8-bit	12-bit
Expansion	Parallel	One-wire 32-bit serial
Command Uplink	400 bps DPSK	400 bps DPSK
Telemetry Downlink	400 bps DPSK	400 bps DPSK
Other Up/Down	None	IQ Modem 20 Kbps max
P3D CAN Bus	Yes	Yes
Engineering Beacon	Generates	Generates or Monitors Engineering Beacon
Size	200mm x 270mm	200mm x 270mm
Power	2-3 watts	1.5 watts
Technology	Static CMOS	Static CMOS
Rad Hard ICs	CPU, SRAM	None

* IHU EDAC can correct any single bit per 8-bit byte. IHU-2 EDAC can bit-wise correct a single bit error per bit location, or 32 bits per 32-bit word.

HARDWARE DEVELOPMENT [CG]

Electronic design matured over the period up to the end of January 1998. During this time it was reviewed and revised many times, until commitment to a PCB layout could be made (and time ran out).

The physical size of the PCB was fixed from the beginning. It would be a P3D standard 200mm by 270mm board. We did have an option to use multiple PCBs if needed but this would have added significantly to the cost. It would have also required wires between the PCBs. Wires are undesirable. Space on the board was at a premium from the beginning. So here is how it was used.

Power supplies: 20 percent. There are five different voltages used by various ICs in the design. Four of them required on-board power supplies. This does not count the RS-232 voltages generated by the ground support serial port (not used on the flight unit). There are also filters on the supplied 10V.

EDAC memory: 20 percent. The EDAC memory scheme used requires the actual memory to be three times as large as the processor actually sees. This is necessary to allow a two-of-three vote for each bit. This scheme results in a much faster memory system than the EDAC system used on previous designs, in order to support the much faster processor.

Unprotected memory: 20 percent. There are eight megabytes of memory here. Any data placed here will have to be protected by software EDAC.

Voltage level converters/buffers: 20 percent. Generally speaking, the lower voltage an IC is designed to operate at, the less power it will consume (it's a square law too). And power is obviously very important in any satellite design. Unfortunately, not all functions are available in low voltage ICs. And the satellite interfaces between modules are typically 10v. Therefore quite a few voltage level converters are needed. This isn't as big a hit on space as you might think since these voltage level converters also function as buffers which, in most cases, would have been needed anyway.

Connectors: 10 percent. There are six connectors, digital and analog, along a 200mm edge. There are also two additional connectors along a 270mm edge which are not used on the flight unit (such as the ground support serial port).

Modems: 20 percent. This board wouldn't be much good without some way to communicate with it.

Miscellaneous: 20 percent. This includes things like telemetry gathering, CAN bus, and a cute little device called the SA-1100. The CPU is a 208 pin surface mount device with lead pitch of 0.5mm, more than five times closer together than a standard DIP IC.

Similarly the three FPGAs have 144 pins with leads on 0.5mm pitch. The FPGAs are mounted on daughter boards to facilitate logic analyzer connection and device removal. On the engineering units,

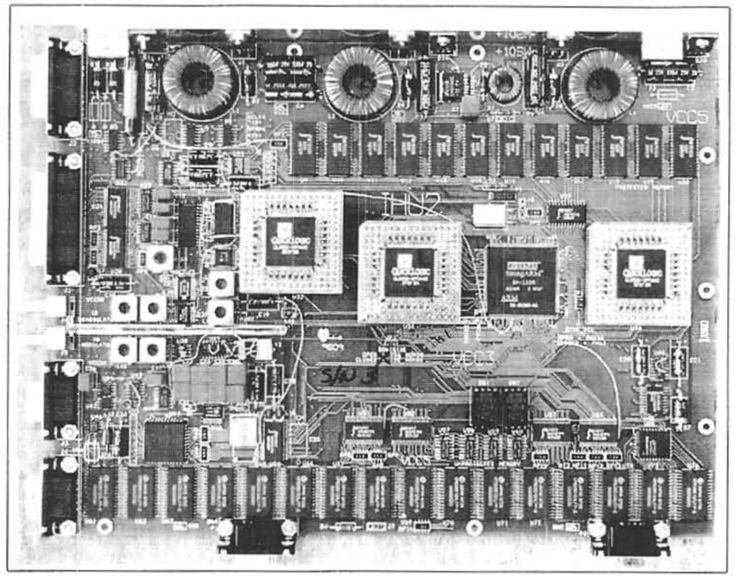

Figure 3. IHU-2 Photograph. Engineering model #3; six-layer board measures 270mm x 200mm. 341 surface mount resistors, capacitors, diodes, and transistors are underside. For flight, the board is surrounded by an aluminum frame/wall to which the connectors and PSU devices bolt. For thermal safety, CPU and both memory systems have heat shunts to the nearest wall. Lower connectors and LEDs are for test purposes only and do not fly, whilst the 3 FPGA daughter boards, presently socketed, are soldered down. The board is then conformally coated.

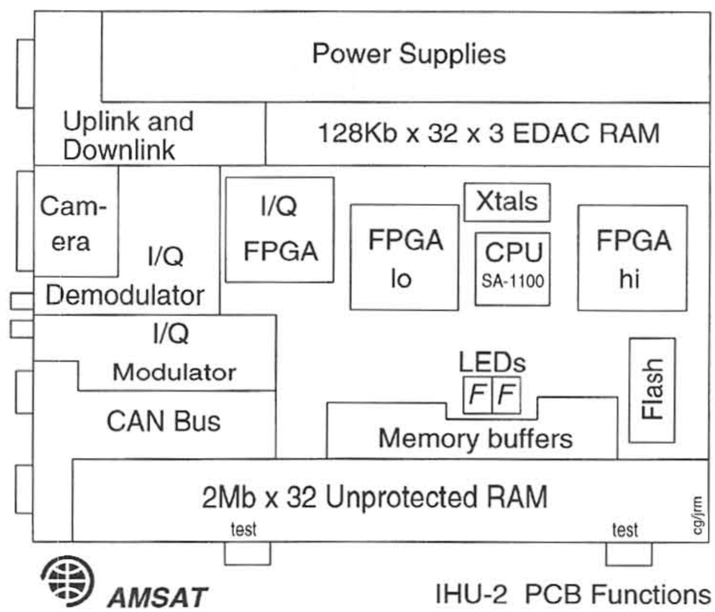

Figure 4. IHU-2 Functions Overlay. This diagram complements the photograph. Connectors from top-left are Spacecraft Interface, Camera Interface, I/Q Demodulator IF I/P, I/Q Modulator IF O/P, CAN bus in, CAN bus out, I/O expansion (single wire), and Ground Test serial port (RS232).

daughter boards are socketed. Due to the tight board layout, it was essential to pre-define the three FPGA pinouts for PCB routing. The rich on-chip routing resources of the QuickLogic anti-fuse FPGAs allowed this pre-definition with no significant impact on performance. In the end, the FPGA utilisations were 99% of pins, 75% of logic and only 25% of routing resources consumed.

As usual, the total of used PCB space comes out at 130%. Nothing new here, most of our projects are like this. But somehow it always seems to fit.

The board is conservatively laid out using 10/9 rules (minimum trace width of 0.010 inches and minimum space between traces of 0.009 inches). The smallest drill size is 0.015 inches for vias. The board ended up being six layers (four signal, one ground and one power). The power plane was divided up to accommodate the various voltages used.

All of the ICs are surface mount devices. Most of the resistors, capacitors, diodes, and transistors are also surface mount. There are, however, quite a few thru-hole devices such as large capacitors, large diodes, inductors, voltage regulators and connectors. There are over 500 parts and almost 4000 soldered connections. The four PCBs (3 engineering, 1 flight) were entirely hand soldered.

IHU-2 device statistics:

Component	Surface-mount	Thru-hole
Capacitors	175	31
Resistors	149	4
Resistor packs	29	-
ICs	77	-
Transistors	13	3
Diodes	6	7
Inductors	4	13
Misc	-	8

3769 solder joints
519 electronic parts

A photograph of engineering model #3 is shown in figure 3, and a key to functional placements is figure 4.

DEBUGGING THE IHU-2 [JM]

Bringing up a new computer from scratch is a fascinating experience. It begins with the application of power and literally checking for smoke (done Orlando, 1998 Mar 11). This is then followed by voltage measurements throughout. Essential services such as clocks are checked, and gradually static reasonableness checks are made to all sub-systems.

Next, since this is a spacecraft computer, one first investigates the command input hardware (uplink) bootloading system. Once this works, simple test programs can be uploaded.

The very first program is typically minimal; drive the numeric LEDs at a rate of one count/second timed by delay loop. That's hardly a dozen instructions, but a successful outcome implies the satisfactory functioning of a considerable amount of circuitry, FPGA logic and CPU set-up. See figure 5. The IHU-2 ran this, its first program on 1998 Mar 27.

```
; IHU-2's first test program.  Drive numeric LEDs at rate of 1/s
; -------------------------------------------------------------
init       LDR    r12,PPC_base ; get PPC Base address
           MOV    r0,#0xFF     ; set pins LDD[7-0] to be outputs
           STR    r0,[r12,#0]  ; write PPDR (Direction Register)
           MOV    r0,#0        ; start display counter at 0

main_loop  STR    r0,[r12,#4]  ; write PPSR (LEDs)
           ADD    r0,r0,#1     ; increment display counter

           LDR    r1,count     ; initialise delay loop counter
loop       SUBS   r1,r1,#1     ; decrement counter, setting flags
           BGT    loop         ; loop if r1 > 0

           B      main_loop    ; repeat forever

count      EQUD   248722       ; around about 1 sec?
PPC_base   EQUD   0x90060000   ; Pin Controller Base address
```

Figure 5. The first IHU-2 debug program. This one was written on Christmas Day 1997, 2-3 months before hardware existed. It worked first time. More demanding tests did not, and required regular software and hardware revision (coding and FPGAs), accomplished via the Internet. Later in the project (April 1998) the UK-AZ 8-hour time zone shift problem required a 5-day non-stop meeting in Tucson to complete the work efficiently.

The next program does something similar, but uses the external 20 ms interrupt to do the 1 second timing. This verifies that we can handle simple interrupts properly. Since there are 15 possible interrupt sources in the IHU-2, this is a useful exercise to get right.

The IHU-2 "talks" to the ground station via a beacon, so the next stage is a program that will drive the downlink system, also by interrupts. Its output is shown in figure 6. Data in the block is snatched from an SA-1100 3.68 MHz internal clock, and gives a clue to processor speed.

To conclude the I/O test phase, we check that there is input capability beyond the boot system. So the next test program is one that simply repeats any subsequent uplink straight back down on the beacon. This exercises two interrupt systems, and also requires circular buffer management to prevent input and output pointers from tripping over each other.

At this point we have verified that we have a computer system with the fundamentals, bootload, input and output functioning. In other words, a basically usable computer.

All subsequent work is checking that the CPU can communicate with the hardware sub-systems, and that those systems themselves work properly. In the order that we tested them; the unprotected 8 MB RAM, IHU-1 Engineering beacon monitor, I/Q modulator, I/Q demodulator, flash ROM read/write/erase, CAN bus, Camera interface, 1 wire serial interface, ground test UART. The memory EDAC system was checked by the simple expedient of omitting 1/3rd of the memory ICs (one bank) during PCB assembly. These ICs were installed later.

In all some 40 programs were needed. Most of the systems worked immediately. A few did not, particularly the specialised ICs used in the I/Q mod/demod circuits.

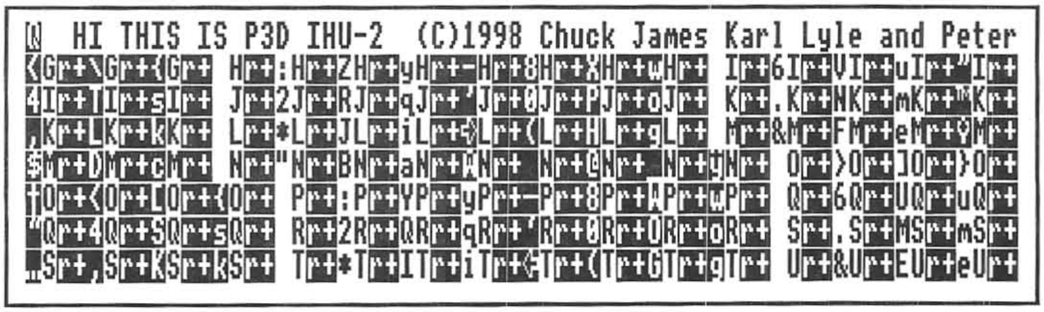

Figure 6. Downlink Screenshot. The first telemetry downlink block from IHU-2, 1998 Mar 29. The data was time snatched from the SA-1100 internal 3.684 MHz timer, giving an indication of instruction speed (0.6 MIPS at that moment). Telemetry aficionados will notice the downlink CRC error. This was traced to having forgotten to enable byte accesses to memory. This simple oversight was the cause of early debug frustration, and shows why trivial clues cannot be ignored.

However, manufacturers' support was willingly given, and all systems were eventually brought up to specification.

Software Development

Writing the test software began as the railway train pulled out of Marburg after the December '97 review meeting, with a read-through of the amusingly entitled SA-1100 Data Sheet; this "sheet" is 350 pages long. [4] In keeping with the spirit of our project, actual coding started whilst on family vacation in Sweden over Christmas, using my host's computer. It continued for a month or so. Throughout all this, the IHU-2 existed only as drawings. Hardware appeared much later, in the middle of March '98.

In addition to the test suite, two more important programs were written in this period. These were the Self-Checking Loader, and the AMSAT P3 Operating System IPS.

Self-Checking Loader

A Self-Checking Loader is essential for loading long programs (i.e. longer than one boot block) into a spacecraft computer. This is because radio links are noisy, and therefore uplinked data sometimes gets corrupted. So, long programs have to be protected by a loader system that first checks itself for integrity, and then checks each target chunk on receipt at the spacecraft, requesting a re-transmission if errors are detected.

IPS Operating System

The AMSAT IPS operating system has been spectacularly successful in AO-10, AO-13 and AO-21's RUDAK system, as well as in a variety of early computers, notably the Atari 800 which was used for many years by P3 command stations. This author (JRM) has ported IPS twice to run on the Acorn RISC Computer family. The first used BASIC to emulate a fictitious 64Kb computer called the M-9096. "C" would have been a better choice (for portability). The second port was written directly in assembler and is, unsurprisingly, about 100x faster. Its designation is IPS-M.

Acorn RISC Computers use ARM architecture processors, so the port of IPS to the IHU-2 was remarkably straightforward. It was simply stripped of all host computer specifics until just three "hooks" remained; 20ms interrupt, keyboard and screen. Conversion to the IHU-2 then only required substitution of these three elements by 20ms, uplink and downlink handlers of the IHU-2. When eventually uploaded to the IHU-2 (in late May '98), IPS came up working immediately.

Once an OS is running, programs can then be written in the native high-level language, IPS itself. Many IPS programs and library sub-routines exist already and run without problems.

The version ported to IHU-2 is called IPS-EM, and is 16-bit oriented, reflecting its pedigree. Much of an IPS implementation is written in IPS itself, and a substantial proportion of IPS-EM high-level code is therefore identical to that of IPS-C/D (AO-13/P3D), both 16-bit environments.

The 32-bit version of IPS, called IPS-E, is presently being designed, and will be coded in the near future. It will be tested on an Acorn RISC Computer, and then ported to the IHU-2 in a manner similar to that described. IPS-EM is already blisteringly fast; IPS-E will improve on it by a factor of 2-3, as well as properly embracing the native ARM 32-bit architecture. This topic is dealt with by KM later in our paper.

About ARM Architecture

Many readers of this paper will be unfamiliar with ARM culture. The name originates from the "Acorn RISC Machine", but is now owned and marketed by Advanced RISC Machines Ltd. The ARM RISC instruction set was devised by Sophie Wilson in 1983 and survives, extended but largely unscathed, to this day. [2] The ARM architecture is formally defined in reference [3].

The first processor using these principles, called ARM-1, was fabricated by VLSI in April 1985, and gave startling performance for the time, whilst using barely 25,000 transistors. [1]. Building on that success, the ARM-2 was developed, and appeared first in a desktop computer in 1987, complete with a multi-tasking, mouse and window environment, drag n' drop, discless OS and much else. It was years ahead of its time, and whilst its prized successors continue in production, Acorn RISC Computers [10.2], along with many equally worthy platforms, have been eclipsed in popularity by global monopoly pressures in a largely naive marketplace.

ARM implementations continued to improve as microprocessor concepts and fabrication techniques advanced, finding wider application in high performance, low-power embedded systems. In 1990 ARM Ltd. was set up, with partners Apple and VLSI with the mission "To be the global volume RISC standard in the emerging markets where computing, communications and consumer electronics converge."

This has certainly been achieved. ARM based processors are in fabrication by a large number of partners, using ARM-6/7/8/9 and SA-1 macrocells. See [10.1] for a long list that includes VLSI, GPS, TI, DEC, Sharp and Samsung.

The embedded processor market is a quiet revolution; but the chances are that you used an ARM processor within the last hour; perhaps in your cell-phone; maybe at a "hole-in-the-wall" cash dispenser linked by ISDN half way across the planet. Who knows? Who cares!

ARM-60 processors are aboard TMSAT, TiungSAT and UoSAT-12 as part of their GPS experiments.

The SA-1100 part adopted for the IHU-2 is an embodiment of the ARM architecture undertaken by Digital Equipment Corporation over the period 1995-7. Costing around $30 in quantity, it offers some 200 MIPS of performance for a fraction of a watt of power. The SA-1100 process has recently been transferred to Intel Corporation.

About RISC

RISC stands for Reduced Instruction Set Computer, an idea proposed by researchers at Stanford and Berkeley universities around 1980. As related to the ARM architecture it means:

a) Fixed length instructions; 32-bits
b) All instructions can be conditionally executed
c) Lots of registers
d) Data processing is register to register only
e) 3 classes of instruction:

Data processing	16	ADD SUB etc., 6 MULTs and a few processor internal management
Memory access	6	Load/store register(s) to/from memory
Program flow	2	Jump, jump subroutine

Other features of the programmer's model, dealt with fully in [3], support a range of interrupts, traps and supervisor calls, all grouped under the general heading of Exceptions.

The ARM handles I/O as memory-mapped devices with interrupt support. That is, devices such as discs, parallel and serial ports, etc. appear as addressable locations within the ARM's memory map.

To support rapid context switching in multi-processing environments, the mapping between virtual addresses generated by the processor, and the physical addresses wired to the memory chips is definable in chunks from 1Mb to as small as 1Kb. ARM architecture handles this through a Memory Management Unit (MMU). Also supported are instruction and/or data caches. MMU and caches are on-chip in the SA-1100; the instruction pipeline is 5 tier. See [2] page 329.

Development tools (hardware and software) are available for many platforms, including the IBM-PC under W3.1, W95 and W-NT, various Unix systems, and Acorn RISC Computers. These tools use C, C++, JAVA and Assembler.

Programming in ARM assembler is best described as exquisite.

ARM - Further Reading

Furber's *ARM System Architecture* [2] is an excellent discussion of the ARM design in particular, as well as contemporary microprocessor issues in general. Written by one of the original 1980's ARM-1 designers, now a professor researching (and making) asynchronous, i.e. unclocked, processors, this is the book for anyone interested in the subject at a serious level.

The ARM RISC Chip [1], also written by an ARM pioneer, takes a programmer's approach, and is weighted more toward the instruction set than the silicon. As does Furber, this book also contains fascinating historical material nowhere else recorded.

ARM Architecture Reference Manual [3] is the authoritative guide, and defines exactly what an ARM processor is. All ARM processors must conform to this text.

Data sheets for individual processors and core macrocells are available from their manufacturers, either on paper or via the Internet.

CMOS CAMERA [PG]

The IHU-2 will have its own "eye." Recently (1997) there have been interesting new developments in the area of camera and CCD chips. A new technology, the so-called CMOS APS (Active Pixel Sensors) can be very simply integrated into digital circuitry.

In contrast to the previous CCD sensors, these picture sensors can be read out like an EPROM. After applying an X and a Y address, the 8-bit value of the picture information is available for the selected pixel. The complicated timing and digitizing of picture data become totally unnecessary due to an on-chip flash Analog/Digital converter. There are no requirements regarding the read-out speed as with normal CCD camera chips. Pixels can be randomly read in any fashion, i.e. the same pixel can be read at high speed or sub windows of the pixel matrix can be accessed. The pixel address can be calculated "on the fly."

This is indeed a very important advantage compared to the standard CCD sensors with the more complex timing. Pixels can be read by an interleaving scheme, and thus the raw image resolution will improve when more pixels are downloaded, etc. The maximum pixel rate of the CMOS Active Pixel Sensor is about 4 MHz. The user has full control over the number of pixels to read out and can exchange image resolution for frame rate.

In addition the CMOS APS exhibits superb picture characteristics, such as a very large logarithmic dynamic range of nearly 120 dB (6 light decades) in comparison to a normal CCD sensor with only 60 to 70 dB. The camera can see very bright and very dark parts in the same image. The well-known "blooming" effects of overloaded CCD sensors also disappear. Pixels are non-integrating; after being activated they measure throughput, not volume. A saturated pixel will never overflow and influence a neighbour pixel. The dark limit is typical 1 lux (0.001 possible) compared to 0.1 lux (<0.0001 possible) of a normal CCD sensor.

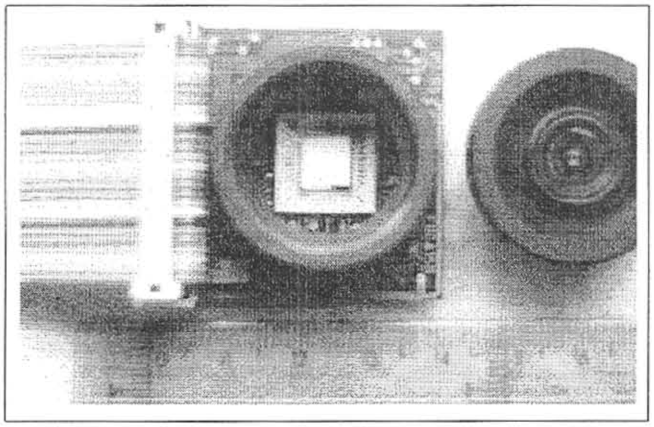

Figure 7. CMOS Camera. 512 x 512 imager shown in evaluation board configuration. From [10.3]. See text.

The camera used has a resolution of 512 x 512 pixels with an 8-bit resolution for the brightness information (black/ white). [10.3] The hardware effort is minimal, as is the interface to the IHU-2. The radiation hardness of CMOS APS sensors is exceptionally good at nearly 1 Mrad. Typical CCD sensors have a comparatively low radiation hardness of approximately 10 Krad.

The diameter of the earth is 16° at a distance of 47,000 km and 20° at a distance of 36,000 km. We decided to use a focal length of 17mm. With the optical sensitive area of 6.4mm x 6.4mm from our image sensor, this gives a Field of View (FOV) of about 21°. In comparison, the SCOPE cameras have a FOV of 16° for the Camera-A (narrow) and 32° for the Camera-B (wide). The precision optic for our camera is produced by Schneider Kreuznach. Because of the optical correction for the wavelength of 400 to 1000 nm, it gives very sharp images without focal difference for the whole visible spectra to the near infrared. Further, no additional IR blocking filter is needed, which will also improve the overall sensitivity. The APS sensor has a large spectral response from 400 to 1050 nm and fits perfectly with the above optics.

Originally it was planned to mount two of these cameras on the satellite. One camera on the upper side and the other on the lower side. The idea was to film and thus document the separation of P3D after launch. Comparably spectacular pictures have already been provided by TEAMSAT [10.4], launched with Ariane-502, which, as it turns out, employed the same camera technology.

Due to space limitations we decided to mount only a single camera on the upper side. Following separation it will still provide pictures of Earth. Later it can be used by IHU-2 as a navigation instrument in order to determine the spacecraft's orientation towards the Earth, and so enable attitude adjustment by the momentum wheels. It would be also possible to measure and track the daylight border line on the earth and re-orient the solar panels to the sun.

A subsequent job could be as star sensor for determining flight orientation, a task that the StrongARM SA-1100 could easily handle. The pictures from the camera will initially be stored in the 8 MB memory of the IHU-2. Without compression 32 pictures could be so stored. Appropriate JPEG compression would allow many more pictures, even a motion sequence to be stored. Pictures and motion sequences can be transmitted either through the IHU-2's own high speed DSP downlink or through the RUDAK experiment. In the second case, images will be transferred over the CAN network into the RUDAK Mailbox.

The CMOS APS camera is not intended to, nor can it, compete with the SCOPE experiment. It will be a technology demonstrator for future experiments.

AMSAT P3 FLIGHT COMPUTERS - PAST, PRESENT AND FUTURE [KM]

Communication Constraints

The P3-IHU was conceived in the mid-70s as a concept to run a spacecraft autonomously without continuous ground intervention. After thinking through and analysing this concept, it quickly became clear that project success would hinge on a sufficiently comfortable mode of programming and interacting with the computer.

An important limitation is the speed by which data can be transmitted between the satellite and the ground stations. The link performance, with distances up to 40,000 km, does not allow more than about 500 bit/s under worst-case conditions, and this only if better than the usual digital transmission techniques are used. For this reason, a format of 400 bit/s employing synchronous PSK was chosen [5].

Synchronous transmission formats are naturally block-oriented, so the adoption of PSK also suggested interacting with the computer in fixed length blocks - 512 byte blocks were chosen (with text this gives 8 lines with 64 characters).

In order to interact with the ground station computers, the same format was chosen. At the time this was a major departure from the "normal" way, because the typical computer of the time used character oriented teletype-like interfaces. Today it is normal to have a desktop with windows - but at the time the available video-units could barely support 16 lines by 64 characters.

Over the last 25 years the concept has proved its value, so there is no motivation to change it. It would be desirable to have higher interaction speeds with the spacecraft, but the link performance cannot be improved significantly. On the other hand the communication formats provide some margin by exploiting high-performance codes. This would in principle allow increasing the link-speed by a factor of 5 - 8. Presently we have provided a coded format for the uplink of the regular P3D IHU, not to increase speed, but to have error tolerance in case of interference. With the IHU-2, the hardware allows experimenting with speed-increasing codes.

Program Performance and Interaction Constraints

Also early on it was recognized that the on-board computer would have to support many programs "running at the same time." Thus a multiprogramming concept was necessary, and using today's parlance, a cooperative multitasking system was chosen. The system is in practice a single-user multi-tasking computer. In this environment a preemptive multitasking environment has more disadvantages than advantages; this was strikingly demonstrated by the nature of the problems encountered with the Sojourner-Rover on Mars (1997).

Furthermore, it was required that at any time it would be possible to interact with the program on all levels. Thus the language handler was made interactive; just another task running along with the other tasks.

For the programming language itself, Forth was found to provide a good starting point, because this language is nearly syntax-free and naturally extendible. In fact the application-programs differ in no way from the original language-constructs. A major advantage was the fact that the system is extremely small compared to any other language handler.

But it also soon became clear that Forth was in many ways too limited for our purposes. In particular:

- Its user interaction was teletype-oriented and not transparent enough.
- The language constructs were very rough and "human engineering" of the language had not really been a consideration in its design.
- The multitasking capability had to become an integral part of the language.

IPS - The Language of P3 Spacecraft

With the above requirements, a language system was designed called IPS. Its basic structure is similar to Forth, i.e. a virtual 16-bit stack-computer emulated on the 8-bit processors of the time. For most control purposes 16-bit words are sufficient; for the few instances where 32-bit words were required, the language could be easily extended to provide the necessary operators for mathematical constructs. The language handler compiles addresses with two-level indirection. The resulting pseudocode allows very fast interpretation (emulation of the virtual 16-bit stack-machine). In addition, an interpretive mode is provided to allow interaction with the system - both programming and debugging. The language handler itself is written in IPS - thus the total system needs only about 8 Kbyte (correct, no mistake!) [6]

The interaction interface was designed from the start to use 512-byte blocks; thus many of the character-handling complications did not have to be addressed in the spacecraft. For the ground-station computers the same interface was adopted in various IPS-versions - early realizations of the windows concept.

The language itself was beta-tested in the University of Marburg keeping track of the typical errors during programming. This allowed identification of those areas which were particularly error-prone. As a result the language IPS was "cleaned up" and a couple of changes were implemented before freezing the design. Just to mention a few: name-redefinition was prohibited, names of objects can have any length using a hashing technique to encode them (all characters significant). Also a number of compiler checks were added to catch the more common blunders. For this reason four distinct classes of code were created.

For multi-tasking a three-level approach was chosen. Routines of moderate time sensitivity can be placed into a "chain" - all the operators in the chain are executed in a round-robin fashion. It is the programmer's responsibility to make sure that no task grabs the processor excessively. Some special routines have been provided to relinquish and recapture control when waiting for external events.

Tasks requiring quicker service, say every 20ms, have a way of interrupting the high-level address interpreter (the so called emulator pseudo-interrupt). Practically no overhead results from this approach when a stack-machine is interrupted. The interrupting routines can be either IPS or assembler. This approach guarantees the atomicity of IPS-instructions. The pseudo-interrupt turned out to be a very powerful concept and greatly helped to overcome the limitations resulting from the relatively small speed of the IHU.

For extremely time critical tasks, real interrupt and even DMA is included in this concept.

IPS Performance on the IHU

We have now about 15 years of in orbit experience with the IHU and IPS. We have learned that the processing performance is quite adequate for the typical control tasks of a spacecraft using the COSMAC 8-bit processor running with a 1.6 MHz clock (0.1 MIPS of 8 bit). Also there have been no problems resulting from the attitude control and orbital mechanics mathematical requirements which need to be performed in real time. But complex communications code-processing or real time image handling (e.g. as sensor complements) are beyond the capability of the old IHU.

An unexpected side effect of the IPS stack architecture is the property of the language to turn most programming mistakes into errors resulting in the wrong number of items on the stack. This is immediately visible and thus allows error detection very early on. Thus IPS-programs, once they run, probably have less hidden errors than programs written in syntax controlled languages. The net effect of this is that IPS has turned out to be a very useful tool to create ultra-reliable programs - for satellites definitely a welcome bonus.

IPS-32 for the IHU-2

With the IHU-2 we have jumped immediately from 8-bit machines to 32-bit machines. But IPS was only intended to emulate a virtual 16 bit machine. Thus the hardware has overtaken the software, and to continue with a 16-bit IPS would unnecessarily tie down the performance of the new IHU-2; it takes more overhead (2-3x more) to emulate the 16 bit architecture of IPS than just passing through the 32-bit performance of the StrongARM.

Fortunately to redefine the word-structure to be 32-bit does not significantly impact the language itself. In fact most programs would run without any changes. Only programs which explicitly exploit the wrap-around properties of 16-bit words (like our angle representation used in the spacecraft) would need some modifications.

Basically the implementation also becomes simpler using the 32-bit words of the processor for the kernel-primitives. But there is a down-side; because now the addresses compiled by the system are 32 bit instead of 16 bit, the memory requirement about doubles. In practice, this is no problem, because during the last 25 years, computer memories have increased about 1000-fold. So a factor of two can easily be absorbed today - the system will be about 16 Kbyte large. Also this allows eliminating some of the specialised memory saving constructs of the old IPS (like 1 byte literals), making the system simpler.

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1. ARM Ltd.	http://www.arm.com/
2. Acorn RiscPC	http://www.acorn.com/acorn/products/strongarm/
3. CMOS Camera	http://www.imec.be/fuga/fuga/datasheets.html
4. TEAMSAT photos	http://www.imec.be/fuga/cmos/vts.html
5. SA-1100	http://developer.intel.com/design/strong/
6. FPGAs	http://www.quicklogic.com/products/pasic2/ql2005.pdf
7. AD7013	http://www.analog.com/pdf/ad7013.pdf
8. AD607	http://www.analog.com/pdf/1824_0.pdf
9. AD9831	http://www.analog.com/pdf/ad9831.pdf
10. MC145151	http://mot2.indirect.com/books/dl110/pdf/mc145151-2rev2-1.pdf
11. Max2452	http://209.1.238.250/arpdf/1240.pdf
12. AD7011	http://www.analog.com/pdf/ad7011.pdf
13. IPS Book	http://www.jrmiller.demon.co.uk/products/ipsbk.html
14. P3 Demod PCB	http://www.jrmiller.demon.co.uk/products/p3dem.html
15. IHU-2 Article (in English)	http://www.aball.de/~pg/amsat/yahue.html

The only remaining obstacle at this time (May '98) is that a different pseudo-code structure needs a new compiler. Previous versions of IPS have been compiled using a special meta-compiler (IPS-X) which creates the specific 16-bit pseudo code. Using this tool, the first 16-bit IPS for the IHU-2 (IPS-EM) was created [7].

For IPS-32, the meta-compiler must first be modified in order to compile the new target pseudo-code. All other tools have been built during the last 12 months on Acorn StrongARM RiscPCs, in particular an assembler for the StrongARM, written in IPS [8].

So it is probably only a matter of a fairly short time, until IPS-32 becomes available for both the IHU-2 and the RiscPC. Then the about 5000-times larger power of the StrongARM will be available from the very convenient IPS interface giving us unprecedented processing power to explore new software communication technologies both for space and for the ground-segment.

THE PLAYERS AND ACKNOWLEDGEMENTS [LJ]

The project leader is Lyle Johnson, WA7GXD. He also did most of the hardware and logic design, and some debugging code.

Chuck Green, N0ADI, did the PCB layout and constructed all engineering and flight units, as well as participated in the debugging process.

James Miller, G3RUH, ported the IPS operating system to the ARM and the IHU-2, wrote the vast amount of debugging code, assisted in the debug process in sunny Tucson and edited this manuscript.

Karl Meinzer, DJ4ZC, provided much of the stimulus for the project, embarked on the design of IPS-32, held out for the single-wire serial interface and IQ modem functions of the system, as well as hosted the design review less than two weeks before Christmas.

Peter Gülzow, DB2OS, initiated the discussions that launched the project, found the camera technology and researched and located much of the information needed in the early design discussions. Peter's more general IHU-2 article, suitable for magazines, is available from [10.15].

All the players participated in the intense design review meeting, evaluation and critiques of the evolving design.

Others who have made technical and logistic contributions include, with thanks, Werner Haas DJ5KQ (AMSAT-DL), Matjaz Vidmar S53MV (high speed data), Larry Brown NW7N (tantalum IC shields), Dick Jansson WD4FAB (heatsink metalwork), MMSI Tucson (test equipment), Stacey Mills W4SM (proof-reading) and our families (understanding). Personnel may be contacted via *callsign*@amsat.org

AMSAT-DL agreed to fund the project, which almost immediately exceeded budget.

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Antarctica and Amateur Satellite Radio.

By Ronald Ross, KE6JAB.

The idea for a trip to Antarctica began 10 years before. I had wanted to travel to the North Pole in 1987, but for the usual everyday reasons I did not do this. I regretted this for many years after, therefore when the opportunity to go to the South Pole arose in early 1997 I vowed I would not let this chance go by for any reason. Travel to Antarctica and the South Pole was arranged for December 1997, and a return in January 1998.

Early in 1997, I had read an account of an attempt to fly to the North Pole by Scott Hamilton, N1VFW. He had sent back messages through the PACSAT's, while onboard a plane going to the North Pole. This intrigued me. I thought while at the South Pole I could send text and images back to my friends and family via amateur satellite. Therefore, the quest to put together a lightweight portable system began. It should draw as little current as possible, yet provide reasonable throughput.

I had been planning on setting-up a PACSAT station for a year or so, but hadn't got round to it, mostly because of the practical, domestic implications of the antennas. I had always been interested in satellite communications, and had worked the MIR and the Space Shuttle in the past while camping in the Nevada desert. These contacts I had done with a fairly basic setup.

In early September 1997, I put a message on the AMSAT-BB, asking what people thought might be the most compact and portable PACSAT station suitable for an Antarctic expedition. I received many messages and many recommendations, the consensus being an ICOM IC821H, a PACOMM modem, a combination of antennas were suggested. I had been using a FT530 HT and a linear amp with a Ringo Ranger up till this time, mostly for voice and packet communications while camping in the deserts of Nevada and California. I had also been doing some ATV experimentation using a 70cm eggbeater, therefore I decided to go with the 2m Ringo for uplink and the 70cm eggbeater for downlink, and purchase an IC821H. While debating over which PACSAT to use, the 1200B or the 9600B, I came across an article written by Steve Ford, WB8IMY, on 9600B modems for PACSAT use. The article compared the performance of the Kantronics KPC9612 modem with several others. I had a KPC9612, but was unaware that it was compatible with PACSAT usage. A quick message on the AMSAT-BB let me know that quite a few hams were using this modem with good results.

For camping and cold weather preparation, we went many times over the course of 1997 to the deserts of Northern Nevada, 350 miles from our home in San Francisco. We tested the PACSAT station mostly in the desert, trying to emulate the conditions and in particular trying to make things work in an environment with only what we had brought with us. Our home environment was not practical for getting antennas on and off the roof, therefore we kept things as simple as possible, when testing at home. After much experimentation, with a very minimal system, a pre-amp was added at the antenna for the down-link and a 2m eggbeater antenna was added for the up-link. This resulted in the bare minimum I thought I could afford in weight and portability, and still provide a reasonable performance.

When I tried to connect with the satellites, UO-22 or KO-25, the competition in and around San Francisco left me somewhat at a disadvantage with no directional antenna for the up-link. Before we headed South I still had only uploaded and downloaded messages of less than 2K, not any images. I had concerns about the setup, especially the modem transmit side. Sending and receiving messages would be OK, sending images would be a bonus. The major benefits I would enjoy while in Antarctica were, at such southerly latitude, there would be no competition for the up-link channel, and a large number of good passes over the day every 90 minutes. I was counting on those two advantages to pull me through.

The only way to get to the interior of Antarctica and to the South Pole privately is with an expedition company called ANI. They have been providing logistical support for private, polar expeditions for a number of years. They have a basecamp 600 miles from the Pole at Patriot Hills, and use a nearby blue ice runway for wheeled aircraft to land. About 100+ adventurers and tourists travel with ANI each year.

During the course of my preparing the PACAST station, I had asked Jerry, N8ULU and Roy, W0SL if they would receive my messages and images from Antarctica. In turn they would forward those via the Internet to my longtime friend and fellow camper Ed, KE6IZN, to post the images on my web site. For text messages, I had set up an Internet mailing list for all interested persons to subscribe and receive those messages from Antarctica.

The weight allowance for the Antarctic flight was 50lbs/person, over that the charge was $30/lb. The radio, laptop, antennas, feedline,battery and all the peripherals easily took up a big part of that allowance, and did not include my clothing and other personal items. I had a 10Ahr and a 18Ahr Gel-Cel battery. The 10Ahr was fine but I decided to go with the 18Ahr just to have a bit more margin, though it would cost in weight, 12lbs.

I packed most of the equipment into two soft travelling bags, the antennas, the radials and fragile stuff was wrapped with heavy woolen socks, thermal underwear and fleece sweaters. The feedline, Belden 9913 and LMR 400, was coiled up with the preamps secured inside the coils, somewhere in between all this was the battery wrapped inside two plastic ziplocks. The radio I carried in a photography shoulder bag, along with the laptop and modem in my rucksack.

We had planned to take images from our camcorder using a frame grabber and send those images over the satellite. My wife, a photographer, had managed to persuade Olympus into lending us a D500-L Digital Camera for the trip, this was a big bonus and enabled us to send excellent JPEG images of typically 70kb or less .

Our route to Antarctica would be from San Francisco to Miami, to Santiago, Chile, to Punta Arenas, which was at the southernmost part of South America, just across from Tierra del Fuego. There, we would meet up with others at the ANI office and fly onward to Antarctica aboard a chartered LC-130 Hercules transport plane.

After waiting 2 days for clear weather, we left Punta Arenas, just days before Xmas, for Patriot Hills, Antarctica. The cloud cover was not too bad and we were able to see our first icebergs, pancake ice and pack ice and then the vast snow landscape that is the Antarctic continent. After 6 hours flying we landed at the base-camp. We settled in to our tent, enjoying everything new, and especially the 24hr sunlight, the temperature was around +15F. We remained on Chilean time for practical reasons, though we were now at 80S, 81W, a few more hours eastward

The next morning it was clear and windy. I got two 8 foot bamboo poles from the camp supplies and secured an eggbeater antenna and it's radials on each one, put the preamp on the downlink pole, and placed each pole on either side of the tent. The tent had a snow wall on each side in order to let the wind blow over the tent and not against it. The poles were driven into the accumulated snow and ice that had built up around the wall. A feedline to each antenna was laid out and fed through a pocket in the side of the tent. The radio, modem and battery were unpacked and carefully setup on my sleeping bag; everything seemed to have survived the journey. The next step was to get the local and UTC time set correctly for pass prediction. We were 3 hours behind UTC, a sat pass of UO-22 was coming up soon. I was ready to monitor the radio receive signal for this pass, I had thought about this moment many times over the months, wondering if everything would work the same down here. Sure enough, as predicted by STSPLUS as the elevation of UO-22 increased the needle started to flicker right and a strong signal was observed, test one was over. Another good pass was due in 90 minutes. As I waited for the next pass I fired up WISP and prepared a short message to be sent to N8ULU, the subject line was "we're here", the message was "Hello Jerry, we made it! pls rply. RR." I had a follow up message much longer in the buffer describing our flight from Punta Arenas.

The pass came, it was one with a high maximum elevation, the strength needle flickered into the red zone on the IC821H, right on cue. WISP responded with an upload request, the request was granted and the file was uploaded then the next one. I was shocked it had worked so easily and I had no other messages to send, nobody else was logged in, and at least five more minutes of the pass was left. WISP began to update my directory, which was seven days out of date. I was elated, I shook my wife awake to tell her the news, this was the first of a few "middle of the night" wakenings she had to endure. The rest of that day I had a permanent grin on my face, all those months of testing, frustration, worrying if I would get everything transported, and whether it would work, had finally paid off big. It felt very satisfying indeed.

The others at the camp were happy at my success, though a little confused by what it all meant, at first. The next big thrill was getting a message back from N8ULU, a day later. I can't say how strange this seemed, having the message pop open on my laptop screen was a surprise when it happened. The strangeness was not the virtual communication which I was used to, but then going out of our tent, realizing how physically remote we were. I could see mountain ranges on one side then just snow stretching for thousands of miles on the other side with nothingness till the coastline.

After this I began to get messages from other hams around the world who had been downloading my reports to N8ULU, and W0SL, those messages were warmly received. The best passes for my setup happened to start after midnight local time and continued till roughly 9am. Each night I would get 5-6 good passes on UO-22. Each morning the other people in camp would quiz me, wondering what new messages had arrived from the world outside. My intention had been to send text on UO-22 and images on KO-25, but I could not make a link with KO-25 to begin with, for the first week I stuck to UO-22.

The next test was to upload an image. We had been having problems with the digital camera, the batteries would run down very soon after powering it up. We thought it might be the cold, but I think the NiMh batteries had not been charged for a while, each subsequent charge appeared to make them last longer. A photo of a penguin from the rookery back near Punta Arenas was selected for the first image upload, and after two passes we got it uploaded completely.

I still had not seen anyone else logged onto UO-22; I also noticed how I experienced less fading than I was used to in SF. A strong signal was gotten right after rising above the horizon then a deep fade, then a strong signal till the end of the pass, with little fading. Later I noticed how strong the signal from the satellite could be, without turning on the preamp I would see the QST message from UO-22 on the WISP screen.

A few days later and always on the early morning passes, as the satellites worked their way down S. America I could see other hams logged into both UO-22 and KO-25. Further tweaking of my setup allowed me to send images on both KO-25 and UO-22. At times, I was sending two to three images a night. The best I could achieve being a 70Kb image in one pass. I found that KO-25 was a better "listener" than "talker" and the opposite for UO-22. However this difference was quite marginal. My main problem when operating was tuning the Doppler shift, not that I couldn't do it, but that I got distracted by things on the laptop screen and was quite far off when I looked back at the radio receive signal.

The PACSAT station drew quite an interest in camp, and often I would have a few other people sitting in our tent watching messages get uploaded and downloaded. We all eagerly awaited that screen to pop up with personal messages. Some of those were from my family, via AOL, via W0SL and some from other people on the mailing list.

We flew from the base-camp to the South Pole in a Twin Otter aircraft, I did not take the PACSAT station to the Pole, mainly because of the antennas, having to dig them out of the snow, and the space limitation on the plane. In retrospect I wish I had. Yet, I did send a report and an image taken at the Pole, several hours after we returned to the base-camp. Those appeared on my web site a few hours later.

The 18Ahr battery lasted for about one week before needing charged. The wind generator in camp was working again after being damaged in a blizzard, but I was able to borrow a solar panel that normally lived on board the Cessna plane used at camp. That allowed me to be independent but I had not brought an inverter, and had to rely on AC power from the official radio tent to recharge the laptop, camcorder and digital camera.

My operating routine for the first week was to just stay up till whenever I got my messages and images uploaded. This often meant sitting in the coldness of the tent for several hours till around three or four am, then turning in for the rest of the night. Once the initial excitement died down, I placed the radio and modem on a box beside the sleeping bag and would have my watch alarm set for each upcoming pass throughout night. I would wake up five minutes before the pass, get the laptop running, turn on the radio and modem, upload a message, and then shut down everything, all without getting out of my sleeping bag. The only time this routine failed was when the wind was blowing so hard enough that I never heard my alarm over the sound of the tent being buffeted. Towards the end of the trip I had enough uplink bandwidth that missing good passes didn't matter so much anyway, I could get an image uploaded, with relative ease.

In camp each day we would take short trips to the surrounding hills and glaciers by skidoo or ski, and if extended good weather permitted we would take a tent and food supplies for a few days camping. Each night I would send back a report of the things we had done and seen, and sometimes send an image of the local terrain.

We had one other ham in camp Art Mortvedt, KL7RL, he was from Alaska, and would often get a phone patch on 20m through Bob Hines, K4MZU in Atlanta to his wife, back in Alaska. In the early hours 1st Jan, I talked to Bob, K4MZU. The signal was strong and clear. We were in Art's tiny Kelty tent while outside a blizzard raged on, it was quite a thrill.

Our return date from the basecamp to Punta Arenas was set for 5th January; this was more of a target than a reality. In fact we never returned because of poor weather for almost another week. Just prior to this a Twin Otter had been sent to the South Pole Station to pick up two expedition groups. The first group were 3 Icelanders a father, son and friend. They had left Patriot Hills 2 months before. Each pulled a sledge all the way to the Pole. The second group was three Australians, who also pulled sledges from Birkner Island, much further Eastward, beginning two months before and they also made a successful trip to the Pole. When they arrived back at the basecamp we were treated to a first hand account of their experience, which was truly fascinating. We took pictures of both groups and sent images back on the PACSAT station. Ed, KE6IZN, who was managing my web site back in San Francisco, sent a copy of the Icelanders picture to their expedition web site in Iceland for their families to see.

A day later, Olafur the father on the Icelandic expedition told me he had just talked to his wife in Iceland, using the Satphone in camp. His wife and family were so relieved to see how healthy they all looked in the picture they had received; it was all possible by amateur radio. Olafur was so happy, and I felt glad I had brought this PACSAT station, and proud of all the amateurs who had made such a system possible. This single event made it worthwhile for me.

The weather cleared, and on Sunday morning the 11th January I filed my last report to Roy, W0SL from Patriot Hills. I then spent the next few hours dismantling the PACSAT station. I had sent over 70 messages, 11 of them were images, it had been a great success, and things had turned out even better than I had hoped. Almost six hours later the HERC landed on the blue ice runway, to take us back to Punta Arenas. We took one last look at the camp then departed, four hours later we saw our first sunset in three weeks, and three hours after that had our first shower!

Back in Punta Arenas at an Internet cafe I was able to look at my web site and see all the messages and images posted. Ed, my friend who had moderated the mailing list summed it up for me in one message, and I quote.

"It's been fun living this vicarious adventure. It all seems to have happened so fast, and I don't want to go home yet."

It was a great adventure; the radio part was a super experience. We hope to go back to Antarctica one day, soon. I'm very grateful to all the people in and out of AMSAT who helped me, especially Roy, W0SL and Jerry, N8ULU, and Ed, KE6IZN.

The complete text will also appear on my web site, www.thistle.org, with links to some of the pictures we took using the digital camera.

Ronald Ross, KE6JAB.

Equipment used.

ICOM 821 Radio.
Kantronics KPC9612 Modem.
Toshiba 486 Laptop, running Windows 3.1 with WISP and STSPLUS.
ARR and SSB 70cm GasFet Preamps.
2m and 70cm eggbeater antenna's with radials from M2.
LMR400 and Belden 9913 Feedline.
Olympus D500-L Digital Camera.

**Taken at Patriot Hills Basecamp,
showing my radio tent, antennas and radio/laptop.**