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AMSAT
RADIO AMATEUR SATELLITE CORPORATION

AMSAT 25 Years In Space 1969 - 1994

PROCEEDINGS OF THE AMSAT-NA

12th Space Symposium and AMSAT Annual Meeting

October 7-9
1994
Orlando, Florida

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FOREWORD

THE AMSAT-NA TWELFTH ANNUAL SPACE SYMPOSIUM

The AMSAT-NA Twelfth Annual Space Symposium is held in conjunction with the 1994 Anual Meeting. This years events are sponsored by the Florida AMSAT Field Organization and held at the Airport Holiday Inn, Orlando, Florida October 7-9. Special thanks is due to all the committee members listed below:

Alan Brinkerhoff, WB5PMR	**Chairman**
Barry Baines, WD4ASW	**Reservations**
Dick DiVittorio, KB4QKD	**Prizes**
Hank Fitz, WB4URU	**Reservations**
Rick Harrelson, WB4ULT	**Transportation**
John Kuklinski, N4PLY	**Communications**
Steve Park, WB9OEP	**Proceedings and Presentations**

Some Words from ARRL

The Twelfth AMSAT-NA Annual Space Symposium takes place in an auspicious year: 1994 marks the 25th anniversary of the founding of AMSAT-NA. During the last quarter century, AMSAT has played a pivotal role in the success of our Amateur Radio space efforts. The future promises even more astonishing achievements with the launch of Phase 3D and many other projects.

These papers reflect AMSAT-NA's commitment to progress. You'll find a wealth of information about the ambitious Phase 3D satellite. Other projects are discussed such as UNAMSAT-1, VOXSAT and more. Even if you're a beginner in satellite communication, you'll find something of interest. And if you're inspired to go farther, contact AMSAT and discover how you can participate in the *next* quarter century of innovation.

David Sumner, K1ZZ
Executive Vice President, ARRL

October 1994

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WELCOME

I am glad that so many of you have been able to attend the 1994 AMSAT Annual Meeting and Space Symposium. It is especially fitting that you are here at this time, because this year marks both a landmark in the history of the Amateur space program and a crucial point in determining its future. This year, and this meeting might be termed our "Janus" point - after the Roman god which was depicted with two heads, one looking one way and the other in the opposite direction.

We look back to 25 years of accomplishment. The Radio Amateur Satellite Corporation, by becoming established in 1969 to carry on the pioneering work of Project OSCAR; not only contributed a great deal to Amateur Radio by building a number of satellites itself, but provided a model for the formation of Amateur satellite based organization in many other countries in all parts of the world. As a result of the formation of these other "AMSAT" organizations, we have informally adopted the "NA" suffix to identify our specific North American based organization. Thanks to Project OSCAR, AMSAT-NA and a number of other overseas amateur satellite groups, Amateur Radio presently has some sixteen operating satellites freely open to licensed Amateurs anywhere in the world. With the promised, imminent, launch of UNAM-SAT and RS-15, two more Amateur satellites should soon join that group.

But even more exciting than the look back, the look forward is absolutely mind boggling. Of course, Phase 3D is on everyone's mind. You, who are attending this meeting, will have the chance to get a first hand look at what is to come in less than two years. How we will use it to enhance our enjoyment of Amateur Radio and increase our hobby's already substantial contributions to our various communities and the world as a whole, will be up to our national amateur organizations and to us as individual Amateurs.

But, should Phase 3D be the end of the design and construction phase of the Amateur satellite program? What projects, if any, should AMSAT-NA undertake after the launch of Phase 3D? Should we work within our own North American organization to build future satellites, or continue to work in cooperation with other overseas AMSAT organizations? Assuming we can find volunteers willing to design and build satellite hardware and create suitable software, where are the launches to come from? Should we cultivate cooperative alliances with various university based satellite construction groups which are springing up all over this country? If we do, how do we "steer" these projects into producing spacecraft that are suitable as Amateur satellites and have the capabilities we want? What capabilities do we want? What kinds of satellites should be considered as qualifying as "Amateur Radio" and thus having the use of Amateur frequencies?

All of these weighty questions, and more like them, will be examined at the Board meeting to be held in conjunction with this meeting. While you're here, take advantage of the opportunity to discuss your thoughts for the future of our organization with any of the Board members or officers who are here.

I hope that you enjoy your attendance at this 25th Anniversary AMSAT Annual Meeting and the accompanying Space Symposium, and that it will be educational and rewarding to you as well as to the organization.

73,

Bill

Bill Tynan W3XO

Phase 3D, A NEW ERA FOR AMATEUR SATELLITES

by

The Phase 3D Design Team

Successful use of amateur satellites, OSCARs 10 AND 13 require a single multi-mode VHF/UHF rig delivering 50 to 100 Watts (or at least a 2 meter receiver and a 70cm transmitter) and two directional antennas (one for 2 meters and one for 70cm) that can be aimed in both azimuth and elevation. Phase 3D, currently under construction, is aimed at significantly simplifying these requirements plus adding many other modes of operation i.e. frequency choices. A number of specific design features are being incorporated into Phase 3D to make it much more accessible to amateurs throughout the world, as well as more flexible for the years to come. However, in addition to substantially reducing the ground station requirements, Phase 3D is being specifically designed to assist the continued march of Amateur Radio toward ever higher frequencies - begun in the early 1920s at 200 meters. This is important, if amateurs are to retain the use of these bands; which, in the next century, may turn out to be some of the most valuable assignments we have. As commercial and government communicators have already discovered, satellites can make these upper reaches of the spectrum very useful for communication between widely scattered points on the Earth. In addition, the time may not be too far off when we are using the GHz bands to talk to hams on space stations, the moon and planets. Phase 3D will give us the incentive we need to begin making more use of these valuable assignments.

A Truly International Project

Phase 3D is truly international in scope. Not only is it being aimed at bringing satellite operation to within the reach of virtually every licensed amateur in the world, but it is being designed and built by an international team comprising people from some dozen countries. Much of the early conceptual work was done in Germany. Two of the transmitters, which will be aboard, are being built in that country, as is the IF Matrix and one of the computers. The 10 meter bulletin transmitter is a product of the South African AMSAT group. The 2 meter transmitter is being designed and built in the U.K. A group in Finland is supplying the 10 GHz transmitter and its associated antenna. The 24 GHz transmitter, along with its antenna, is coming from Belgium. Receivers are being constructed in Belgium, Germany, Slovenia and the Czech Republic. The propellant tanks came from Russia. What promises to be a very interesting camera experiment is the product of the Japanese JAMSAT group. All of the spacecraft's antennas, with the exception of those associated with the 10 GHz and 24 GHz transmitters, are being developed by a U.S. team. The construction of the spaceframe and the launch vehicle adaptor, are taking place in the U.S. Much of the mechanical and thermal design work has also taken place in this country.

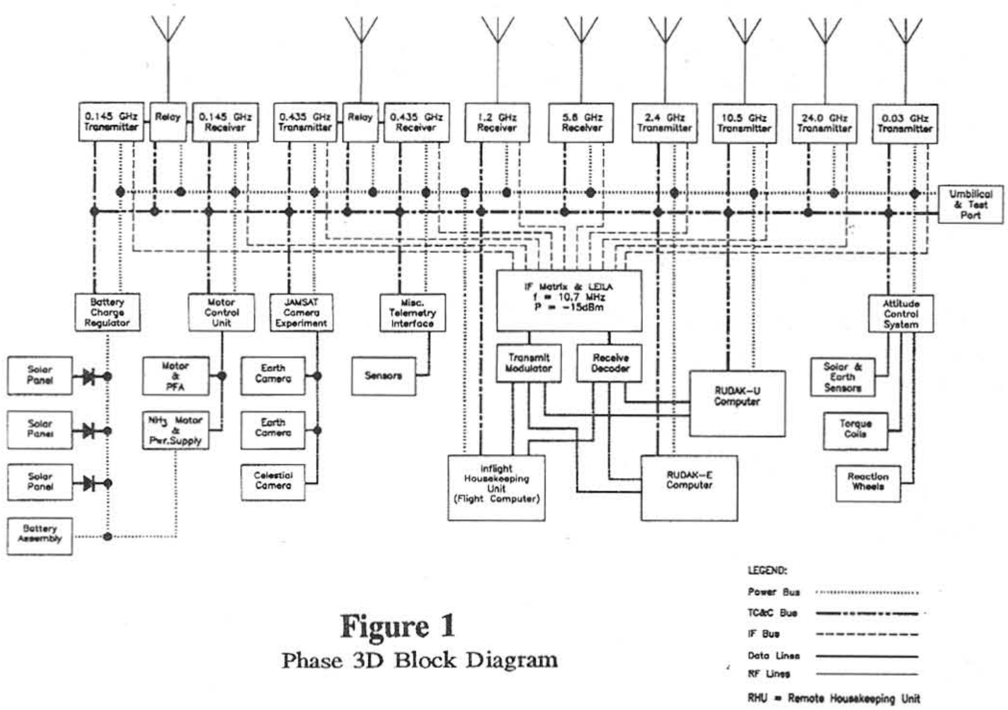

Figure 1
Phase 3D Block Diagram

Other contributions to the Phase 3D project, from this part of the world, include the design and construction of the GPS subsystem, the latter with some help from Canada. Much of the basic design for the main spacecraft computer, the IHU, came from Germany; but it is being built by a U.S. team with German and British help. In addition this same U.S. group, again with help from Germany, is also undertaking the design and construction of two other Phase 3D computers. One of these is called RUDAK-U and the other is a dedicated computer for the GPS experiment. Another computer, RUDAK-E is to come from a group in Germany. The Arc-jet motor is currently under development by a group at the Institute for Space Systems at the University of Stuttgart in Germany. Radiation testing of various solid state components has been taking place in Canada. This is the subject of a separate paper.

Assembly and check-out of the spacecraft is taking place at a facility set up in Orlando Florida. Launch, aboard the second test flight of the European Space Agency's new heavy lift Ariane 5 vehicle in April 1996, will be from ESA's launch complex at Kourou French Guiana in South America.

A New Approach

Previous amateur satellites have utilized transponders. A transponder can be characterized as a single box which receives signals on one band of frequencies and puts out an amplified replica of these same signals on another band of frequencies. Instead of dedicated transponders, which limit flexibility, Phase 3D will employ the approach shown in Figure 1. The satellite's communication package will consist of a series of receiver front-ends and transmitter mixer/power amplifiers linked by a common IF. The outputs of any of the receiver front-ends can be connected to the IF Matrix, which in turn can be connected to any of the mixer/power amplifiers - all under computer control. This means that uplinks and downlinks can be set up on any of the bands for which hardware exists on the satellite. This is very important, because no one can say for sure what bands will be most viable for uplinks and downlinks in, say 2005 -the year that Phase 3D (OSCAR ?) will be nine years old, and expected to be still going strong. By configuring the satellite in this manner, a variety of circumstances can be accommodated by software loaded from the ground. Fig 2 illustrates the expected arrangement of uplink and dowlink frequencies.

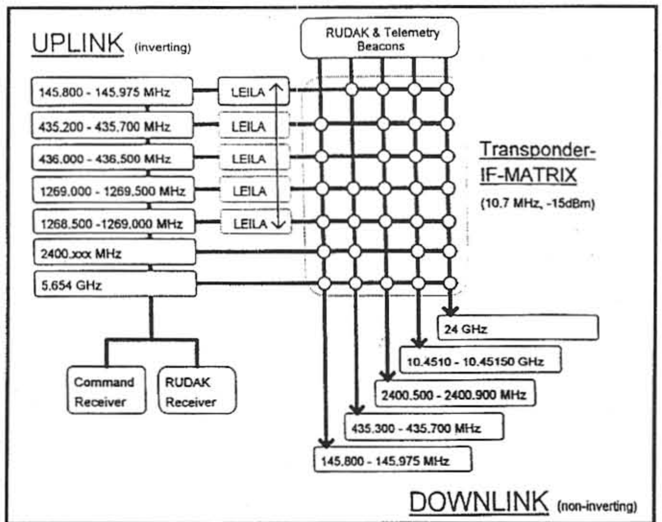

Figure 2

Phase 3D Transmitter/Receiver Matrix

Because of this flexibility to interconnect various receivers with various transmitters; the old "Mode" designations, amateur satellites have used for years, has become obsolete. As a result, a new system of designations will be put into use with the launch of Phase 3D. This calls for separate letters designating the various uplink and downlink bands. Each uplink/downlink configuration will employ one or more letters depending on what uplink(s) and downlink(s) are activated. The uplink(s) will come first and followed by the downlink(s), separated by a "/". The various bands, currently planned for Phase 3D, will be designated as shown in Table 1.

Table 1 Phase 3D Band Designations.

Band	Uplink	Downlink
15m (21 MHz)	H	None
10m (29 MHz)	None	T
2m (146 MHz)	V	V
70cm (435 MHz)	U	U
23cm (1260 MHz)	L	None
13cm (2.4 GHz)	S	S
5cm (5.6 GHz)	C	None
3cm (10 GHz)	None	X
1.25cm (24 GHz)	None	K

Thus, what we currently call "Mode B" will become "Configuration U/V". No doubt, in use this will be shortened to "Config. U/V" . Obviously, combinations such as "Config. UL/VSX are possible. (Satellite tracking software writers please take note.)

Figure 2 illustrates the flexibility afforded by this new approach.

Overall Design Considerations

Four specific design features are being incorporated into Phase 3D to provide this greater ease of use and to increase its flexibility. First, the transmitters will have significantly higher output powers. Second, the antennas on Phase 3D will have higher gain than their cousins on AO-10 and AO-13. Third, the antennas on Phase 3D will always point toward Earth. Both OSCARs 10 and 13 were designed to be spin stabilized in inertial space. Thus, for one part of the orbit, the "high" gain antennas might be oriented toward earth. However, for the rest of the orbit, they are pointed out into space. In order to provide some operation during this time, both satellites include low gain antennas. Not surprisingly, the "high" gain antennas are used near apogee and the low gain antennas near perigee. But there are lots of times when nether set of antennas is optimum. Of course, since the failure of OSCAR 10's flight computer, it has not been possible to orient it, so its low gain antennas are used at all times. Table 2 shows how Phase 3D will stack up with OSCAR 13 when that satellite is using its "high" gain antennas.

Table 2 Comparison of Transmitter PEP and Antenna Gain for Phase 3D and OSCAR-13

Downlink	AO-13			P 3D			P-3D Adv.
	Xmtr pwr	Ant gain	EIRP	Xmtr pwr	Ant gain	EIRP	
	W	dB	W	W	dB	W	dB
2m	50	5.5	180	200	11	2,518	11.4
70cm	50*	9.5	300	250	15.3	8,471	14.5
13cm	1	9.0	8	50	19.5	4,456	27.4
3cm	--	--	--	50	20	5,000	--
1.25cm	--	--	--	1	20	100	--

* This transmitter is no longer functioning.

Keeping Phase 3D always oriented toward Earth is major undertaking in itself. Just meeting this one objective, adds considerable complication to the spacecraft's design. First, the satellite must "know" its orientation with respect to space and then calculate its orientation with respect to Earth - depending on its location in the orbit. To determine its spatial orientation, two approaches are being taken. The primary one employs sun, and Earth sensors. A secondary, experimental system involves the use of signals from the GPS satellites. This makes use of the phase difference between GPS signals arriving at different points on the spacecraft. However, merely determining the orientation of the satellite is only part of the problem. Once this is known, it is necessary to do something to correct for the continual misorientation caused by the satellite traversing its orbit as well as smaller drifts that build up over time. The way most of the big geostationary TV satellites do it is to use gas jets to keep the satellite in the right attitude as well as in the right orbit. When their stored gas is used up, their useful life is over. In fact, depletion of their stored gas is the principal cause of the demise of geostationary satellites. In addition, most big TV satellites spin. This is done primarily to keep one side from becoming too hot and the other too cold. Their antennas are mounted on platforms which are driven by motors which turn at the same speed as the satellite's spin, but in the opposite direction. In this way their antennas are always aimed toward Earth. In order to obtain as long a life as possible for Phase 3D, it was decided early-on that some means, other than stored gas, had to be used to provide continuous orientation of the satellite. The method adopted employs a set of spinning wheels. The momentum, associated with the spin of these wheels, reacts to reorient the satellite. Proper operation of this system is essential if Phase 3D is to meet its main objective of bringing satellite operation to many more hams on the ground.

Attitude Control Subsystem

As stated above, Phase 3D differs from previous OSCARs in that it can maintain any desired pointing angle (attitude). This is accomplished through the use of a complex attitude control subsystem. During normal operation, the pointing angle will be adjusted continuously throughout the orbit to cause the antennas on the top of the spacecraft to point towards the center of the Earth. The other degree of freedom (rotation of the spacecraft about the antenna boresight axes) will be used to maximize the amount of sunlight illuminating the solar panels.

All pointing operations are continuously operated by the main onboard computer, the IHU or Integrated Housekeeping Unit. During the times of motor firing, the computer will direct orientation of the spacecraft such that the motor thrust points into the correct direction. The mathematical calculations to compute the necessary angles are quite involved. Fortunately, because these same kind of computations were also needed for OSCARs 10 and 13, the necessary programming already exists. Thus, it is planned to draw heavily on this existing software,

The attitude Control Subsystem hardware consists of the following five components:.

1. A set of three magnetically suspended, orthaginally mounted reaction wheels.
2. A compliment of Earth and Sun sensors and associated electronics.
3. Two rings of electromagnets, the field of which can be stepped through six directions.
4. Three Nutation Dampers.
5. The Inflight Housekeeping Unit (computer).

All of these components are necessary to achieve successful attitude control. Basically the three reaction wheels store the momentum to provide the spacecraft with some intrinsic attitude stiffness, like any gyro system - or, a spinning spacecraft. But because the momentum now is in the wheels, the spacecraft itself can remain at a fixed attitude.

Because there are three wheels, mounted 90° to each other, it is possible to redistribute momentum between the wheels by simply controlling the individual speed of each. Since the initial momentum of the spacecraft is conserved, and thus fixed in space, the only way a redistribution of momentum can take place is by the spacecraft itself changing its attitude. As previously stated, these wheels employ magnetic bearings, thus eliminating the problems inherent with lubricants in space, or the frictional wear which might occur with conventional bearings over the expected 10 to 15 year life of the spacecraft.

In order to effect the attitude control, the IHU computer requires data on the current actual attitude of the spacecraft with respect to inertial space. The aforementioned Sun and Earth sensors will be used as a primary references to obtain this information. As stated earlier, it is also planned to be able to employ information from the GPS subsystem to determine spacecraft attitude.

It is unavoidable that solar radiation pressure exerts a small, but finite, force on any spacecraft. It would be very unusual, and fortuitous, if this force were to pass through the center of gravity of the spacecraft. Thus, this misalignment of radiation pressure causes some small amount of torque to act on the satellite. This "nuisance" torque must be compensated for in some way or the wheels would have to be driven at an ever increasing speed. This eventually would lead to disaster, unless some means is provided to get rid of this accumulated torque. In Phase 3D, this "momentum dumping" will be achieved against the Earth's magnetic field with the two ring electromagnets.

The operation is similar to the magnetic torquers in AO-10 and AO-13. Of course the IHU computer needs a strategy to regularly dump momentum by this system. The algorithms are not very much different from those of the above mentioned satellites. Additionally, since Phase 3D will be spin stabilized during its early life in orbit, including its first motor burns, it, like AO-10 and AO-13, will have the need for nutation dampers.

The Phase 3D attitude control system will be described more fully in a future paper. But from this description, it should be clear that quite a sophisticated system is necessary to maintain optimum antenna pointing for the Amateur Radio payloads as well as to achieve a high level of power generation by the solar arrays.

Thermal Control Subsystem

Three axis stabilization carries with it another consideration. As stated earlier, the TV-sats spin in order to keep any side from getting too hot and the opposite side too cold. As noted earlier, once in its desired orbit and orientation, Phase 3D will not spin, but will be oriented in three-dimensional space, with the antennas continually facing Earth. This continual attitude adjustment, with one side facing the sun, causes some interesting thermal design problems. The Phase 3D solution to overcome most of these problems is through the use of the four heat pipes. A heat pipe is a thermal linkage of very high conductivity consisting of a closed, evacuated tubular chamber with walls lined with a wick and partially filled with a pure fluid. The fluid used in Phase 3D is anhydrous ammonia. The fluid is vaporized at the hot end. The vapors then move through the hollow core of the tube, and condense at the cold end; from which the resulting liquid is returned through the wick to the hot end by capillary action. By this process, heat is transported from the hot to the cold end. Heat pipes typically offer heat transport characteristics that are many times greater than the heat transfer capacity of the best heat conducting materials, while maintaining an essentially uniform temperature. The process requires no power and operates satisfactorily in a zero-gravity environment.

In the case of the Phase 3D spacecraft, the internal ring-shaped heat pipes can be likened to a meat-cooking rotisserie, removing heat from one part of the spacecraft and re-distributing the energy to other parts where it is ultimately transported through the sides of the spacecraft and thence radiated to space - the ultimate "heat sink". What is felt to be a unique feature of this heat pipe system, as employed on Phase 3D, is that none of the pipes come in direct contact with space-facing panels. Instead they depend upon indirect re-radiation of the heat from internal equipment mounting panels to side panels that are deliberately allowed to become cold. All along, however, the electronic equipment modules maintain their desired temperatures because of the thermal influence of the heat pipe system, regardless of whether those modules are mounted on the solar heated side, or on the space-cold backside of the spacecraft.

The earlier Phase 3A, B and C satellites employed several multi-layer thermal insulation blankets to assist these spacecraft through the thermal rigors of spaceflight. Quite simply such blankets are a first-class nuisance to fabricate, as the required assembly technology is very exacting. In the case of Phase 3D, the side panels of the spacecraft will be painted black to provide heat rejection. The top and bottom panels will be mostly solar energy absorbing metallic finishes of several different types, depending upon the location and desired temperatures of that section of the spacecraft. In general, the thermal design calls for the mean spacecraft temperatures to be between -5 and +20° C for the expected range of sun angles (β) from -80° to +80°.

Extensive computer thermal analyses of the Phase 3D spacecraft have given us a very comfortable confidence that this design will provide the desired results, without the use of the kind of thermal blankets used on most other satellites including AO-10 and 13. These thermal analytic computations were accomplished on a home computer of the 80486-DX2/66 class; a process that required crunching through numbers for 10 to 13 hours at a time to produce a series of temperature performance curves.

More Power Needed

As stated, one of the design features intended to make Phase 3D more accessible to smaller ground stations will be the use of higher power transmitters. This increased power carries with it another set of problems. First, the power must be generated. This means more solar array area. To achieve this, Phase 3D will employ four deployable solar panels in addition to the two mounted on the spaceframe. This will be the first use of deployable panels on an amateur satellite. Of course, deployable panels means mechanisms to initiate the unfolding plus appropriate hinges and latches to achieve the desired final configuration. The answer to the right type of hinge was found at the entrance to German bistros, the same kind of device seen in old-style North American western saloons - the cabaret hinge. This type of hinge is able to swing both ways but always return to the desired center position. One of the German members of the Phase 3D Design Team first suggested the use of this type of hinge, and actually obtained one at a German hardware store to demonstrate the utility of the principle on the models of the former Phase 3D "Falcon" spacecraft design. As there is not the luxury of a lot of excess space around the current Phase 3D spacecraft when installed in the Ariane 5 launch vehicle, this hinge design had to go through several gestations in order to achieve the desired device in a compact manner. This effort included finding a spring wire able to withstand the metallurgical and thermal rigors of anticipated operation at temperatures as low as -100° C.

Power System

Since satellites must get their primary power from a source other than the local power company, some means of carrying energy on board, or using the sun, is required. Currently, the only practical means of obtaining power, open to amateurs and most other satellite designers, is the use of solar panels. As stated above, generating the power needed to support the transmitters aboard Phase 3D requires large solar panels. The design which evolved calls for a total solar panel area of 4.46 m^2 (48 ft^2) and solar cells of 14.3% efficiency. This array, will produce about 620 Watts of power at the beginning-of-life (BOL) and with β=0°. After 10 years in orbit, this power number will still be about 350 Watts at a β=45°. This amount of power is still sufficient to operate at least two transmitters and the other necessary spacecraft systems. Like almost anything else, solar arrays deteriorate with age. This is why their performance after a specified number of years is an important design consideration. The cells for Phase 3D are being obtained through a very attractive agreement with DASA, the German Space Agency. While other source and configurations of solar cells were considered, it was concluded that this one represents the best trade-off between performance and cost. Solar cells represent one of the single highest cost items which go into building a spacecraft.

While solar panels are satisfactory as a sole source of power, some form of energy storage must also be provided. This is accomplished with a battery. Energy storage is necessary, not only to power the spacecraft during times that the sun is eclipsed by the earth, but also to operate the plasma thruster, described later. It's power requirements exceed the capability of the solar arrays, even under the best of conditions. Actually the Phase 3D satellite will carry two batteries, a "main" and an "auxiliary". This is provide redundancy in case of failure of the main battery. The Phase 3D design team evaluated several sources and types of batteries. A final decision was made to select a more or less conventional nickel-cadmium battery, albeit with a new plate design, as proposed by a German firm. Another contender was from a U.S. firm which proposed the use of an assembly of Nickel-Metal Hydride cells for the main battery and a more conventional Nickel-Hydrogen stack for the auxiliary. As in the case of the solar cells, cost was an important factor in reaching this decision.

Transmitters

In addition to challenging the spacecraft power system, higher power transmitters also require careful circuit design, particularly at the microwave frequencies. High power, at microwave frequencies, is hard enough to come by in itself, but in a satellite, more difficult yet. In order to produce relatively high power, and live within the tight power budget imposed by satellite's power system, high efficiency RF power amplifiers are a must. However, attaining high efficiency, particularly at microwave frequencies, is a formidable task. Fortunately, the amateur community has already addressed this problem. It is called "HELAPS" and stands for High Efficiency Linear Amplification by Parametric Synthesis. This concept has been proven on the 2 meter and 70 cm transmitters employed in AMSAT satellites since OSCAR 6.

HELAPS will be a mainstay on the high power amplifiers used in the 70 cm (U Band) and 13 cm (S Band) transmitters aboard Phase 3D. Designing such amplifiers is a very exacting process, and an approach not understood by very many microwave designers - amateur or commercial. Design, construction, troubleshooting and final checkout of these amplifiers is one of the major tasks confronting the Phase 3D design team.

LEILA (The Alligator Eater)

One of the problems faced since the first transponder amateur satellites has been that of the "power hog", sometimes also referred to as "alligators". This a ground station which uses much more power than necessary to produce a useful signal through the satellite. In the past, the only recourse, other than turning the satellite OFF completely, was to warn the offending individual or refuse to talk to the person. But Phase 3D will incorporate a circuit designed to counter "power hogs". It's called LEILA which stands for LEIstungsLimit Anzeige (in German) or Power Limit Indicator as a suitable translation. The circuit works at the spacecraft's main IF, and thus is available to all uplink/downlink combinations. A block diagram of LEILA is shown in Fig. 3.

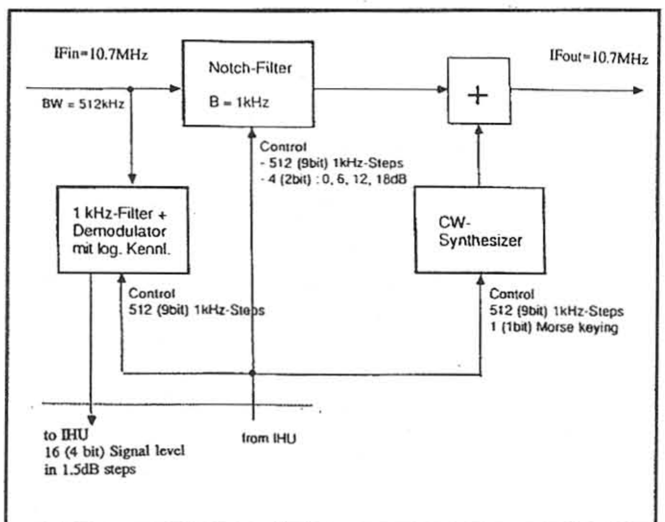

Figure 3
LEILA Block Diagram

Receivers

Phase 3D will have receivers for at least 2 meters (V Band), 70 cm (U Band) and 23 cm (L Band). In addition, receivers for 15 meters (H Band), 2.4 GHz (S Band) and 5 GHz (C Band) have been promised. If these are produced and meet standards, they will be incorporated.

Link Performance

Another of Phase 3D's design features, intended to accommodate smaller ground stations, is the use of spacecraft antennas with higher gains than employed on previous amateur satellites. However, there is a limit to how much gain is desirable. If full earth coverage is to be provided, there is a limit to how much antenna gain can be used. At Phase 3D's apogee of 50,000 kilometers, the earth will have a diameter of approximately 13 degrees. A half power beamwidth of 13 degrees corresponds to a gain of approximately 20 dBi. On a 2.5 meter (8 feet) diameter satellite, such gain cannot be achieved on 70 cm or lower. But, for 2.4 GHz and above, antennas with such gains are small enough to be accommodated. Thus, above 1.26 GHz antenna gain is limited by the desire to provide full earth coverage, while on the lower bands it is driven by available spacecraft real estate.

If one considers a ground station with a particular fixed parabolic antenna size, the effective link attenuation on the various microwave bands is the same on each. The rise in antenna gain with frequency compensates for the greater attenuation, the so called "wavelength factor". In reality, the difficulty of producing RF power on the higher microwave frequencies, for example 10.5 GHz and above, as well as the greater antenna pointing precision required, (receiver sensitivity being no longer a significant factor at least up to 10 GHz), results in a preference for the lower microwave bands. On the VHF and UHF frequencies the links tend to be less favorable, as the lower satellite antenna gain has its effect on link performance. In addition, the effective noise temperature is higher at the lower frequencies. Of course, some of these disadvantages can be overcome by higher transmitter power which is easier to come by as one goes to lower frequencies. Nevertheless, it is expected that the microwave links on Phase 3D will significantly outperform those on the lower bands and will become more and more popular as time passes.

IF Matrix

The IF matrix provides the facility to be able to connect any receiver with any transmitter and includes the LEILA. The IF frequency is 10.7 MHz and the matrix has an input and output level of -15dBm.

Antennas

The subject of antenna design has been a major thrust in the Phase 3D effort. Since Phase 3D will incorporate receivers and transmitters on many bands, a number of antennas will be required. Optimizing the gain in accordance with the considerations of the preceding section, and/or reducing the size of each of these antennas, was another of the major challenges that faced the Phase 3D design team. Because of launch vehicle constraints, effort was concentrated on the use of low profile circularly polarized antennas. Table 3 lists the types of antennas which have been designed to meet the needs of Phase 3D for the various bands.

As the launch date approaches the team effort is to transform antenna theories and prototypes into flight hardware. The computer design work is complete as well as the construction of prototype antennas. The feed systems are designed and the required relays selected. Most of the coaxial cable and connectors are at the integration facility for installation on the spaceframe.

The 10 meter antenna design is complete with only the fabrication of the flight hardware to be accomplished.

On V Band, a 1/4λ flexible open sleeve antenna will be used for the omni. The final design of this antenna is dependent on the specific location of the arcjet motor. The V Band high gain antenna design is finalized with prototype testing almost complete. The transmission line to both V Band antennas employs a 4-port relay to interchange the transmitter and receiver between the omni and high gain antennas.

The first U Band patch antenna is now bonded on an inner top panel of the spacecraft. Tests show it to be slightly low in frequency. Effort is continuing to trim this element to bring it on frequency. The impedance is 49.4 ohms on the resonant frequency. The U Band omni antenna consists of a pair of 1/4λ whips mounted on opposite sides of the V Band whip.

A prototype L Band Short Back Fire (SBF) antenna is presently under test. It consists of a 21 cm diameter cavity with a 1/4λ high wall forming the cavity. The feed is a turnstile feed with a split-feed balun and mounted 1/4λ above the floor of the cavity. A 0.61λ reflector is mounted 1/4λ above the turnstile. The antenna is similar to a parabolic dish but is easier to build and has more gain at the smaller diameter. The L Band Omni is a pair 1/4λ vertical stubs mounted next to the V Band and U Band whips. The flight models of the S Band and C Band Parabolic Dish Antennas are in hand. These are commercial spun aluminum dishes with feed horns designed for Amateur frequencies. The highest bands, 10.45 GHz (X Band and 24 GHz (K Band), will employ conical horn antennas with gains in the 20 dBic range. These will be provided by the constructors of the respective transmitters and mounted directly on the units, protruding through the top of the spacecraft.

Table 3
Phase 3D Gain Antenna Configurations

Operation Band	Antenna Type	Gain
10 M	2 El. Deployed Whip	4.5 dBi
2 MHz (V Band)	3 Low Profile Dipoles	10+dBic
435 MHz (U Band)	6 El. Patch	13+dBic
1269 MHz(L Band)	Short Back Fire	15+dBic
2.4 GHz (S Band)	Parabolic Dish	18-20dBic
5.6 GHz (C Band)	Parabolic dish	18-20dBic
10.45 GHz (X Band)	Dual Horn	20dBic
24 GHz (K Band)	Horn	20dBic

Spacecraft Computers

The Phase 3D satellite incorporates a primary and several secondary computers. The main computer, the "IHU" mentioned earlier, is the main spacecraft computer and is tasked with running all aspects of the satellite from power management to attitude maintenance. It is the IHU which will command the turning ON and OFF of transmitters, the switching of antennas etc. It is similar in design to the IHU used on OSCAR-13. As AO-13 does, it employs a radiation hardened 1802 COSMAC processor. While this is a rather "old" CPU unit, and performance improvements might have been achieved by the use of newer technology, it was decided that it would adequately serve the needs of Phase 3D. It has the advantage of being a "known quantity" with much of the needed software already in hand. The old adage, "If it ain't broke, why fix it" was applied. The Phase 3D IHU incorporates an eight-bit analog-to-digital converter for analog measurements (voltage, power, temperature, current, and the like). It has fifty-six independent input and output bits for measurement and control. Some of these bits are used internally, but most are brought out to connectors to route to the rest of the spacecraft. The AO-13 scheme to allow multiplexing many of these bits was expanded for the additional I/O requirements of Phase 3D.

The primary differences between the older IHU and the Phase 3D design may be summarized as follows:

1. Phase 3D has 64k bytes of error-detection-and-correction (EDAC) memory, compared to 32k bytes for AO-13.

2. The physical size of the IHU modules is different. The one used in AO-13 measures 200mm x 300mm, whereas the Phase 3D module is smaller - 200mm x 270mm.

3. The AO-13 IHU occupied two double-sided PC boards with a wiring harness joining them and attaching the connectors to the rest of the spacecraft, while the Phase 3D IHU is on a single, multi-layer PC board with all connectors soldered directly to the board. There is no internal wiring harness in the Phase 3D IHU.

4. The AO-13 IHU required a separate command decoder, housed in a separate module. The Phase 3D IHU incorporates the command decoder on its PC board.

5. The Phase 3D IHU also incorporates an experimental networking adapter called the Controller Area Network (CAN) Bus. This is based on an automotive standard widely used in Europe and Japan as well as the U.S. The CAN bus will be used to tie the IHU into the other spacecraft computer-based experiments such as GPS, RUDAK-E, RUDAK-U and SCOPE.

In addition to the IHU, there are two digital communications experiments slated for flight on Phase 3D. They have been dubbed "RUDAK-E" and "RUDAK-U". RUDAK is an acronym from the German "Renerativer Umsetzer fur Digitale Amateurfunk Kommunikation." In case your German is a bit rusty, this translates to "Regenerative Transponder for Digital Amateur Radio Communication." The name is from the RUDAK experiment built by Amateurs in Germany and flown on AO-13.

A second, improved RUDAK was flown on AO-21. On that spacecraft, it has been used for some time in an "FM Repeater" mode; receiving FM voice transmission on 70 cm, digitizing and processing them, and finally retransmitting them as FM voice modulation on 2 meters. This mode has become quite popular and done much to bring satellite operation to amateurs not heretofore familiar with it.

The initially proposed Phase 3D RUDAK is now called RUDAK-Experimental, or RUDAK-E. As the name implies, the unit's intent is to supply a platform for experimental digital communications. RUDAK-E is being designed to support future digital modes, including digital voice, digital imaging, multimedia communications, etc. Like the AO-21 RUDAK, it will be based on the Harris RTX-2000 series RISC processor, augmented by digital signal processor (DSP) based modems. Both narrowband and wideband experiments are envisioned.

RUDAK-U

In February, 1994, it was decided to add a second RUDAK, called RUDAK-User. It is aimed at providing packet-based communications, similar to those performed by the existing MICROSATs and UoSats, immediately after launch and checkout of Phase 3D. The system is also being designed, however, to allow changes in the way Amateurs use digital communications satellites as time passes.

Actually, RUDAK-U consists of two computers. The first is based on the NEC V53 processor. It has numerous serial communications ports using direct memory access (DMA) techniques. It incorporates 16 megabytes of memory for program and data storage. A portion of this memory uses EDAC for integrity. The second, based on the Intel i386EX processor, has its own memory array; likewise using EDAC. It also uses DMA-based serial I/O ports for communications.

Each computer has its own set of modems. At a minimum, hardware-based FSK modems operating at 9600 bps will be employed, with commandable switching to higher data rates. At least two channels of DSP-based modems will also be incorporated to allow support of other modulation techniques and communications rates. In this way, RUDAK-U hopes to avoid obsolescence over the expected 10 to 15 year life of Phase 3D.

In addition to the tasks outlined above, both RUDAK-U and RUDAK-E will be used in conjunction with the GPS and SCOPE experiments.

Orbit

Another important aspect of the Phase 3D project is the selection of the final orbit for the satellite. Like all of the other design considerations, it too has been engineered to bring the most benefit to as many amateurs throughout the world as possible. Like OSCARs 10 and 13, it will go into a highly elliptical orbit of the Molniya variety. But there, the similarity ends. The apogee (high point of the orbit) for Phase 3D will be much higher than the previous satellites - about 48,000 km versus 36,000 km. The perigee (low point) will also be higher, about 4,000 km. This yields an orbital period of 16 hours. The significance of this will soon become apparent.

Because the Earth rotates once every 24 hours (twice in 48 hours), a 16 hour orbit results in three complete orbits in the same 48 hours, or two days. This two day repetition will make it much easier for us mortals to remember when Phase 3 D will return to the same position. Furthermore, because of the 16 hour orbital period, Phase 3D goes through an apogee every 16 hours. In this time, the Earth rotates 240° or 16 time zones. The orbit will be such as to place one apogee over North America, one over northern Europe and one over Japan. Because of this synchronism between the satellite's orbit and the Earth's rotation, it will go through apogee at approximately the same local time in each area every two days. To illustrate how this will work, take the example of an amateur in the Midwest section of the country. Phase 3D will be visible for many hours, at a high elevation angle, centered on say 8:00PM. It will then drop rapidly and reappear 16 hours later over Japan. But it will be high enough so that it will be within sight of this Midwest location. Thus it will appear to rise rapidly in the northwest and hang for a number of hours and then drop very suddenly. Sixteen hours later it will do the same thing, this time in the northeast during its European apogee. But the local times for each apogee will always be centered on 8:00 PM - a peak time for amateur activity.

Put the elements form Table 3 into your tracking program and see how Phase 3 will behave at your location.

Table 3
Phase 3D Orbital Elements

1996	
Epoch	91 80.0000000
Epoch Rev.	1
Mean Anomaly	0.0000000000°
Mean Motion	1.5000000000
Inclination	63.4343490°
Eccentricity	0.6774378 0
Argument of Perigee	220.000000°
Rt. Ascension of Ascending Node	225.0000000°

Of course, some of these elements may vary somewhat from the final orbit Phase 3D attains, but they will serve to illustrate what tremendous potential the new bird holds.

GPS Subsystem

Phase 3D will be one of the first satellites, amateur or otherwise to utilize the GPS satellites. It will be the first to do so in a high elliptical orbit. As used on Phase 3D, GPS will have the following uses. First, it will enable the satellite to determine its own orbit, put this information into the form of Keplerian elements and transmit them to us here on the ground via the telemetry system. In addition, as noted earlier, it will serve as a back-up to the sun and earth sensors to provide orientation information.

The GPS Subsystem, consists of an array of eight L-Band antennas (four on the "top" and four on the "bottom") and a 24-channel GPS receiver using digital signal processing techniques. Any of the eight antennas can be electrically connected to any of the 24 receiver channels, and unused resources can be powered down.

The L-band signals from the eight antennas are amplified and routed to the RF portion of the GPS module. The RF section consists of eight single chip (Plessey GP-1010) downconverters. These chips are optimized for GPS use and are a complete triple-conversion microwave front end, complete with phase-locked local oscillators.

Each of the eight RF sections provides a digital output stream (2-bit sampled) for processing in an array of four VLSI Correlator ICs (Plessey GP-1020). The purpose of the correlators is to extract the weak, spread-spectrum GPS signals and include the final local oscillator and spreading code generators; the correlator chips average the weak signals to improve detection. They then present the output data in a format suitable for processing by a computer. The computer is based on the AMD 29200 RISC controller. This is a 32-bit RISC machine with high throughput for the demanding real-time filtering and position solution calculations required. Like all the other computers aboard Phase 3D, the 29200's memory has EDAC protection. The 29200 CPU completes the digital signal processing of the GPS signals and closes the final phase- and code-locked tracking loops in the GP1020 correlators.

All the oscillators -- the phase-locked LOs in the GP1010 chips and the phase- and code-locked loops in the GP1020 chips -- are derived from a high-stability crystal oscillator operating at 10.000 MHz. The 10 MHz signal is also counted down to provide long-term high-stability clock functions.

Data from the GPS experiment will be accurate enough to determine the Phase 3D orbit to within 10-20 meters accuracy. This knowledge will be especially important in calibrating the performance of the arc-jet motor. When operating to determine the spacecraft attitude, the GPS experiment will provide supplementary sensor data accurate to within 0.1 to 0.2°. At the same time, the GPS experiment will know UTC time to an accuracy of better than 1 µsec.

The GPS unit will communicate with the rest of the spacecraft via the CAN bus, and has a dedicated serial link to RUDAK-U for backup purposes. It will rely on these data links for controlling its operation, for loading new software, and for sending data to the ground. It is planned that the GPS experiment will send <UI> packet radio frames to the user community giving the GPS-derived Keplerian elements, spacecraft attitude data as well as experiment housekeeping telemetry.

Propulsion Systems

To move the spacecraft from the low-inclined initial orbit provided by the Ariane 5 launcher to its final orbit, and keep it there, Phase 3D incorporates two propulsion systems. The primary system is a high thrust bi-propellant liquid rocket motor with its associated tankage, plumbing and control circuitry. The other is a much lower thrust Arc-jet system mentioned earlier.

The bi-propellant 400 Newton propulsion system is a repackaged version of the one used successfully in the OSCAR 10 and 13 projects. It incorporates a 400 Newton (95 pound) thruster, being provided by a German aerospace company, that utilizes one of the hydrozine compounds for fuel and nitrogen tetroxide for the oxidizer. Because of the higher mass of the Phase 3D spacecraft, multiple tanks are required to carry the quality of propellent required for this mission - over 60 kilograms of Hydrozine fuel and 130 kilograms of Nitrogen Tetroxide oxidizer. The plumbing used to transfer the propellants from the tanks to the thruster has been designed for simplicity but with sufficient redundancy to assure safety and reliability. Helium gas from a high pressure storage tank is regulated to a lower pressure by the pulsing of an electrically operated valve referenced to a pressure transducer, used to pressurize the propellant tanks through redundant check valves and feed the propellants to the thruster. A second electrically operated valve in series with the first is ready to take over should the first fail.

The electronics module that controls the motor ignition and burn sequence is the Liquid Ignition Unit (LIU). This module contains the circuitry required to validate coded firing commands, initiate the firing sequence by opening and pulsing the Helium isolation valves, control pressure in the propellant tanks, open the motor valves, clock the commanded motor burn time and safe the system at the end of burn. This system has proven that it is fully capable of supporting the multiple burns necessary to place the Phase 3D spacecraft in its final orbit.

To provide for stationkeeping and minor adjustments once the spacecraft is in final orbit, a small Arc-jet thruster is also being incorporated in Phase 3D. Compared to the 400 Newton thrust of the primary propulsion system, this motor puts out a puny 100 milli-Newtons, but it does this at very high efficiency over very long burn times. This is accomplished by striking an electrical arc at the tip of the Arcjet motor, then feeding a small quantity of gaseous ammonia fuel through the arc heating it to very high temperatures, and thus causing it to rapidly expand, and thereby providing highly efficient thrust. The Arc-jet thruster will make possible a long-term capability to perform minor orbit adjustments to correct for the kind of orbit instabilities introduced by lunar and solar perturbations that are causing the predicted reentry of the OSCAR 13 spacecraft in late 1996. Extended testing of the system is well underway at the University of Stuttgart with good results. A plumbing system will covey ammonia from propellant tanks, heat it to a gaseous state and meter its flow to the thruster. An electronic module supporting the Arc-jet will provide the high current required to initiate and maintain the arc. It will also provide the electronics necessary to initiate, time and terminate the thruster's burn.

Spaceframe and Launch Adaptor

Naturally, all of this equipment must be housed in something. That something is the spaceframe. Spacecraft payload specialists always insist that the spaceframe should weigh nothing, and the structural engineers always want to construct the strongest "battleship" to withstand the rigors of the launch environment. This is a technological version of an age-old head-butting confrontation. In the case of Phase 3D, those designing and building the structure were continuously urged to do better and better. Along the way a number of quite good lessons on light-weight aircraft structural construction methods were learned. While the end product is not as light as some would have liked (about 60 kg), it has already demonstrated itself to be very strong. The spaceframes for OSCARs 10 and 13 weighed only 7 kg, and that fact was held over the heads of the structure design and construction team like a sword of Damocles!

The Phase 3D spaceframe is principally fabricated of thin-gauge sheet aluminum. Its formation, to rather unusually close tolerances for sheet metal structures, caused more than passing concerns by all who were involved in the effort. Typically these tolerances are in the range of ± 0.2mm (± 0.008in.). The secret to this type of construction is to place all of the load stresses into the sheer plane of the sheet metal, where it is notably strong for its weight. An example of this are the six Divider Panels, one on each corner of the spaceframe. Three of these will be anchored to the launch vehicle which will get Phase 3D into space. Thus, during launch, these three points will be quite heavily loaded in all motions. The only machined parts in the spaceframe are the six Corner Posts at the outer ends of the Divider Panels. These must be robust enough to carry all of these launch thrust loads into the spaceframe, translating all of those forces into the plane of the 0.8mm thick sheet metal Divider Panels as sheer forces. It is difficult to completely convey these concepts in words and pictures, but those seeing the spaceframe in-person will be able to more readily grasp the concepts employed in the design.

SBS

Since Phase 3D will be a secondary payload on the Ariane 5 launch vehicle, it must conform to whatever space the European Space Agency (ESA) can make available. ESA already has a conical adaptor which interfaces between the 2624 mm diameter bolt circle on the Ariane upper stage to a 1194 mm diameter clamp-band used for payloads. However, although hollow, the conical adaptor does not provide sufficient space to house Phase 3D, or any other reasonably sized payload. Accordingly, ESA offered the amateur satellite community the opportunity to launch aboard the new, big vehicle if we would provide a cylindrical "spacer" that could be mounted between the 2624 mm diameter bolt circles on the bottom and the conical section on the top. Phase 3D could then ride to orbit inside this cylinder. But that's not all. ESA also wants to be able to launch another satellite on the same mission, which would sit on top of the conical adaptor. Thus, they require that our cylindrical section must be able to support the launch loads of this other fellow passenger. This means that this 2624 mm diameter Specific Bearing Structure (SBS), which we must produce, must be able to withstand the load forces imposed by a 4.7 metric tons (10,350 lb.) satellite load. In order to assure ourselves that our design is capable of handling such a load, extensive computer analyses have been performed (on the same home computer used to accomplish the thermal analysis). In addition, the SBS must be subjected to Qualification Static Loads (QSL) tests to confirm that it will perform properly, even to anticipated overloads and added safety margins.

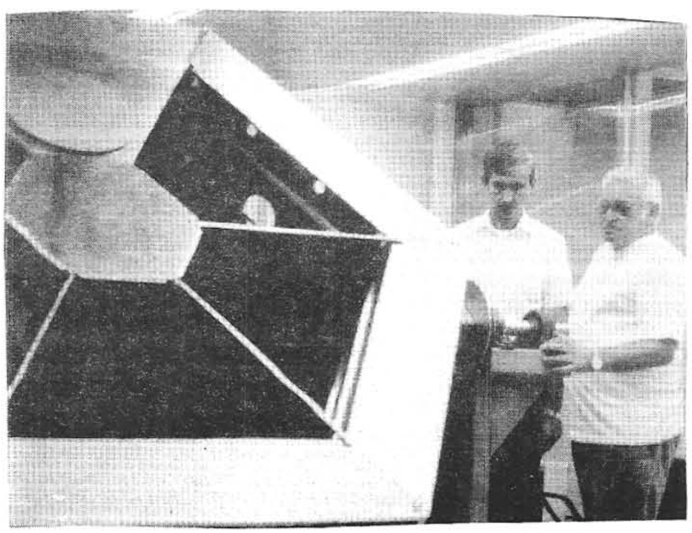

Figure 4

Stan Wood WA4NFY (L) & Konrad Müller DG7FDQ examine Phase 3D on its assembly cart at the Orlando Integration Facility. Note 70cm patch antenna on one of the top panels. (WD4FAB.photo)

The construction effort 2624 mm diameter SBS has commenced with the ordering of machined aluminum rings, called Frames, for the top and bottom of the cylinder that form the bolting flanges. This is a single-piece machining that is about over 8-1/2 feet in diameter with a pattern of 244 bolts and 488 rivets for each 2624 mm diameter Frame. The SBS construction will take place at Weber State University on a specially fabricated steel table that has been machined, measured and adjusted to be flat to ±0.025 mm (±0.001 inch). This is to insure that the SBS will be a "true" structure that will fit to the other components of the load-carrying composite "stack" that support the prime payloads.

On the interior of the SBS, we will provide a supporting structure for the Phase 3D spacecraft. Three of these structures will terminate in three high-strength bolts that are attached to the spaceframe. These bolts each have concentrically mounted springs to provide the "push-off" forces needed to separate Phase 3D from the launch vehicle, with a velocity of 0.5 meters/sec.

These bolts hold the satellite to the SBS with three pyrotechnic nuts. The nuts are opened on electrical command to separate Phase 3D from the launch vehicle.

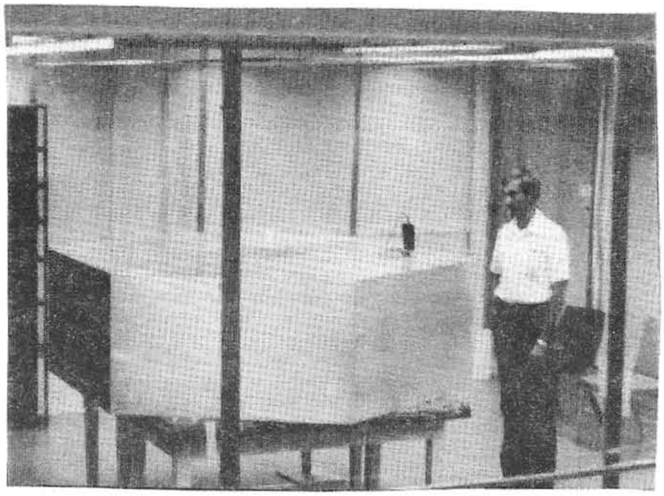

Figure 5

Stan Wood WA4NFY makes acoustic noise measurement on the newly arrived Phase 3D spaceframe in the Orlando, Florida Integration Facility clean room. (WD4FAB photo)

A Team Effort

Design, construction, management and financing of the Phase 3D satellite is an international team effort. Without the cooperative of all of those involved, this ambitious project could not be completed. Whether it is the scientists and engineers who come up with the innovative design approaches, the technicians who fabricate the various spacecraft component parts, those who coordinate the arrival of these parts at the required time, or those who have made financial contribution; all participants on this team are contributing to the successful completion of Phase 3D. When it is put into orbit on ESA's huge new Ariane 5 heavy lift launch vehicle in April 1996, everyone who participated can take justifiable pride in their accomplishment. Because of the dedication of these selfless individuals, Amateur Radio will be presented with a significant new resource for use well into the next century.

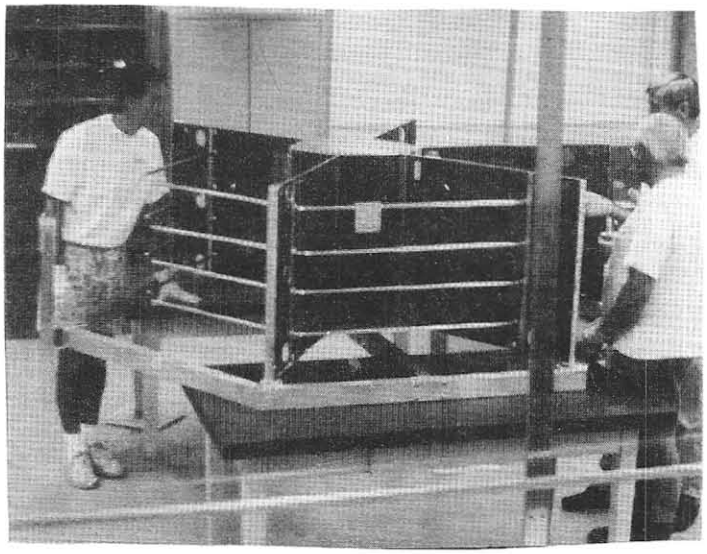

Figure 6
The first step in the assembly of Phase 3D - The heat pipes and five of the Divider Panels have been "intertwined" and attached to the Central Cylinder. The three admiring their work are Frank Lavra (L), Konrad Müller (foreground) and Stan Wood. (WD4FAB photo)

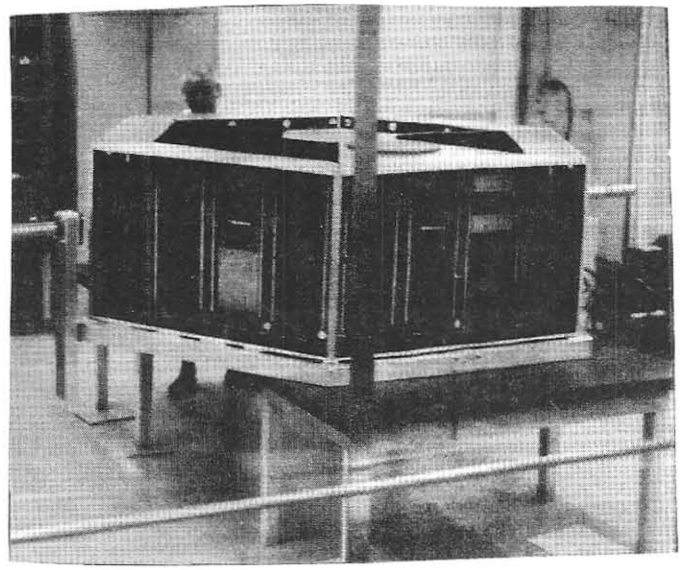

Figure 7
Konrad Müller checks the fit-up of the Spaceframe Panels onto the Heat Pipes. (WA4FAB photo)

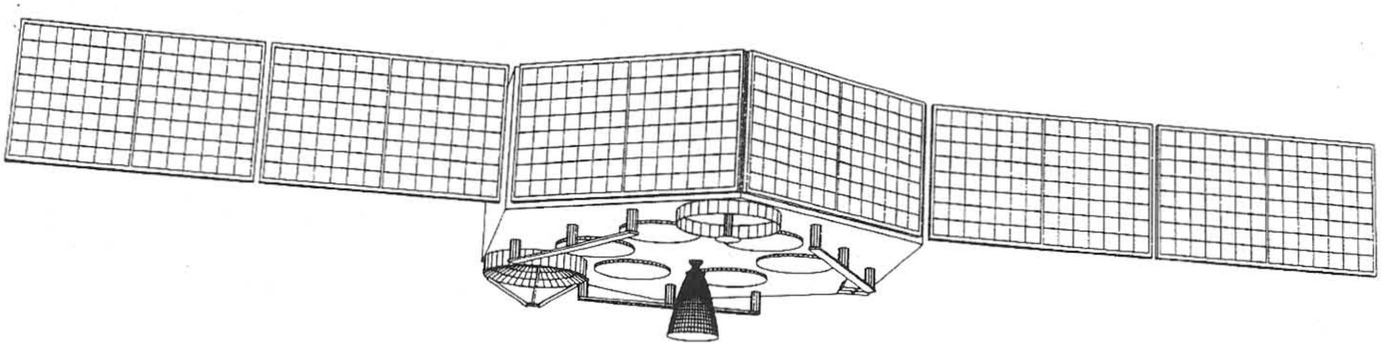

Figure 8
How Phase 3D will look in orbit with it solar panels deployed.
Note the liquid propulsion motor nozzle in the center surrounded by the antennas.

Phase 3D Critical Component Radiation Testing

by

Paul A. Barrow, VE6ATS

Abstract

Design decisions for electronic components used in communications satellites are subject to a number of environmental and performance tradeoffs. Radiation exposure poses problems that are not typically found in terrestrial applications, and for which there is often inadequate information to base engineering decisions. The radiation testing strategy being used by the group designing the Phase 3D Global Positioning System (GPS) receiver, and certain other critical subsystems of the satellite, is described in this paper.

The path of Phase 3D will pass through the Van-Allen Radiation Belt twice on each orbit. Over the 10 to 15 year design life of this satellite the cumulative effects of the radiation can result in significant degradation of the satellite's components. The components at the greatest risk of damage from this radiation are those with the highest degree of integration, i.e. Microprocessors and their memory, as well as VLSI components such as used in the GPS receiver. Components with significant internal capacitance are also vulnerable, such as devices with charge pumps.

Several techniques may be used to ameliorate radiation effects on electronic components. Radiation induced memory errors are typically handled by Error Detection And Correction (EDAC) units, which act in a manner similar to "active" parity bits. Latch-up, an error state that results in junctions acting like an SCR (Silicon Control Rectifier) with attendant damaging currents, are protected against through the use of current sensing switches. Also, shielding can be employed, but with a potential tradeoff of a reduced payload because of the shielding's mass.

The most efficient method of radiation resistant design is the use of radiation resistant components. However, all too often, radiation data is not available on desired components because they were not necessarily intended to be used in space applications, and because testing to determine their resistance to radiation is quite expensive.

Approach Employed

The radiation testing program undertaken by the GPS receiver development group, and to be used for various other Phase 3D subsystems, has four objectives. Where data is not available for susceptible parts appropriate testing will be undertaken. Where data and alternatives exist, the testing will identify, parts which have superior radiation resistance. Where alternative components are not available, the program will identify vulnerabilities to which special approaches, such as shielding, or subsystem by-passing, is dictated. Finally, during the final design stages, the program will identify those components which are most susceptible to radiation. This information can be used to determine if additional shielding is warranted.

An example of one of the programs results so far, is that the frequency multiplier circuit which is internal to one of the microprocessors was identified for special consideration. The internal clock circuit was found to be the circuit first affected by radiation, thus indicating that an external, high frequency clock circuit would be required in order to utilize this processor in a satellite like Phase 3D.

A specific, future objective involves choosing the density of the memory chips. Here, the tradeoff is available physical space, and component count, versus total memory capacity; in the light of radiation susceptibility. In the case of the memory units desired for use in Phase 3D, manufacturers data are not available. This lack mandated that testing be carried out in order to make certain that the satellite would perform properly over its desired life in orbit.

AMSAT Members' Diverse Backgrounds Can Lead to Special Opportunities

In this particular case, the writer's employment for a number of years had involved implementing data acquisition systems for a nuclear medicine department. Although I have not been involved in this activity for over a decade, several key contacts I had retained, resulted in my being able to gain access to therapeutic radiation devices capable of emulating some of the radiation environments encountered in the Van-Allen Belt [1]. Specifically, the Medical Physics Department of the Cross Cancer Institute in Edmonton, Alberta Canada donated access to a Cobalt machine.

Facility Capability

This machine is capable of producing, in its standard configuration, a gamma ray dose rate of about 8 kRad/hour

(140.75 cGy/ min at a distance of 80cm with a field width of 10x10cm.). As it is used for medical purposes, these numbers are applicable to water. (The human body is considered to be water for calculating radiation dosages.) Therefore, a correction factor must be applied for electronic components which are made of silicon, rather than water. The medical physicist in charge of the machine used the factor of 0.8953 (ratio of mass energy attenuation coefficients of silicon to water). This yielded a dose rate of about 7.6 kRads/hr (Si) for the configuration described above. (1 cGy = 1 Rad) [2]

A tradeoff exists here too, as field width, total elapsed testing time, and similarity to dose rates found in satellites in the Van-Allen Belt (a number of some debate) are all parameters. The testing process also took into account the relationship of the orbit to the Van-Allen Belt, the environment that we wanted to simulate. Phase 3D's transition through the Van-Allen Belts involves relatively short peaks of radiation spread over a number of days months and years; rather than a prolonged, continuous exposure. This, intermittent exposure, gives components some chance to self-heal, which it turns out is a factor of considerable importance as some of the tests have determined.

Procedures

The initial testing was performed using a field size of 11x33cm., which increases the dose relative to the 10x10 cm. field by a factor of 1.028. In addition, the distance from the source to the components under test was extended to bring the dose rate down to approximately 3 kRads/hr. (The dose rate drops according to the inverse square law.) The distance used in the first battery of tests was 130.5 cm., therefore, the dose was:

Dose (Si) = 7.6 kRads/hr*1.028 * $(80/130.5)^2$ = 2.9 kRrads/hr. [2]

Three testing alternatives exist; in-flux, in-situ and remote testing. In-flux tests are those in which the electrical parameters are monitored while the device is being subjected to the radiation field. In-situ tests measure the parameters in its application environment before and after the radiation is applied, as is suitable when testing a surface-mount-technology (SMT) device that is acquired on a plug-in PC board. Remote testing carries the in-situ tests one step further by maintaining a bias on the component being tested while it is transferred from the radiation field to its parametric testing environment. [3]

All tests performed to date have been a variation of the in-flux approach. Each two hour session has been an in-flux test, but power was removed at the end of the session. This approach was both convenient and reproducible (possibly even desirable from a power budget perspective) on Phase 3D for the GPS experiment and in fact for virtually all components except the IHU and the power switches. Some of the devices to be tested in the future, such as the internal data acquisition system of the GPS experiment, may be tested initially using the in-situ approach. Final system level testing, which would determine if any special shielding must be added, will be of the in-flux type

Support Equipment

A TAPR MetCon unit and custom software, was utilized to control and acquire device parameters during in-flux tests that were performed on a LM2574 power converter which is being considered as a power switch for various GPS experiment sub-systems. In-flux tests performed on a microprocessor did not measure individual parameters (at least not in tests performed to date), but instead focused on device functionality. Time and equipment availability are the major limiting factors in these decisions.

In addition to the MetCon unit, a HeathKit IP-2718, variable power supply was modified (slightly) to permit a remote control resistance. This remote control resistance was provided by the MetCon by switching four of the digital outputs to shunt precision resistors. Output load for the switch was controlled in a similar manner. The MetCon's A/D add-on board was used to monitor input voltage and current draw and output voltage. Output power was calculated and the power converter's (switch) efficiency became the parameter of interest.

The experimental process began in April of this year with the testing of two devices, an LM2574 Power Switcher by National Semiconductor and a Motorola MC68332 microprocessor mounted on a evaluation board. The power switcher is the device that will be used to control power consumption by the GPS receiver sub-systems, as the receiver will be much more active during perigee than during the rest of the orbit. The MC68332 was one of a number of processors being considered for a variety of uses on Phase 3D, although the selection has since shifted to other devices for reasons unrelated to these tests, the information gathered is useful both in a generic sense and potentially for other applications as well.

The MC68332 test was preceded by writing a computer program to exercise the "debug" ROM on the evaluation board and capture the resulting output from the board's serial port. This data was time stamped and saved to a disk file. In this manner a number of the diagnostic tests that are available on the evaluation board ROM could consistently exercise as many of the processor's functional units as possible. A similar program was written to control the

MetCon unit for parameter data acquisition. The MetCon program was also designed for both keyboard and script-file control.

A two week schedule was prepared for radiation testing. The total dose to be applied was broken into two phases, with initial dose rates at about 3 kRad/hr then increasing to about 6 kRad/hr. The first phase was for 4 exposures, each for 2 hours. The second phase consisted of 5 exposures for the same time. If the devices survived they would receive a total dose of 84 Krad at the end of the test, which, because it was delivered at a higher rate than expected in the Van-Allen Belt would be a conservative estimate of mission radiation susceptibility [4].

Initial Results

The MC68332 failed on the second day of testing, with 213 minutes of irradiation and a Total Dose (TD) of 10.35 kRads. The failure mode was a loss of serial port functionality with an unknown cause. After the failure was reported to the GPS group, it was suggested that the internal clock's frequency multiplier was possibly at fault as described previously in this paper. There are two options for clocking an MC68332. The first is with a low frequency crystal at 32.767 KHz. That frequency is multiplied by a programmable unit in the MC68332 by a power of 2, to a maximum of 2^9, or 512, giving a processor clock of 16.776 MHz. The multiplier circuit may be by-passed and a high frequency clock signal can be directly applied. About five weeks after the failure, three AMSAT members from the Edmonton area assembled with a spectrum analyzer and some surplus signal generators to attempt to apply a 16.776 MHz. signal directly. During the intervening weeks the processor had been powered up several times with some characters of the Debug Monitor's initial message being received before the device "lost sync." with the terminal, an observation which supported the hypothesis concerning the frequency multiplier. When the Edmonton group assembled to perform the test, the processor had completely "self-healed" and the entire suite of test procedures successfully completed. Because much time and effort had gone into acquiring the equipment, the clock replacement experiment proceeded. Two interesting results were observed. The signal generator available for the tests was not capable of producing a square wave at 16.776 MHz and a successful clock was not established. An accurate square wave oscillator was available at the lower frequency and as the frequency was changed by a couple hundred hertz, the serial port lost sync with the terminal. Synchronization was not reestablished when the oscillator was returned to 32.767 KHz unless power was removed and reapplied to the MC68332.

Testing of the LM2574 proceeded without incident until a total dose of about 60 kRad. The only observed reaction to radiation was a slow deterioration of the output voltage from an initial 5.1V to 4.92V (efficiency deterioration). The testing process included the exercise of the on/off switching function and the variation of the supply voltage in several steps from about 7.5V to 18V. The load on the output was also varied in several steps. The supply voltage was never turned off during a test as that situation did not seem likely during use. However, the apparatus was dismantled after every two hour session. The beginning of the test on the final evening, resulted in an output of 0.04V. Further exercising, including removal of the load, resulted in the voltage rising to about 0.4V. Finally, the input was pulsed (and later slowly raised from zero with the same result) and the 4.92 level of output was reestablished. After that exercise, initial application of full voltage (vs gradual or pulsed application) gave an output of about a diode drop (0.7V). No further radiation was applied. The testing process no longer seemed to simulate the expected flight situation of having input voltage constantly applied.

Future Plans

The next radiation testing is expected to commence in mid October of 1994. It will test the Plessey GP1010 and GP1020 IC's which form the major components of the GPS receiver. The AMD29200 processor and some of the memory chips being considered for the GPS control and calculation processor as well as the National LM12458 data acquisition evaluation board, will all be tested at this time.

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Contingency ACS Configurations for the AMSAT Phase 3D Spacecraft

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The baseline Attitude Control System for the AMSAT Phase 3D spacecraft is a zero-momentum design with three reaction wheels, an Earth sensor, and a Sun sensor. The controller keeps the antennas pointed at the Earth while maximizing the sunlight on the solar panels. If a wheel or sensor fails, the baseline system cannot maintain the desired orientation. A contingency configuration in which one wheel is commanded to a bias momentum value for passive stability is proposed in this paper. The resulting dynamics are similar to those of AO-13, but the spacecraft body would not spin.

Introduction

The AMSAT Phase 3D spacecraft will include a zero-momentum three-axis stabilized Attitude Control System (ACS). This ACS design has the advantage of always pointing the antennas at the Earth while maximizing the amount of sunlight on the solar panels. One disadvantage is that a failure of a sensor or actuator will prevent the ACS from maintaining the desired orientation.

Baseline ACS

The baseline ACS for the Phase 3D spacecraft uses three reaction wheels, an Earth sensor, and a Sun sensor [1]. Magnetic torquers are used to apply torques near perigee to keep the reaction wheels from spinning at excessive speeds. The Z-axis is pointed towards the Earth at all times to maximize antenna gain for users, a great improvement over AO-13. The Y-axis is pointed as close to the Sun as possible while maintaining Earth pointing; solar power is maximized at all times, another improvement over AO-13. See Figure 1 for a drawing of this orientation.

In a zero-momentum ACS design, the control loops for each of the three axes is independent. One reaction wheel is aligned with each axis to generate control torques. The Earth sensor is aligned with the Z-axis and generates X rotation and Y rotation error signals. The X wheel is driven by the X output of the Earth sensor and the Y wheel is driven by the Y output. The Z wheel is controlled by the Sun sensor.

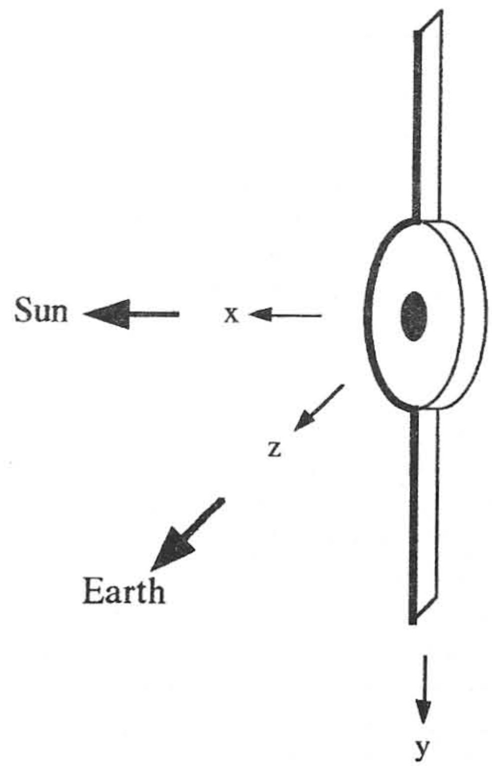

Figure 1. Baseline ACS Orientation

If higher-order effects are neglected, the dynamics for each axis (assuming principal axes and small angles) are

$$M = I \ddot{\theta}$$

where M is the applied torque, I is the mass moment of inertia, and $\ddot{\theta}$ is the second time derivative of the error angle θ [2]. The sensor angle for an axis directly generates the error angle θ from which the rate $\dot{\theta}$ can be estimated. An alternative is to use rate gyroscopes to generate rate signals about each axis. A simple proportional-derivative or PD linear control law can be used to both null the error angle and damp the rate. The expression for wheel torque would be

$$M = - k_R \dot{\theta} - k_P \theta$$

so the dynamics about the axis are given by a second-order differential equation:

$$I \ddot{\theta} + k_R \dot{\theta} + k_P \theta = 0$$

This equation describes the motion of a damped oscillator such as a spring-mass-dashpot system. The two gains k_R and k_P are chosen for the desired dynamics and the control law is implemented in the onboard computer. Gains are selected for each of the three axes.

Reasons for Contingency

A spacecraft with a zero-momentum ACS would usually have a fourth "skew" wheel for redundancy. If any of the three wheels fails, the control laws can be reprogrammed so that the skew wheel replaces the failed one while the other two wheels remove the effects due to the skew of the fourth wheel. A redundant wheel would have been desirable for Phase 3D, but neither the funds nor the launch mass could be spared. If a wheel fails, another ACS configuration must be implemented in order for the spacecraft to continue the mission.

Reaction wheels do fail in orbit. The usual failure location is in the wheel control electronics. For example, two large Canadian communications satellites were damaged by a solar particle event in early 1994 that resulted in both spacecraft losing attitude control. In one spacecraft, the primary momentum wheel control electronics were damaged, but the backup wheel functioned properly and the satellite was quickly returned to service. The second spacecraft had control electronics for both primary and backup wheels damaged.

Attitude sensors can fail as well. Scanning Earth sensors are required for satellites in elliptical orbits where the disc of the Earth subtends varying angles. The problem lies in that the scanning mechanism represents a single point failure for both the error angles reported by that sensor. Sun sensors are quite reliable but only provide one attitude observation. Magnetometers are also reliable but are much less accurate than Earth or Sun sensors.

Bias Momentum Passive ACS

A simple ACS configuration that can be implemented in the event of a wheel or sensor failure involves biasing one wheel for passive stability. Any one of the three wheels could be used. A spacecraft with angular momentum will point in the same direction in inertial space in the absence of external torques. There are small external torques present (solar pressure, gravity gradient, etc.), so the spacecraft orientation would tend to drift slowly. Note that no active control system is used.

The spacecraft would be reoriented by the magnetic torquers under ground command, not unlike how the spin-stabilized AO-13 is controlled. The momentum in the biased wheel provides the passive stability of spin stabilization without actually rotating the spacecraft. Attitude planning would be done much like AO-13 operations at present--compromises must be made between sunlight on the solar panels and antenna pointing (see Figure 2) [3]. Passive stability means that the antennas would point at Earth near apogee only, but the satellite transponders would still be useful.

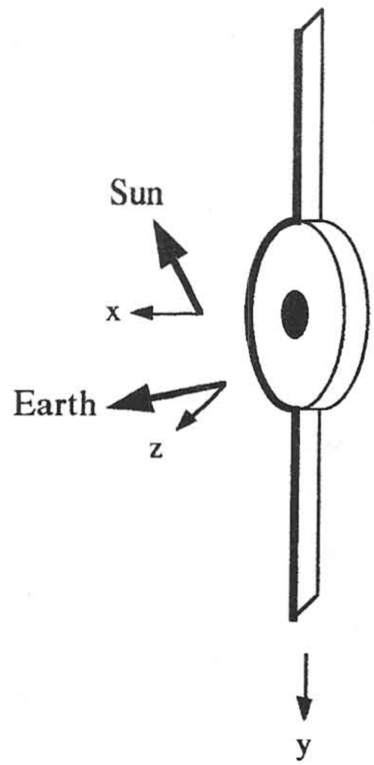

Figure 2. Bias Momentum Passive ACS Orientation

Although an active control system would not be used in this mode, attitude determination must still be performed to verify the orientation of the spacecraft. Two non-parallel observations are necessary. The simplest combination would be the Sun sensor and magnetometer outputs. If an Earth sensor is available, those signals could be used. The SCOPE cameras [4] could be used as star sensors [5] since attitude processing does not have to take place in real time.

Other ACS Configurations

The number of actuators and sensors on the Phase 3D spacecraft would make other ACS configurations possible. If the Earth sensor is functional and either the X or Y wheels is available, bias momentum modes with active control can be implemented. The wheel momentum would be aligned with the orbit normal vector so that the spacecraft could maintain Earth pointing throughout the orbit. These configurations require that the solar panels remain either in the orbit plane or normal to the orbit plane; such restrictions are not of concern unless the solar panels received insufficient sunlight.

Conclusions

With multiple sensors and actuators, the Phase 3D ACS is a versatile system. While the baseline system should function for years, the ACS can be configured for many contingency pointing modes.

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TELECOMMUNICATIONS SATELLITES FROM THE WORLD'S GARAGE -- THE STORY OF THE AMATEUR RADIO SATELLITES

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ABSTRACT

Radio Amateurs have been in the forefront of wireless telecommunications technology from the very beginnings of the art and science of radio. Guglielmo Marconi, the "father of radio" referred to himself as only an "amateur" when he began working in his Bologna, Italy laboratory. Since that time, in the late 19th century, Radio Amateurs (Hams) have continued to explore new and innovative ways to communicate. Many of those ways, once perfected by Hams, have been readily adapted and exploited by both governments and commercial interests.

The world of satellite telecommunications is no exception. Indeed, since the very dawn of the space age, Radio Hams have been in the forefront of this new communications technology, building and launching their first satellite barely four years after they helped the world hear the very first sounds from Russia's first Sputnik. In 1958, a West Coast group of Hams formed the Project OSCAR Association (the acronym *OSCAR* stands for Orbital Satellite Carrying Amateur Radio), an organization that designed, built, and later, with the aid of the United States Air Force, successfully launched the very first Amateur Radio satellite into Earth orbit.

Since that time, Hams around the World, inspired by the early Project OSCAR, and its modern day counterpart, AMSAT (The Radio Amateur Satellite Corporation) have built and launched over 30 of these satellites into orbit. Working quite literally in their garages and basements to build these orbital *flying test beds*, Radio Hams were the first to both pioneer and perfect many of the satellite telecommunications technologies that we take for granted today.

In this paper, we will outline some of the satellite communications technologies that first evolved in the Amateur Satellite Service, and how they have been subsequently adapted for use in other governmental and communications services. We will also explore some of the very latest satellite telecommunications technologies that Hams are now perfecting, and then offer insight into how these new technologies might be (or *are* being) adapted for commercial use. Our goal will be to give the reader a better understanding of where and how some of the satellite communications technologies that are now enabling the explosive growth of worldwide telecommunications first came from, and what could possibly be on the horizon for the future.

INTRODUCTION

Groups of Amateur Radio Operators (Hams) have shared an active interest in building, launching and then communicating with each other through non-commercial satellites for years. Since 1961, several groups of Radio Amateurs have banded together to use predominantly volunteer labor and donated resources to design, construct, and, with the added assistance of international government and commercial agencies, successfully launch, over 30 Amateur Radio satellites. Today, almost 20 of those satellites remain in orbit and operational.

What's more, in the process of building and launching these satellites, these same Radio Amateurs have also pioneered a wide variety of new communications technologies that are now taken for granted in the world's satellite marketplace. By any measure, the Hams' track record has been impressive. These breakthroughs have included some of the very first satellite voice transponders as well as highly advanced digital *store-and-forward* transponder techniques. But what remains most baffling to commercial vendors and government agencies is that *all* of this spacecraft design, development and construction effort has occurred in a fiscal environment of individual member donations, thousands of hours of volunteer effort, and the creative use of leftover materials donated from aerospace industries worldwide.

BACKGROUND AND HISTORY

The story of Amateur Radio satellites begins very near the beginning of the space age. Four months after the successful launch of Russia's Sputnik I, the United States launched Explorer I on January 31st, 1958. At about that same time, a West Coast group of Hams began toying with the idea of launching an Amateur Radio satellite. Far from being simply a "pipe" dream, this group later organized a group called Project OSCAR, with the expressed aim of building and launching amateur satellites. After a series of high level exchanges among Project OSCAR members, the American Radio Relay League (the largest Amateur Radio fraternal organization in North America), and the United States Air Force, a launch opportunity on Discoverer XXXVI from Vandenberg AFB, California was secured for the very first Amateur Radio satellite called OSCAR I. It was successfully launched into a circular, *Low Earth* orbit on the morning of

December 12, 1961 -- only four short years after the launch of Sputnik I.

OSCAR I weighed just 10 pounds. It was built, quite literally, in the basements and garages of the Project OSCAR team. It carried a small beacon transmitter that allowed ground stations to measure radio propagation through the Ionosphere, as well as the internal temperature of the satellite. It also was the very first satellite to be ejected as a secondary payload from a primary launch vehicle and then enter its own separate orbit. Davidoff (1990) noted that OSCAR I's ejection from the main payload structure was accomplished using a very high technology and thermally balanced ejection system for its day -- a $1.15 spring from Sears Roebuck!

OSCAR I was an overwhelming success. More than 570 amateurs in 28 countries forwarded observations to the Project OSCAR data reduction center. Unfortunately, OSCAR I lasted only 22 days in orbit before burning up as it re-entered the atmosphere. But Amateur Radio's *low-tech* entry into the *high-tech* world of space had been firmly secured. Davidoff (1990) noted that when scientific and other groups subsequently asked the Air Force for advice on secondary payloads, the Air Force suggested they study the OSCAR design. What's more, OSCAR I's "bargain basement" procurement approach and management philosophy would become the hallmark of all the OSCAR satellite projects that would follow.

OSCAR II was built by the same team, and although it was similar, both structurally and electrically, to OSCAR I, there were a number of improvements to OSCAR II. One such upgrade modified the internal temperature sensing mechanism for improved accuracy. Another improvement changed the external coating of the satellite to achieve a cooler internal environment. Yet another modification lowered the beacon transmitter output to extend the battery life of the satellite. Thus, a *continuous improvement* strategy that has since become an integral part of the amateur satellite approach was set into place very early in the program.

In the years that OSCARs I and II were designed, built and flown, most satellites were still for scientific or exploratory purposes. It appeared that nobody had yet thought about using a satellite to actually rebroadcast messages sent up to it -- nobody, that is, except the Hams. In reality, ever since 1959, when an article written by a California Ham named Don Stoner (1959) first appeared in the Amateur Radio press proposing the construction of a so-called "repeating satellite", *every* Ham had been dreaming of a repeater in space that anyone with an Amateur Radio license could use. Such a satellite would be able to relay Amateur Radio signals over the horizon without relying on the unpredictability of the Ionosphere. Needless to say, with this thought in mind, and fresh from their success with OSCARs I and II, it didn't take long for the Hams at Project OSCAR to turn the *dream* of a repeating satellite into a workable design for a *real* one. It ultimately became OSCAR III.

OSCAR III would later become the first Amateur Radio satellite (and, it turns out, one of the *very* first satellites ever built) to carry a transponder. A *transponder* is the electronic circuit that receives signals beamed to it from the Earth and then relays them back to the Earth. OSCAR III's transponder was designed to receive a 50 kHz wide band of uplink signals near 146 MHz and retransmit them (with the *whopping* power of 1 watt!) near 144 MHz. However, even at these weak power levels, amateurs with relatively modest Earth stations were able communicate with each other through the satellite over transcontinental distances.

Unfortunately, the thought of a radio repeater in space developed and launched by a group of amateurs working in their basements and garages wasn't always looked upon with favor. While details of the incident are sketchy, Dick Esneault (1993), a member of the original Project OSCAR team, recently reported that the builders of TELSTAR I, the first *commercial* telecommunications satellite, were quite upset to learn that an "uneducated" group of Hams were also working on a telecommunications satellite (OSCAR III) just as TELSTAR was nearing completion. For a while, it also appeared that OSCAR III might even upstage their multi-million dollar TELSTAR effort by actually *beating* them to orbit! In fact, Esneault went on to note that TELSTAR's builders *did* eventually (and reluctantly) change their public relations approach to include the word "commercial" in subsequent references to TELSTAR I as the "world's first telecommunications satellite." This was a *direct* result of OSCAR III's successful launch and operation.

And succeed it did. OSCAR III's transponder operated for 18 days and about 1000 amateurs in 22 countries were heard operating through it. In addition, Davidoff (1990) noted that, unlike TELSTAR, where only one user could access the satellite at a time, OSCAR III was the *very first* telecommunications satellite to clearly demonstrate that *multiple* Earth stations could successfully use a satellite simultaneously. Thus, the work by the Hams on OSCAR III set the stage for the very large, geostationary telecommunications satellites that are now in widespread commercial use. These modern day satellites (and the transponder technology that they carry) enable the nearly instantaneous, intercontinental communications carrying a wide variety of audio, video, and digital signals that we now take for granted. It is also the technology that most people think of when referring to satellite telecommunications. However, as will be discussed, this technology, for a variety of reasons, is *already* becoming saturated.

The fourth Amateur Radio satellite, OSCAR IV, was targeted for a nearly geostationary circular orbit some 22,000 miles above the Earth. OSCAR IV would ride to space aboard a Titan III-C rocket. Unfortunately, despite a valiant effort on the part of the Hams and others involved, (most of whom were members of the TRW Radio Club of Redondo Beach, California), the top stage of the launch vehicle failed, and OSCAR IV never reached its intended orbit. However, despite this apparently fatal blow, OSCAR IV operated long enough for amateurs to successfully develop innovative workaround procedures to salvage as much use out of the satellite as possible.

The story of the follow-on organization to Project OSCAR, an organization called AMSAT, actually begins in Australia. There, a group of students at the University of Melbourne had pieced together an amateur satellite that would evaluate the suitability of the 10 meter Amateur Radio band as a downlink frequency for future satellite transponders. It would also test a passive magnetic attitude stabilization scheme (another Radio Amateur contribution to the space sciences), as well as demonstrate the feasibility of actually controlling a spacecraft in orbit via uplink commands. Unfortunately, the completed OSCAR satellite (called OSCAR 5) languished as launch delay followed launch delay. At about that same time, a group of Radio Amateurs with space-related experience in the Washington, DC, area met to form what initially became known as the East Coast version of the West Coast Project OSCAR Association.

As a result of that meeting, AMSAT, The Radio Amateur Satellite Corporation, was born. AMSAT was later chartered as a 501(c)(3) scientific, educational non-profit corporation in the District of Columbia on March 3, 1969. Its aim was (and is) to embrace and expand on the pioneering work first started by Project OSCAR by advancing the state of the art in Amateur Radio and the space sciences. The new AMSAT organization selected, as its first task, to arrange for the launch of OSCAR 5. After some modifications by AMSAT members (again working mostly in their basements and garages) OSCAR 5 (later to be called Australis-OSCAR 5, or simply AO-5) was successfully launched on a National Aeronautics and Space Administration (NASA) vehicle. Previous OSCARs had all been launched using US Air Force rockets. The OSCAR 5 satellite performed nearly flawlessly.

DISCUSSION

Since its birth in 1969, AMSAT has grown into an international organization that has encouraged the formation of a number of AMSAT organizations in other countries. (The 'original' AMSAT organization is now often referred to as AMSAT North America, or simply AMSAT-NA.) While the affiliations between these groups are not formal, they do often enter into agreements to help each other with space-related projects. Most of the subsequent work done on amateur satellites since OSCAR 5 has been by way of international efforts where teams of volunteers from one or more countries have helped build, launch, and/or control each other's satellites. Usually, one or more national group(s) define the basic spacecraft and its interface requirements. Then, teams are formed from the various international pools to be responsible for the various systems and subsystems of the spacecraft. This gives AMSAT's design engineers substantial flexibility to create and manufacture innovative system and subsystem designs. Usually, any design is acceptable as long as it meets AMSAT's basic operational criteria. This approach also allows each group to take maximum advantage of whatever materials and resources they already have on hand (or whatever they can find in the form of leftover materials or donations of materials from the aerospace industry!)

While worldwide AMSAT organizations are now largely responsible for the design and construction of the modern day Amateur Radio satellites, the term "OSCAR" is still being applied to most satellites carrying Amateur Radio. However, Amateur Radio satellites are not assigned their sequential OSCAR numbers until *after* they successfully achieve orbit and become operational. Even then, an OSCAR number is only assigned after its sponsor formally requests one. If the satellite subsequently fails in orbit, or it re-enters the Earth's atmosphere, its OSCAR number is retired, never to be issued again.

AMSAT's major source of operating revenue is obtained by offering yearly or lifetime memberships in the various international AMSAT organizations. Membership is open to Radio Amateurs and to others interested in the amateur exploration of space. Modest donations are also sought for microcomputer-based satellite tracking software and other satellite related publications. In addition, specific spacecraft development funds are established from time to time to receive both individual and corporate donations to help fund major AMSAT spacecraft projects. For instance, several such funds have now been established around the World to help support design and construction of AMSAT's largest and most expensive satellite to date -- the Phase 3-D project. However, in corporate terms, these funds usually yield operating capital that's *well* below project budgets for comparable commercial telecommunications satellite activities. For example, according to the 1993 AMSAT-NA Financial Statement, AMSAT North America's *entire* 1993 operating budget, including all the development funding generated from member donations toward the Phase 3-D project, amounted to little more than $400,000.

From a personnel standpoint, AMSAT-NA is a *true* volunteer operation, which is also the case for most other AMSAT organizations. The only person in the entire 8000 member North American organization drawing a paycheck is the office manager at its headquarters near Washington, DC. This person conducts the day to day business of membership administration and other key organizational tasks. The rest of the membership, from the President of the corporation, on down to the workers designing and building space hardware, all donate their time and talents to the organization.

When speaking of AMSAT's management approach, one of us (Dick Jansson, 1987), noted that, "While the use of a decentralized, all-volunteer army does have its drawbacks in managing a space program, the dividends are enormous in that it allows a single project to draw on the talents of many highly capable and well motivated people." Many of these volunteers are also aerospace professionals. To them, the aura of building, launching, controlling and then actually *using* the fruits of their labor once the satellite is in orbit is a powerful motivation for them to contribute their very best professional efforts.

Also, because vast sums of money are simply not available for development efforts, AMSAT's management philosophy encourages innovation and simplicity by not over-specifying spacecraft design. During development, subsystem designs are based predominantly on interface specifications with the rest of the spacecraft rather than by reams of detailed technical specifications at the subsystem level. The KISS approach -- short for "Keep it Simple, Stupid" -- is far more than just a buzzword for AMSAT's design engineers. KISS, quite literally, permeates the *entire* management and design philosophy of AMSAT's operations.

As would be expected after nearly three decades of technological improvements, substantial advancements have been made in the features and capabilities of the OSCARs. However, the *home-brew* flavor of these satellites lives on even in the most current AMSAT spacecraft. For example, a substantial number of the subsystems for OSCAR 13, AMSAT's current high altitude OSCAR, were concocted in home workshops. Several pieces of the spacecraft's structure were purchased from an electronic surplus store in the Orlando, Florida area. In addition, *all* of OSCAR 10 &13's fiberglass module mounting rails were cured in the oven of one of our kitchen stoves. Materials for spacecraft thermal blankets were also donated to the cause, and were subsequently hand sewn together by yet another AMSAT volunteer in his home workshop.

Elements of the new AMSAT Phase 3-D spacecraft structure are now being fabricated using similar "bargain basement" techniques. For example, the new Phase 3-D satellite's 20 foot solar array will be both deployed and held in place using a device no more complex than an ordinary bar door hinge. This innovative technique was suggested by Konrad Müller, DG7FDQ. The spacecraft's structure will be made from ordinary sheet aluminum which will be subsequently painted to assure proper thermal balance. In addition some of the spacecraft's antennas will consist of ordinary flexible steel carpenter's rule material and its kick motor is leftover from a earlier commercial launch. Likewise, the batteries are being obtained at a greatly reduced cost from a leading aerospace firm well known in this exacting field. Funds for the purchase of these batteries were provided by AMSAT-UK.

THE MICROSATS

While the story of AMSAT's management approach is interesting in and of itself, the quality and technical sophistication of the satellites AMSAT has produced over the years is nothing short of phenomenal. While Hams have made a number of significant contributions to satellite technology along the way, few AMSAT satellite technologies have had more potential impact on current commercial telecommunications satellite operations than have AMSAT's fleet of MICROSATs. These satellites have ushered in an era of small, cheap, but nonetheless extremely capable satellites in entirely different orbits than the commercial satellites now carrying the bulk of the world's satellite telecommunications.

During the early 1980's Hams in the United States began seriously experimenting with a digital transmission mode called "packet radio". Without getting into the technical details of how the technology works, suffice it to say that these efforts were the forerunner of what are now termed *Wireless Wide Area Networks (WANs)* in today's computer jargon. That is, Hams developed, then later perfected, a digital communications technology whereby microcomputer-to- microcomputer telecommunications could be achieved over the airwaves using specially built modems connected to a Ham radio instead of a telephone line. Soon, Ham Radio "Packet Bulletin Board Systems" (BBSs) were flourishing around the country and Hams were routinely passing digital electronic "mailgrams" back and forth among themselves by way of a sophisticated, *nation-wide* network of store-and-forward Packet Radio mailboxes. Today, the technical sophistication and utility of this radio network, albeit totally non-commercial, rivals the services provided by many wire-based commercial telecommunications companies. From the comfort of their "shacks", Hams can now send and receive highly reliable, near-real-time, digital messages to and from others like them operating similarly equipped stations *anywhere in the world.* What's more, this can all be accomplished *without interacting in any way with a commercial telecommunications provider!* So, with the "boom" ongoing in terrestrial Ham packet radio networks in the middle 1980s, AMSAT's engineers naturally began searching for ways they might incorporate this new packet radio, store-and-forward technology into a design for a new breed of amateur satellites. Unfortunately, the days of easy, low cost access to space for "freeloaders" like AMSAT were fast drawing to a close.

While donated labor and salvaged materials had always helped keep the cost of designing and building amateur satellites to a minimum, AMSAT had also always relied on government or commercial space agencies to launch their satellites. Often, the rides to orbit were free, or offered at *greatly* reduced cost. However, in the mid 1980's, AMSAT managers were faced with a dwindling supply of low cost launch opportunities as more and more commercial, scientific and military satellites were competing for a fixed number of launch vehicles and space agencies. It became increasingly clear that AMSAT simply could no longer compete with the commercial and government enterprises who were, at that time, quite willing to pay many millions of dollars to get to space. Davidoff (1990) rightly observed that, for a while, it looked as if the plug had finally (and permanently) been pulled on all future low cost launch opportunities.

Fortunately, the lack of launch opportunities and the escalating costs of building and launching large satellites drove AMSAT's volunteers to simply innovate in the *opposite* direction. That is, by the later 1980's, while most commercial satellite builders were still touting the "bigger is better" mantra, AMSAT's volunteer engineers were discovering that electronic microprocessor, battery, and solar cell technology had all advanced to the point that very small, lightweight, yet relatively powerful satellites could now be reliably and inexpensively built for extended space service. Armed with technical information on these new technologies, AMSAT engineer Gordon Hardman, KE3D, began examining designs for a series of extremely small satellites to carry one or more of these new store-and-forward, packet radio "mini-mailboxes".

Former AMSAT-NA Presidents Vern Riportella, WA2LQQ, (1980) and Doug Loughmiller, KO5I (now G0SYX), (1990) independently described how a flying digital store-and-forward mailbox, carried by satellites in either high and low Earth (about 600 mile high) orbits, might operate. First, the satellite's orbit is carefully selected so that it will pass within range of *every* spot on the Earth at least once or twice a day. Next, when the satellite comes within view of a particular ground station, that station can, by way of a radio uplink signal, upload data (a message) into the memory of the onboard computer destined for a station at any other point on the globe, *regardless* of whether the stations share a common window of visibility at the moment. Then, as the satellite passes within view of the destination station, that station can simply connect to the satellite (again via a radio signal) and retrieve the message. In this way, global communications can be supported with the use of satellites operating in non-geostationary orbits.

Starting in late 1987, and after two years of exhaustive and sometimes hectic volunteer work, AMSAT engineers finally produced four small cubical satellites, each measuring about 9 inches on a side and weighing about 20 pounds. Dubbed the "MICROSATs", two of the four contained a pair of 1.5 watt transmitters, highly sensitive receivers, an onboard 8-bit computer, 10 Megabytes of RAM storage and an internal LAN housekeeping unit. They were designed specifically to make the satellite capable of receiving, storing and then retransmitting digital electronic messages among Hams equipped with ordinary Amateur Radio packet equipment. The two remaining MICROSATs were customized for scientific purposes. However, these satellites also used the same MICROSAT structure and many of the same internal electronics.

Unfortunately, a firm ride to space for the satellites remained elusive. That is, obtaining a launch opportunity for not one, but now *four* satellites posed a rather daunting challenge. In early 1988, AMSAT-NA's Jan King, W3GEY, and Dick Jansson began an examination with Arianespace on the payload envelope of the Ariane IV launch vehicle soon after work had begun on the MICROSAT project. Independently, the University of Surrey's Dr. Martin Sweeting, G3YJO, began a similar set of discussions with Arianespace. These discussions suggested that there were several places around the base of the Ariane IV's upper stage where very small satellites could be mounted without interfering with primary payloads. In fact, on some launches, Arianespace was using ballast to compensate for the lift capability of the launcher that is excess compared to the mass of the satellites carried. AMSAT's engineers, working with Arianespace evolved this concept with an idea of how they might exploit this unused space on the Ariane launch vehicle.

After a number of engineering concept exchanges, Arianespace designed a single circular honeycomb panel platform (called Ariane Structure for Auxiliary Payloads or ASAP) and accepted the AMSAT MICROSAT separation system as one of only two approved for the ASAP. The structure fits around the base of the Ariane IV's upper stage, and it served as the platform from which *all four* of AMSAT's first MICROSATs, along with two University of Surrey's UOSAT's, were simultaneously placed into orbit by Arianespace in 1990. In return, AMSAT obtained a significant reduction in launch costs. The Ariane ASAP structure has since been used to launch similar small satellites into orbit. Thus, using a classic example of the "you-scratch-my-back-and-I'll-scratch-yours" approach, AMSAT obtained a virtually *gratis* launch opportunity while also advancing the state of the art in the space sciences. By so doing, AMSAT also helped a commercial launch agency find a new way to improve the quality of their launch services and generate the potential for added revenue in the process. In short, everybody won.

Today, over half of the 20 Amateur Radio satellites now in orbit carry some form of digital mailbox. Some of these satellites allow Radio Amateurs to connect to them at speeds up to 9600 Bits Per Second (BPS) using little more than laptop computers and shoe-box-sized radios. Using the current set of packet radio satellites, messages can be (and frequently are) sent by Hams from literally any place on Earth to any *other* place on Earth, often within a matter of minutes.

Ground station equipment to work these satellites is also easily obtainable and relatively inexpensive. For example, for about $3000 (much less if older or *home-brew* gear is employed) *any* Ham can purchase enough commercial Amateur Radio equipment to assemble a ground station capable of interacting with any of the AMSAT satellites now in orbit. This equipment can also usually be obtained *off-the-shelf* via a simple telephone call to any one of the hundreds of Amateur Radio dealers throughout the world.

Included with the first launch of AMSAT's first MICROSATs back in 1990, were two other store-and-forward Amateur Radio digital satellites, constructed by Dr. Martin Sweeting, et.al., of the AMSAT-UK in England, and the University of Surrey. This Surrey group has designed, built and successfully launched, on the Ariane ASAP, a series of small satellites, somewhat larger than the MICROSATs, but still significantly smaller than their commercial and military cousins. In recent years, these satellites have carried the bulk of the high speed digital packet radio traffic being communicated in the Amateur Radio Service. What's more, three satellites (called the UOSATs) also carry Charged Coupled Device (CCD) cameras that can take *snapshots* of the Earth below, store the pictures on the satellite in a digitized format, and then download them to any Ham operator in the world equipped to properly receive them. As Loughmiller (1992) put it, "Apart from the military, there are only two organizations in the world (SPOT and LANDSAT) that can take images with this flexibility -- now, for a fraction of the cost, AMSAT has joined this elite group."

SIGNIFICANCE

The commercial exploitation of this new store-and-forward packet radio satellite technology has been growing -- albeit slowly. One of its very first applications was to use a spare transponder on board one of the Amateur Radio UOSATs for a program called SATELLIFE. This non-profit organization was formed in 1985 to provide an electronic mail network for health professionals in developing countries. This program enabled medical people in remote, third-world areas to send and receive medical consultations and up-do-date treatment methods from other parts of the globe for a tiny fraction of the cost of real-time satellite communications. Because it uses simple ground stations and equipment, this program was an immediate success. In fact, it was so successful that in 1993, SATELLIFE launched another UOSAT (also built at the University of Surrey) dedicated *exclusively* to this program. In addition, a number of search and rescue applications for this technology have also been perfected and are now in use throughout the world. Each is modeled after AMSAT's initial concept for a small, Low Earth orbiting digital satellite. It's also safe to say that the work AMSAT's volunteers have done in developing and perfecting this *low-tech* approach to digital satellite communications is coming to fruition none too soon.

For most of us, satellite telecommunications today are transparent. That is, we hook computers or our modems to a local telephone line and simply dial the number of our overseas counterpart and proceed with our business. Our conversations are usually handled through one of several geostationary telecommunications satellites orbiting in a very precise orbit over the Earth.

The uniqueness of the type of orbit of these satellites means that they can only be parked over the Earth's equator in a ring called the *Clarke Belt* (named for Arthur C. Clarke who first advocated this use). Because of the high power transmitted by their transponders, and the crowding of the radio spectrum used for their transmissions, each satellite must be physically separated from others in the same orbit, often by several hundred miles, to prevent them from hopelessly interfering with each other's signals. So, it follows that geostationary satellite parking places, far from being limited only by the vastness of space are, in fact, a *finite* resource! Unfortunately, the orbital "parking lot" is already getting full over some parts of the Earth. Put another way, a very real possibility now exists that the world could eventually run out of enough orbital slots to park these large, powerful, real-time satellites

Fortunately, a number of forward-thinking commercial telecommunications companies are now beginning to discover what AMSAT has known all along -- that small, Low Earth, store-and-forward digital satellites offer some *very* significant advantages over their big, expensive, high powered and short-lived geostationary cousins. That is, what these small satellites may lack in real-time telecommunications capability, they more than make up for in simplicity, lowered launch costs and simplified ground station equipment, not to mention *greatly* extended on-orbit lifetimes, along with virtually limitless orbital slots. What's more, as these satellites often produce a communications window on the Earth about the size of the continental United States, a *constellation* of multiple small satellites could even offer their users quasi-real-time communications. This could be accomplished if, for example, both the sender and receiver just happen to be in view of the same satellite at the same time.

One of the very first commercial telecommunications companies to jump on this Low Earth, digital store-and-forward bandwagon was the Orbital Sciences Corporation (OSC). The company is planning to launch a constellation of 26 satellites, each weighing just 87 pounds, into multiple Low Earth orbits. An interesting sidelight to this story is that Jan King, the key motivation behind AMSAT's original MICROSAT project, was hired by OSC *specifically* to help with their Orbcomm project.

But electronic messaging isn't the only AMSAT-developed technology that is currently being exploited in the commercial arena. The Motorola Corporation is also now planning a 66 satellite, 3.4 *Billion* Dollar constellation of Low Earth satellites in a similar program. Called Iridium, it's aimed primarily at a growing, and potentially lucrative market of satellite-based mobile telephone subscribers. For the record, digital voice messaging is a transponder technique that AMSAT-DL in Germany first successfully flew on OSCAR 21 back in 1991.

A host of other companies are now scrambling for available spectrum and launch space for what at least one analyst (Foley, 1993) sees as a market of "several million" subscribers by the year 2000. Potential subscribers for these low cost services include individuals and companies in developing countries where ordinary commercial telephone and data services are not advanced enough to handle the growing need for reliable voice and data communications. Along with the satellite builders, launch companies are also now working on innovative and cost-effective ways to carry large numbers of these satellites to orbit. No doubt, the Ariane ASAP design is serving as the starting point for many of these efforts. Werner (1994) reports that at least one company (Lockheed) is now drawing up plans to bundle a generic Iridium spaceframe, launch adapter, and launch vehicle into a single, low priced package for its future telecommunications customers.

CONCLUSIONS

The communications satellite world has come a long way since that first group of Hams started building satellites in their own homes. The innovative technologies AMSAT volunteers have freely developed in their spare time (and then freely shared with anyone who asked) have cut *years* off the development times for some critical telecommunications satellite applications in the past as well as several satellite telecommunications applications now emerging in the marketplace. It can also be stated that the work of these people and their steadfast commitment not to give up when the going got rough (or when the money ran out!) is now starting to pay rich rewards for all of us who currently use, or will use, digital telecommunications technologies in the coming information age.

The story of AMSAT is one of simplicity, selfless donation of time and resources, and a pioneering spirit. The Amateur Radio Operators of Project OSCAR, and their later counterparts in a number of AMSAT organizations around the World, have built and launched over 30 OSCAR satellites since 1961. Their efforts are largely responsible for many of the commercial satellite technologies we take for granted today. Real-time and near-real-time satellite communications technologies ranging from voice transponders to digital store-and-forward techniques to multiple satellite launch adapters that allow simultaneous launch of small satellites were *all* outgrowths of the vision of AMSAT members and the actual fabrication of space-qualified materials by many of them in their basement workshops. What's more, AMSAT was pioneering small satellite technology when large satellites were being touted in the commercial and government sector as, "the only way to go." Now, a number of *billion* dollar commercial ventures are poised to launch constellations of *hundreds* of similar small satellites for digital store-and-forward messaging as well as real-time voice and digital relays. These satellites will exploit many of the technical breakthroughs that were first pioneered by AMSAT, and will allow users to continue expanding their telecommunications networks beyond today's traditional geostationary satellite links to help feed the world's growing appetite for long distance connectivity.

In the past, people have scoffed at AMSAT's "amateurs" who work in their basements and garages to build space satellites. However, the past and present volunteers of AMSAT are "amateurs" only in the sense that the Wright Brothers, Marconi or Robert Goddard were "amateurs". The latter were pioneers who used available materials and creativity to design, build and operate devices whose modern day counterparts we now take for granted. That same pioneering spirit has been a hallmark of AMSAT's technical and managerial approach since its founding in 1969.

For the past 25 years international AMSAT groups have played a key role in significantly advancing the state of the art in the space sciences, space education and space communications technology. Undoubtedly, the work now being done by AMSAT's volunteers throughout the world will continue to have far reaching, positive effects on the very future of Amateur Radio communication.

The nearly 20 operational OSCAR satellites now orbiting the Earth are a living testament to the spirit and vision of AMSAT members. Rarely has a group of volunteers managed to do so much -- for so many -- with so little.

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Launch Opportunities beyond Phase 3D

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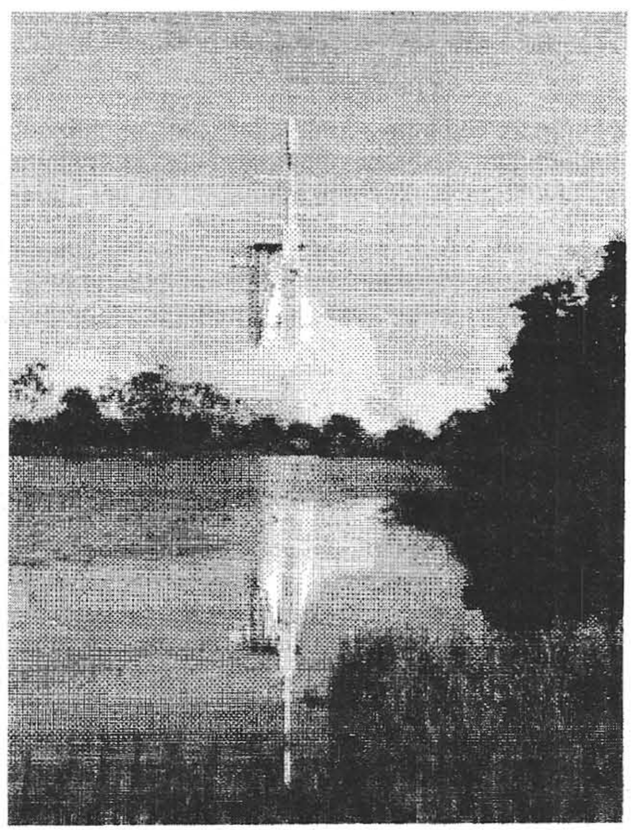
Out of necessity Amsat has always needed to obtain inexpensive rides into space, as secondary payloads for other launches. One of the most common methods is to use a test flight of a new launch vehicle, where commercial customers wouldn't be as likely to purchase capacity. Phase 3C was launched on a test flight of the Ariane 4 launch vehicle and Phase 3D will be launched on an Ariane 5 development flight. Other OSCARs have flown as secondary payloads of opportunity. But what about the future? This paper will discuss several possible opportunities, and several cases where opportunities existed, but were not used.

Amsat has always relied on the kindness of strangers, especially where launch services are concerned. The earliest OSCARs were carried as piggyback payloads, often replacing ballast which would have been required to meet the primary payload's objectives. Those opportunities have all but disappeared with the evolution of commercial launch vehicles. Excess launch vehicle capacity is now used to put satellites into more precise or efficient orbits, eliminating unused capacity. In cases where there is room for additional satellites that space is now sold to commercial customers, anxious to use microsats. The Phase 3 satellites have all obtained rides on new versions of Ariane launch vehicles, primarily due to AMSAT-DL's excellent relationship with the European Space Agency. But Ariane 5 is planned to be the workhorse for European launch vehicles well into the next century, limiting our launch opportunities there. So where can we find future rides into space?

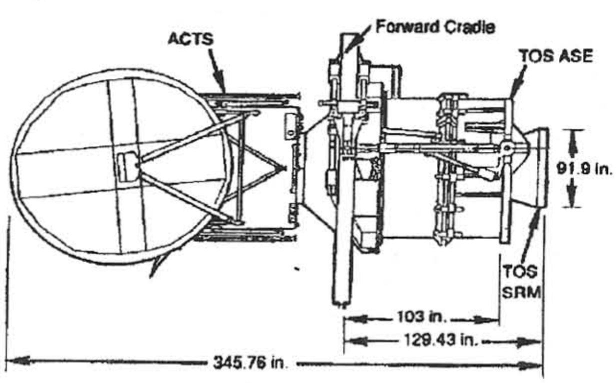
Here's several opportunities which we missed, for one reason or another:



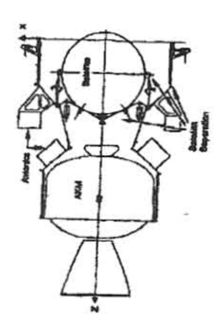
Phase 3C launch on Ariane 401
photo from Arianespace

In two cases satellites were launched from the shuttle where the upper stages had plenty of excess performance which we could have theoretically used. In the mid 1980s startup aerospace company Orbital Sciences Corporation (OSC) proposed to built a mid-size upper stage for the shuttle, the Transfer Orbit Stage (TOS). TOS would fill the gap for orbits which the shuttle couldn't reach between the PAM-D2 and IUS class satellites. At that point OSC projected the sales of dozens of TOSes to commercial customers. It turned out that due to the Challenger accident and elimination of low cost launch services only two TOS were sold - both to NASA. NASA had to find payloads for its TOS and selected Mars Observer and the Advanced Communications Technology Satellite (ACTS). Mars Observer was launched on a Titan III-TOS combination which used all of the TOS's capabilities. ACTS, due to its large antennae, had to be launched from the shuttle. The ACTS satellite was based on a standard communications satellite bus, the same one used for the PAM-D2 class RCA Satcom Ku series. Quite obviously TOS was over-powered as the ACTS perigee stage. The ACTS satellite, with its built-in apogee kick motor weighed 2,733 kgs. TOS's quoted geosynchronous transfer orbit capability, with a full propellant load is 6,090 kgs. - a difference of 3,357 kgs! As it turned out the TOS's solid propellant motor was offloaded to fit the ACTS mission's requirements. Could we have built a satellite to fit in between the TOS and ACTS spacecraft similar to the original 'Falcon' Phase 3D design? There's no technical reason why we couldn't have had a payload on Discovery last September when it deployed the ACTS spacecraft.

Another similar case was the Italian IRIS upper stage. The Italian space agency, ASI, decided that there was a market for satellites in the 1/2 PAM D class. They signed an agreement with NASA and went ahead with the IRIS development. Much later they realized that they needed a payload to fly on IRIS. Since there were no satellites in that weight class ASI made a market survey to look for potential customers. Since there was no launch vehicle at the time for that weight class satellite it isn't surprising that there weren't many payloads searching for an IRIS-class launch vehicle. ASI investigated some possibilities, and eventually decided to built a duplicate of NASA's LAGEOS satellite. The very fact that ASI had to build its own payload for its planned upper stage's first mission should have indicated that they may have over estimated their potential market. As with the ACTS case LAGEOS used less than half of the IRIS's quoted capacity. If we 'piggybacked' the IRIS/LAGEOS mission we could have had a satellite in a high circular orbit with a 52 degree inclination, or used that as a springboard to a more useful orbit for our purposes.



STS-51 ACTS/TOS configuration

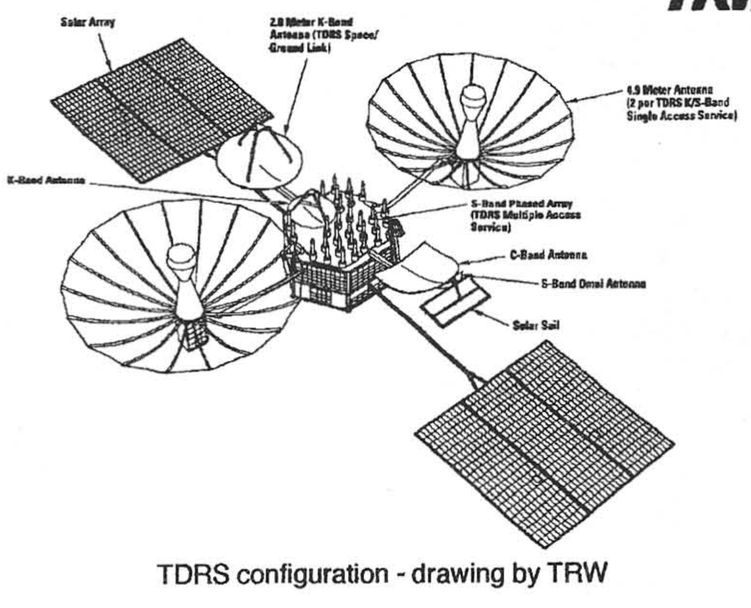

STS-52 LAGEOS/IRIS configuration

It's not likely that new upper stages will come along with so much excess capacity in the future, but we should keep our eyes open for every potential opportunity.

Another possibility is to piggyback on an existing satellite, similar to the Russian RS series. Russian RS 'satellites' are actually just amateur transponders which fly on Russian navigation satellites. The mother satellite provides power to the amateur payload and other housekeeping functions. The advantages are many - we only have to build our communications payload - what hams are most interested in. We don't have to build propellant tanks, propulsion systems, power subsystems, or all of the other components required to make a working spacecraft. On the other hand there are disadvantages to the piggyback route. We have to go where the primary satellite wants to go, we may have limited power available, our antenna farm may be limited depending on the primary spacecraft's requirements, and - perhaps most importantly - we have to go by their rules. Our payload has to be built to the primary customer's specifications, increasing our costs.

Nevertheless - here's two interesting possibilities for upcoming U.S. satellites where their ballast could have been our payload.

When NASA's Tracking Data and Relay Satellite (TDRS) system was designed it was supposed to be everything for everybody. Besides tracking the shuttle and other low orbiting satellites and providing relay functions TDRS was also supposed to include transponders for commercial communications in both C and K bands. Two things made this plan fall apart. Because NASA was offering extremely low costs for shuttle launches many communications satellites were being built on speculation - build and launch now while prices are low in the hopes of an expanding market in the future. In the mid 1980s there was a massive glut of excess capacity on commercial transponders - nobody really needed the extra TDRS capacity. In addition NASA had to include the provision that TDRS's commercial circuits could be preempted by 'national security requirements'. No commercial customer wanted to sign a lease with that requirement. It wasn't until 1991 that NASA was able to sell the commercial transponders on two of the operational TDRS to Columbia Communications. After the Challenger accident NASA received funding for a replacement TDRS and IUS upper stage. Knowing that there was no longer a requirement for commercial transponders the decision was made to leave them off the TDRS-G spacecraft. To keep things simple the existing design was retained with the commercial transponders replaced with ballast.



TDRS configuration - drawing by TRW

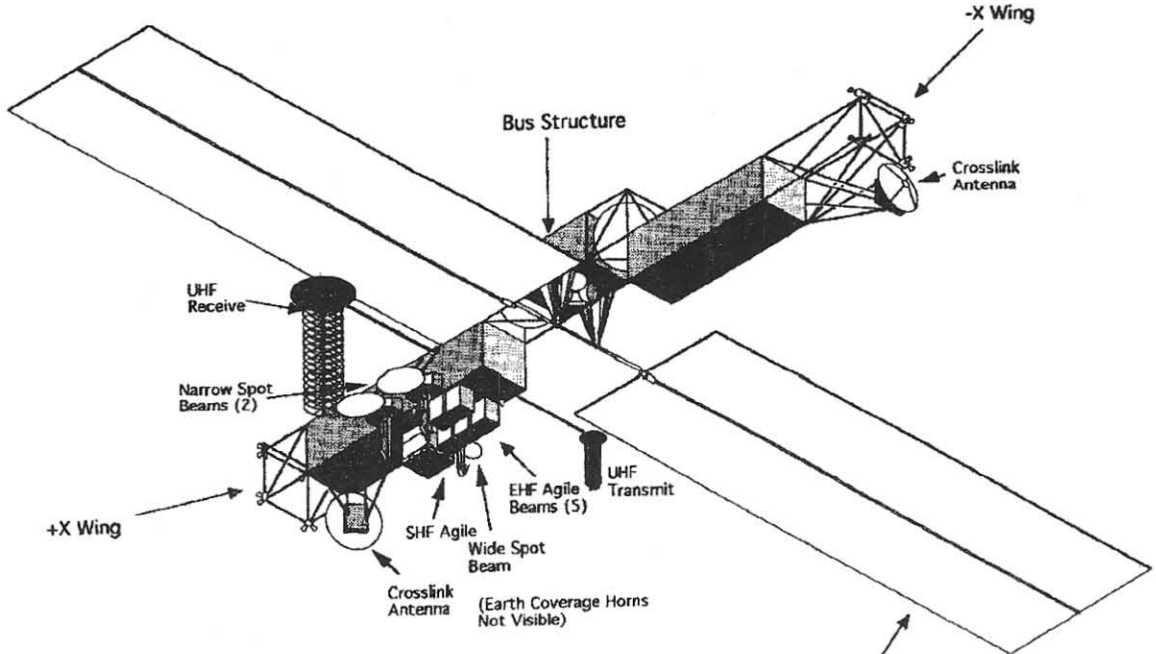
I discussed this situation with NASA Associate Administrator for Communications Charlie Force. He indicated that he would be quite willing to accept an Amsat payload on TDRS-G, as long as it didn't interfere with TDRS's operation. There was a small amount of interest in the project, but all of our resources were dedicated to the Phase 3D program and nothing was done about the TDRS-Amsat concept.

A similar situation exists with the Air Force's Milstar spacecraft. The first satellite includes a classified communications payload. Due to the end of the Cold War, and Milstar's changing role from a strategic to tactical satellite there is no longer a requirement for that payload and it will not be included on future spacecraft. There will only be one additional Milstar 1 design spacecraft. It will include ballast in place of the payload. Future Milstar will include additional medium data rate transponders. Could we have included a set of amateur transponders? It would be a nice idea, but imagine a crisis situation in the future where Milstar is moved to give better coverage over the crisis zone. It's quite conceivable that we could be put into a situation where we would not be permitted to publish or distribute the Keplerain elements for our own payload!

Regrettably the TDRS and Milstar opportunities for a geosynchronous amateur payload have been lost and future TDRS and Milstar will probably have revised designs which will eliminate the ballast requirement.

In any case we certainly should keep looking for future piggyback opportunities. As with the microsat series we can get redundancy and additional coverage through multiple spacecraft.

In 1992 the Superbird B1 spacecraft flew by itself on the Ariane 55 mission with an Ariane 42P launch vehicle because Arianespace couldn't find an additional spacecraft ready to go at the same time. Considering how long Arianespace has been launching spacecraft this is an excellent record. There was excess capacity on the mission and if we had a spacecraft ready-to-go we could have negotiated an extremely inexpensive launch rate. If we had planned ahead of time for an opportunity like this we would have had a year's advanced notice before launch to complete our 'standby' spacecraft. The concept of building a spacecraft to wait in a warehouse for potentially many years before a launch opportunity is available may not appeal to everybody, but the price is certainly right!

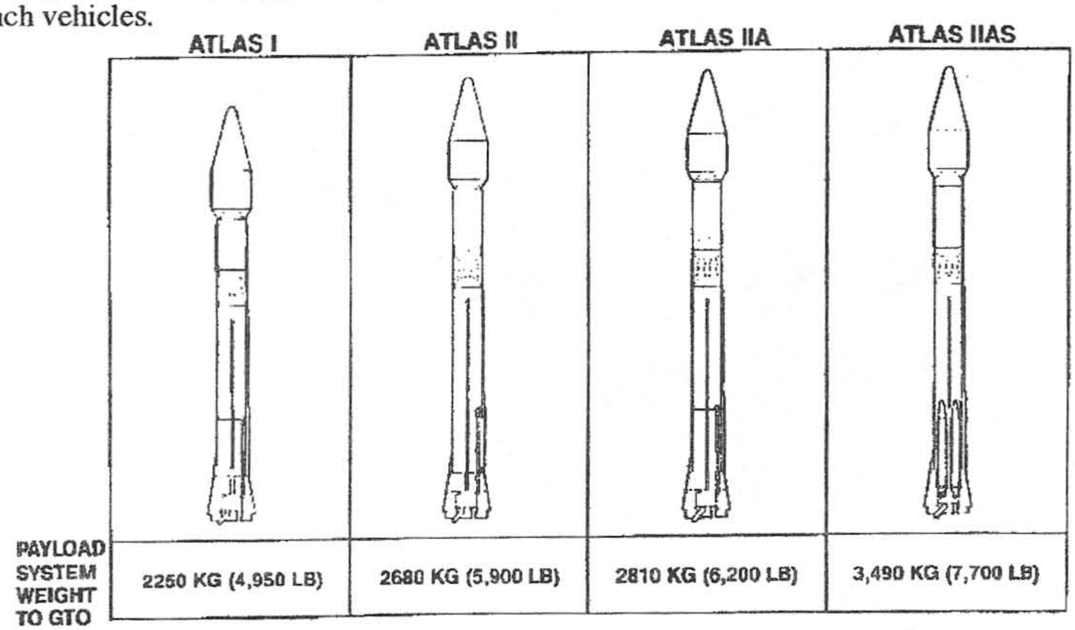


Milstar 1 configuration - drawing by Lockheed

Another potential for launch services is incremental launch vehicle improvements. If an existing primary customer is already launching a medium class launch vehicle we can offer to pay for part of the difference to upgrade to the next higher model. This is especially appealing for a customer who would prefer to purchase the larger model but has not decided whether or not it's worthwhile. For example, when Eutelsat chose to launch one of their satellites on a commercial General Dynamics Atlas they selected the Atlas I, the least powerful model. The contract included provisions for an optional upgrade to the Atlas II model which was the one which actually flew. Most future Atlases will be the Atlas IIA model which includes higher performance upper stage engines. We could offer to customers to pay for part of the upgrade to the Atlas IIAS model which adds four Castor IVA solid motors for additional performance. A call to Thiokol confirmed that four Castor IVA motors would cost about $4 Million. While this amount of money would be difficult to raise by ourselves it's more than likely that we would split the difference with the primary launch vehicle customer and contractors. Martin Marietta, which now owns the Atlas launch vehicle and what used to be General Dynamics Commercial Launch Services, has indicated that they would certainly be interested in developing the capability to fly piggyback payloads on their launch vehicles.

Several small payloads have flown as piggybacks on NASA and Air Force Delta second stages. In some cases the payload remains attached to the Delta's second stage and only operates for a couple of hours. in other cases lightsats have been ejected after the primary payload has completed its mission. NASA Marshall has tested the SEDS (Small Expendable Deployer System) tether on two Delta missions. In these cases diagnostic payloads have been deployed on a tether. There are plans to use the SEDS tether to deploy microsats into higher orbits, most notably SEDSAT from the University of Alabama. Currently there are plans to move the SEDS program from the Delta to the shuttle, which would result in more limited spacecraft lifetimes though.

While launch vehicles to geosynchronous transfer orbits and cases where the spacecraft has been optimized for a particular launch vehicle have little excess capacity most other launch vehicles will have some unused capacity. In some cases ballast is used or propellant is offloaded. In other cases the launch vehicle will actually make a little 'side trip' on the way to orbit to get rid of that excess velocity. Naturally that capability should be used.



Commercial Atlas launch family - Martin Marietta Commercial Launch Services

Orbital Sciences is offering its Picolab, microsat-class satellites which can be flown on Pegasus launch vehicles with excess capacity. Currently their prices are too expensive for us to even consider ($3M for the satellite and launch services), but OSC may be willing to offer space to us in many special cases. We could fly as standby payloads when other Picolab customers aren't ready to go, our payloads could include multi-purpose spacecraft like the Eyesat spacecraft, and there's always the possibility of special deals.

To date eight satellites including two classified spacecraft, have been ejected from Getaway Special canisters mounted within the shuttle's cargo bay. Before the Challenger accident it was a relatively inexpensive system. Since the new GAS policy was released optional services, like ejectable spacecraft, are now in a new category - Hitchhiker Junior. The pricing policy has not been released, but is almost certainly too expensive for us to consider. In addition GAS ejected satellites have very limited lifetimes, on the order of a year before reentry. There always is the possibility to get out of the shuttle's orbit into a more useful orbit though. Jan King has proposed a system based on the electrolysis of water driving a hydrogen-oxygen thruster as an upper stage. Another possibility would be some kind of tether deployment system.

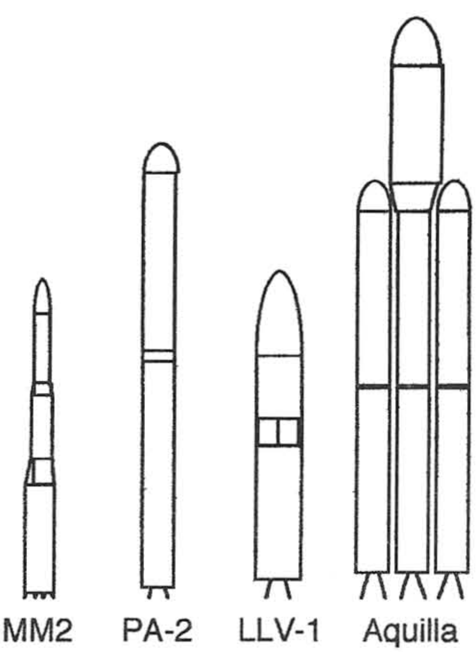
One method to get inexpensive launch services which we have always used is new, unproven launch vehicles. Established customers do not want to risk their spacecraft on new launch vehicle designs unless absolutely necessary. When a launch vehicle manufacturer doesn't have a proven track record they are often willing to offer launch services extremely inexpensively to get themselves established. Some potential launch vehicles include AeroAstro's PacASTRO, Lockheed's LLV, and AMROC's Aquilla. Still, we should be aware of the additional risks associated with launch vehicles without proven track records. Most of us still have painful memories from the loss of Phase 3A on the second Ariane launch.

In addition to all of these possibilities we shouldn't forget launch vehicles from other countries. Japan, China, India, and - of course, Russia all have strong launch vehicle programs which may offer additional launch opportunities.

From a strictly technical point of view, the best existing launch site in the world for Molniya (Phase 3D) orbits is Plestek, near Archangel in Russia at 62 degrees North. This site also has the political advantage of being within the Russian Republic.

One of the most unusual launch platforms is hand ejection from Mir's airlock. Some small spacecraft, including two Russian amateur satellites, have been shoved out of Mir's airlock by a spacesuited cosmonaut. The primary disadvantage to this method is limited lifetime. Mir is in a relatively low orbit and any hand-ejected spacecraft will have extremely limited lifetimes.

In conclusion we should be aware that future launch vehicle opportunities will be more limited than they have been in the past. We will have to pay more for launches than we have had to pay before, and will have to get more creative in finding new opportunities to put amatuer transponders into space.



New Launch Vehicles under development

The Re-Entry of OSCAR-13

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Abstract

Without an atmosphere, Oscar-13 would collide with the Earth's crust on 1997 Feb 03. But we do have an atmosphere, which means that the satellite experiences a gradual retardation every perigee pass. Thus re-entry will be sooner, approximately 1996 Dec 05. This paper outlines the computer program and discusses the circumstances.

Introduction

Satellites such as Oscar-13 that are in orbits that take them a long way (>10,000 km) from the Earth experience significant forces from the Sun and Moon. This causes the orbit shape and orientation to oscillate slightly with periods measured in years.

Geostationary satellites have on-board thrusters to compensate for these inescapable deviations. But Oscar-13 does not, and its orbital eccentricity is now (1994) monotonically increasing, with an attendant decrease in the height of perigee. When this height reaches a little under 200 km, atmospheric drag becomes significant, converting the satellite's energy into heat and slowing it down.

Thus each subsequent apogee is slightly lower and gradually the orbit circularises. Mean motion increases, and finally the friction is so great that the orbit goes parabolic and the satellite plunges, burning up as it re-enters.

Somewhat prior to that of course, it will have overheated, and the electronics will certainly fail before burn-up.

Modelling

The numerical methods used for this study are outlined in [2] *May the Force be with You* which should be studied. That paper also contains a bibliography of all amateur work in this field up to 1992 December, and these references are repeated here.

Briefly, integration of the 3 dimensional equations of motion by both direct (Cowell) and Encke's method have been used. The results here use direct integration by a Runge-Kutta-Nyström 6th order (RKN6) algorithm.

Forces modelled are Earth's gravity plus bulge terms J2, J3 and J4, the Sun and Moon, and atmospheric drag. Drag depends on the atmosphere's density, and the model documented in [1] chapter 4.4 and appendix L.3 is implemented.

The integration step size varies from approximately 100 sec at perigee to 1800 sec at apogee. At each apogee a set of osculating (kissing) keplerian elements is dumped to disc for later analysis. The program stops when the orbit goes parabolic, eccentricity < 0.

The program is written in BASIC, uses 8-byte floating-point arithmetic and runs uncompiled on an Acorn RISC Computer at a rate of 2.5 seconds computation per orbit, which is about 30 minutes per simulation year.

When seeded with post launch keplerian elements, the agreement with subsequent elements over the 6 years to 1994 July is within a fraction of 1°, and gives full confidence in predictions for the future. See figure 1.

Drag

This is the retarding force experienced as the satellite collides with gas molecules. It's a function of the frontal area of the satellite, its velocity relative to the revolving atmosphere, and most crucially, the atmosphere's density (kg/m^3).

Figures for the mean density are well documented by many authors. But *all* caution that density is a function of several factors, including day/night, time of year, solar activity, sun's rotation, position in 11 year sun-spot cycle and so on. In consequence spot density figures on any particular day can be expected to deviate temporarily from the mean density typically 50% either way.

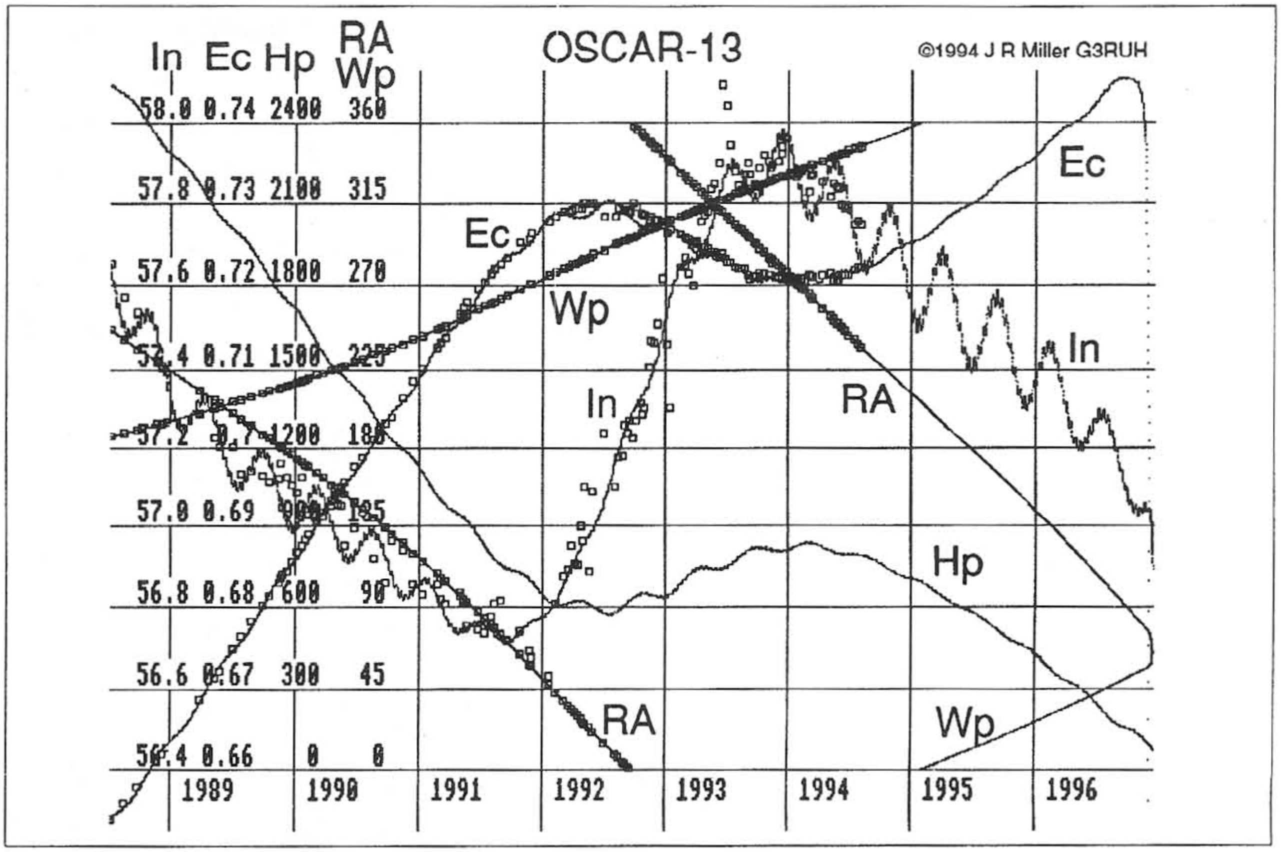

Figure 1. Oscar-13 keplerian elements from launch to re-entry. Superimposed is Nasa/Norad data showing close agreement between model and reality. Abbreviations: In = Inclination deg, Ec = Eccentricity, Wp = Argument of Perigee deg. RA = Right ascension of ascending node RAAN deg, Hp = Perigee height km.

Clearly then it is important to examine the way Oscar-13's orbit decays with changing density. This can be be done coarsely by starting with a reference model as per [1], and then running the program with the density x0.01, x0.1, x1, x10, x100 of nominal and observing the changing outcomes.

Drag acts against the direction of motion through the atmosphere. However since the satellite is asymmetric, like an aircraft's wing it will also experience side-thrust. This is called lift. Since it is somewhat difficult to model, is hopefully small and probably averages out to zero over a perigee encounter, it has been ignored. Lift affects the orbit's orientation rather than its shape.

Heating

If the drag force is F_d Newtons, and the satellite's velocity relative to the atmosphere is V_r m/s then it is converting kinetic energy into heat at a rate of $Pwr = F_d \cdot V_r$ watts.

Half (say) of this energy is swept away by the gas, the remainder is absorbed by the satellite, which warms up.

Oscar-13 is in comfortable equilibrium with the Sun's incident energy of 500 watts. Clearly then additional heat of (say) 10x more will overheat the satellite, or at least damage the external structure, in particular the solar panels.

So as a rule of thumb, we could expect the satellite to fail through overheating when $Pwr = F_d \cdot V_r = 10$ kw or so. This occurs about 3-5 weeks before re-entry.

Study of the peaks however shows them to be short lived, of duration about 100 sec, and with -10db power points spaced about ±1½ minutes. See figure 2 which shows this for several successive perigees that peak at 10 kw.

About a week before re-entry thermal heating reaches 100 kw, and exceeds 400 kw on the last orbits.

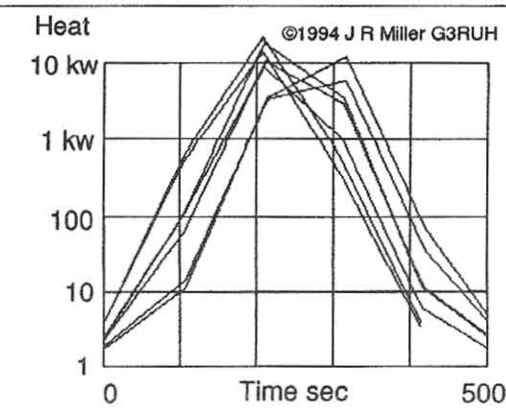

Figure 2. Profile of heating due to friction. Depicts several successive perigees peaking at the 10 kw level.

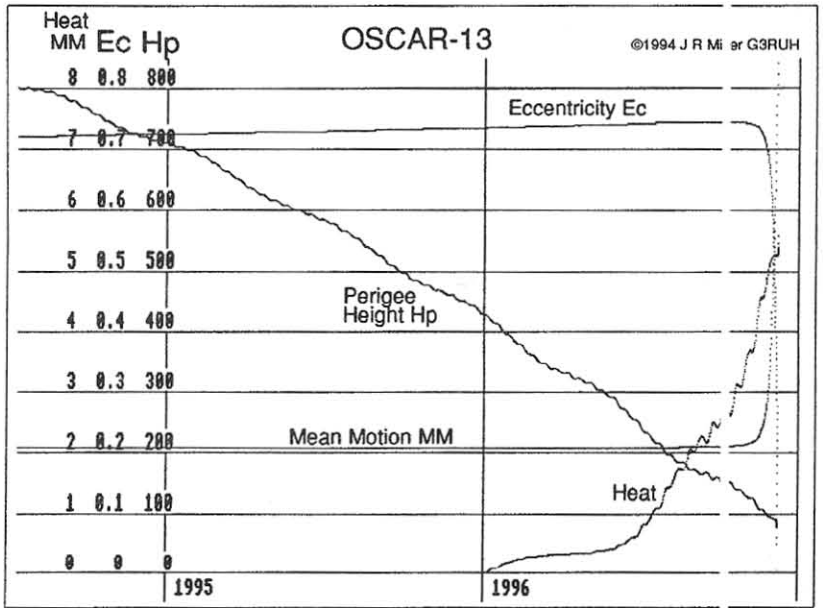

Figure 3. Nominal re-entry conditions. Abbreviations: MM = Mean motion rev/day. Heat shown as Log_{10} (power in watts).

Break-up?

The actual drag force is very small. Since from the above, $F_d = Pwr/V_r$ the total drag at 10 kw heating is 10,000/7,000 = 1.4 Newtons, equivalent to 0.15 kg weight on Earth. This is unlikely to rip any parts off.

Even on the last fireball orbits, the total drag is less than 400,000/7,000 = 57 Newtons, equivalent to 6 kg weight on Earth. This force is vastly less than the satellite endured during shake testing, but when parts of it are momentarily melting one must suppose that extremities such as antennas will be swept away during this last week.

Nominal Re-entry Conditions

Figure 3 shows Oscar-13's eccentricity, perigee height and peak frictional heating from 1994 Jul 14 to the end of 1996. This gives a nominal overview of the proceedings.

From the user's point of view nothing will appear to change until about 1996 Oct 10 when peak friction reaches 500 watts which will be noticeable on the perigee telemetry. Transponder performance and satellite visibility should be exactly as they have always been.

Around Nov 13 peak frictional heating reaches 10 kw, and the satellite will probably fail. Changes in the eccentricity and mean motion will be just perceptible.

Twenty-five days later, on 1996 Dec 08 the satellite re-enters.

Re-entry with more/less drag

Figure 4 shows the last year of life computed using the nominal drag model, but superimposed with drag scaled up x10 and down /10.

In the higher drag case, decay is rather more protracted, with the 500 watt point reached on Aug 17, 15 weeks before re-entry, the 10 kw "failure" point is around Oct 28 followed by re-entry 36 days later.

If the drag is 10 times too low, the onset of heating is later, showing 500 watts on Nov 03, 6 weeks before re-entry, rapidly reaching 10 kw on Nov 24, followed by re-entry just 22 days later

The spread of re-entry dates here is 1996 Dec 03 - Dec 16.

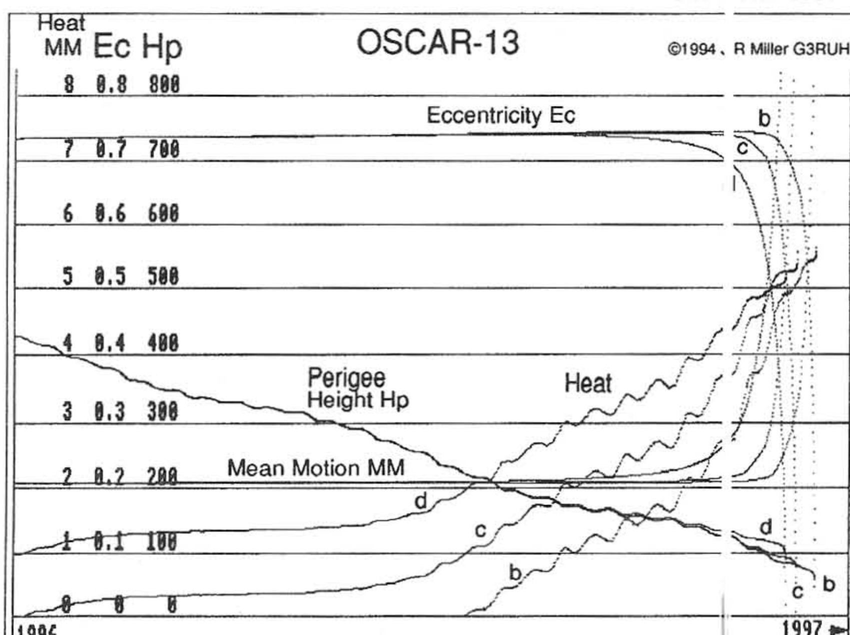

Figure 4. Last year of life with drag model scaled x0.1 (b), x1 (c), x10 (d).

Even more/less drag

Figure 5 shows the last 3 months life, with a spread of drag scaling from x100 down to /100; mean motion is omitted for clarity.

We discover that when the drag is modelled x100 more than nominal, the re-entry date is later than for the x10 case. This is further illustrated in figure 6.

From this the earliest possible re-entry date is 1996 Dec 03.

Conclusion

The purpose of this paper is to demonstrate that accurate modelling of spacecraft orbits by direct integration of the equations of motion is well within the capabilities of today's personal computers. Readers should not assume that a *Cray Vector II* ™ is required! Far from it.

In fact this work was started in December 1987 in 5 byte floating point interpreted BASIC on a 64K 6502 machine running at 3 MHz, and achieved comparable results in "overnight" runs.

Today's hardware and software is perhaps 100x faster than that, and allows very long term analyses as well as "what-if" situations to be studied rapidly. For example, all the runs and re-runs presented in this report, plus the text, were generated in just a couple of days work.

The program listing is available on request from the author via the Internet, and will be seen to be very straightforward and non-mysterious. It will allow many more people to study the options for the forthcoming Phase IIID satellite. Reference [3] is already a major contribution to this field and signposts routes for further exploration.

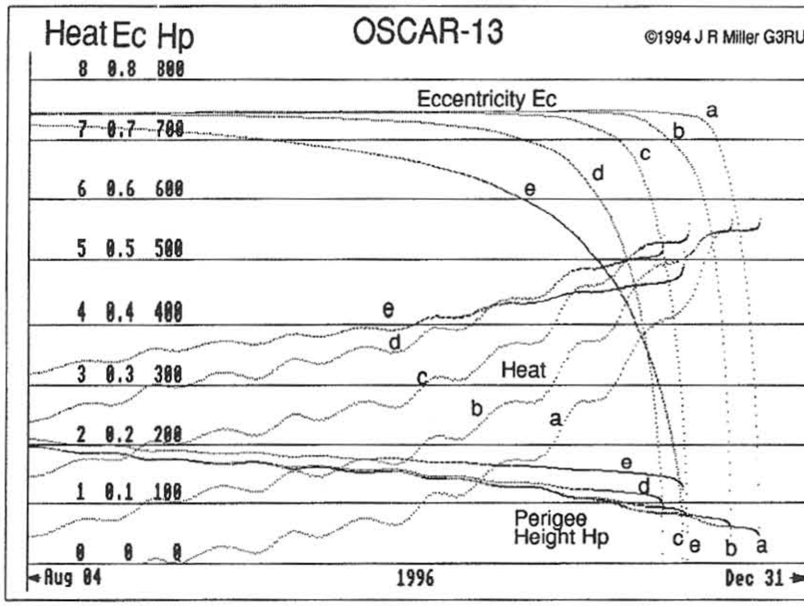

Figure 5. Last 3 months of life with drag model scaled x0.01 (a) to x100 (e).

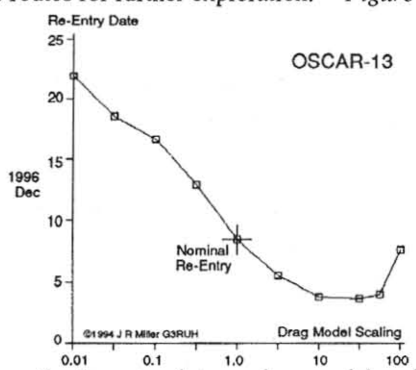

Figure 6. Re-entry date vs. drag model scaling.

Chicken Run

Doubtless during 1996 the usual "Chicken Little" re-entry competition will be run for Oscar-13. The author's prediction is 1996 Dec 5½.

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1993-94 REPORT ON DOVE RECOVERY ACTIVITIES

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ABSTRACT

The DOVE (DO-17) satellite was returned to service in the 2 m band on November 6, 1993. Since its recovery, DOVE has accumulated a 95 percent uptime record. This paper reviews the recovery plan developed and published in 1993 and describes the activities that have resulted in the successful implementation of the plan. Future software development required to support uploading files of digitized speech is also presented.

INTRODUCTION

Of the four AMSAT Microsats, DO-17 or DOVE has been plagued with the most operational problems. Fortunately, during the past year, procedures and software have been developed to circumvent the problems and realize much progress toward the original mission of DOVE. Jim White's paper [1] published in last year's *Proceedings* provides an excellent review of DOVE's mission objectives, operational problems, recovery plans, software development activity, and plans for future operations. Since this paper concentrates primarily on the steps taken to implement the recovery plan, readers are encouraged to review the previous paper. The mission objectives, operational problems, and other issues are discussed only to the extent required to set the stage for describing the recovery operations.

BACKGROUND

DOVE's primary mission is educational and its systems were designed to facilitate the mission. Unlike the other Microsats, DOVE's downlink is in the 2 m band (145.825 MHz) and has sufficient power (approx. 6 dBW) to provide a good link margin for ground stations using simple antenna systems. Besides having the downlink in the 2 m band, the modulation scheme used for digital data transmission is the same as that used for terrestrial VHF packet radio (AFSK FM). Consequently, no special modems or other equipment are required for stations that may already be setup for terrestrial packet radio.

Another feature of DOVE is that it has two other downlink modulation sources besides the AFSK FM modulator used for packet transmissions. They are a Votrax SC-02 phoneme speech synthesizer and an Analog Devices AD-558 digital-to-analog converter. These two devices are controlled by a separate Motorola 68HC11 microprocessor in the DOVE "speech" module. The name of the satellite comes about because of the speech module with DOVE being an acronym for *D*igital *O*rbiting *V*oice *E*ncoder.

A primary motivation for the speech module was to increase interest in space science among students, especially in third world and less developed countries. Because DOVE can transmit voice, students in such situations would only have to build or obtain simple low-cost receivers. To serve these students, digital telemetry would be translated into voice messages such as: "I am in the beautiful sunlight." or "I am in the cool darkness." or "My battery is being charged." Furthermore, the speech module would allow short messages suggested and/or developed by students to be uploaded and transmitted from space.

As noted above, DOVE's primary downlink is in the 2 m amateur band. Since the command and control uplink is also in the 2 m band, DOVE has a secondary transmitter in the 13 cm band (2401.220 MHz). The original operational plan was to turn off the 2 m downlink and use the 2 m uplink and 13 cm downlink for full-duplex command and control. The 2 m downlink would be activated again when commanding was completed thus eliminating any in-band interference. Unfortunately, the modulator for the 13 cm transmitter failed, either at launch or shortly after, causing the modulation index to be very low. Since the problem is in the modulator, the transmitter power is not affected but at the ground station the signal must be 15-20 dB above the noise before any modulation is detectable. Even with a very-high performance receiving system, the combination of low modulation index, spacecraft motion, and high Doppler rates at 13 cm make demodulation of the digital data very difficult.

RECOVERY PLAN

A summary of the DOVE recovery plan as published in 1993 can be found in Table 1. Almost all of the items listed in Table 1 have been accomplished. Item nos. 10-12 were skipped, because once PHT had been successfully loaded, it was determined fairly quickly that the spacecraft systems were in good condition. Item nos. 1-4 and 6-8 were accomplished by November 6, 1993. The original speech synthesizer test program was not included in the initial software upload. Consequently, item nos. 5 and 9 were not accomplished until the successful speech synthesizer test of June 11, 1994 which implemented a new phrase rather than the one previously used. Item nos. 14-17 in the recovery plan referred to development and implementation of the telemetry-driven speech feature. This feature is under development now. Besides assisting with software loading, the command stations have accomplished item nos. 13, 18, and 19.

Work has also been done on some items that were not a part of the original recovery plan. These include developing the new digital-to-analog converter (DAC) test and implementing a communications path from the 68HC11 in the speech module back to the housekeeping task (PHTX). The following section provides a more detailed accounting of DOVE recovery activities during 1993-94. Table 2 lists those participating in the activities and their responsibilities.

Table 1
DOVE Recovery Plan as Published October 1993

1. Reset MBL again and see if it responds to commands and attempts to load RAM. If it does not, reset and try again.

2. Develop a simplified RAM-resident loader that operates in half-duplex mode using the 2 m uplink and downlink. The loader should include a memory "wash" routine to protect itself and the modules it loads.

3. Load the RAM-resident loader using the s-band receive capabilities of NK6K or K0RZ and test its operation.

4. Load the operating system kernel using the RAM-resident loader.

5. Load the housekeeping task (PHT) using the RAM-resident loader. PHT will include the previously-used speech synthesizer test phrase "You are listening to DOVE Microsat" to verify the hardware in the speech module is still operative.

6. Test the operation of the kernel and PHT by listening on S band. Stay in this mode a few hours to be sure the software is stable and normal telemetry and information frames are being transmitted.

7. Return DOVE to limited operation by turning on the 2 m transmitter. Normal PHT telemetry should be sent with the 2 m transmitter cycling on and off as before.

8. Using the loader in PHT, load the three operating system modules comprising the full-up system which includes the more elaborate housekeeping task PHTX.

9. Turn on the voice briefly to insure the speech module is working.

10. Do a quick WOD survey to assess spacecraft health.

11. Do a full WOD survey.

12. Make DOVE WOD available for analysis by students and other interested parties.

13. Make DOVE available for short text broadcasts.

14. Test new software features on ground-based simulator.

15. Load software with new features using the half-duplex loader in the running PHTX.

16. Test new software capabilities and carefully adjust the power control algorithm in PHTX.

17. Test the voice capabilities of the new software.

18. Adjust transmission intervals of the various downlink messages.

19. Turn on the S-band transmitter to see if a positive power budget can be maintained and attempt to demodulate data on S band using DSP techniques.

Table 2
DOVE Recovery Team Members, Locations, and Functions

Team Member	Amateur Radio Station and Location	Specific Tasks performed
J. White	WD0E Littleton, CO	Software development coordinator. Command station coordinator. Housekeeping task programming. Software testing on simulator. Software uploading.
H. Price	NK6K Bethel Park, PA	Onboard operating system design and programming. Intertask communications.
R. Diersing	N5AHD Corpus Christi, TX	Speech extraction programming. Speech module 68HC11 programming. RAM-based boot loader.
R. Platt	WJ9F Concord, NC	Command and control station. Software uploading and telemetry monitoring.
R. Howlett	VK7ZBX Rokeby, Tasmania	Command and control station. Software uploading and telemetry monitoring.
W. McCaa	K0RZ Boulder, CO	High-performance S-band receiving system. RAM boot loader uploading.

RECOVERY ACTIVITIES

The DOVE operating system software (which is common to all the AMSAT Microsats) allows loading new system tasks and unloading those no longer needed. After a system reset, a two-stage process is required to bring DOVE to a full-up operational state. In the first phase, the operating system kernel, which is about 15 Kbytes in size, is loaded followed by a minimal housekeeping (PHT) task of about 35 Kbytes. In the second stage, the production housekeeping task (PHTX) is loaded by using the loader in PHT.

Soon after the failure of the S-band modulator, the loader in the minimal housekeeping task (PHT) was modified to support half-duplex rather than full-duplex communications. Even though this change allowed the production housekeeping task (PHTX) to be loaded in half-duplex mode, the kernel and PHT still had to be loaded in full-duplex mode using the S-band downlink because of the ROM bootloader. Coping with the failed S-band modulator made the loading of the kernel and PHT essentially a "blind" operation.

Adding to the complications was the fact that software to operate the voice module was still in the developmental stage. Consequently, despite extensive ground simulator testing, it was likely that certain software problems would cause DOVE's operating system to crash. The result of such crashes would be a system reset back to the boot ROM code at which point another blind load of the 15 Kbyte kernel and 35 Kbyte PHT was required. Several of these blind reloads were successful prior to the first tests of the speech synthesizer chip in the voice module in May 1992. However, in the summer of 1992, one of the speech synthesizer tests did not run as expected and ground controllers made the decision to do a system reset.

For a multiplicity of reasons, most of which are related to the unpaid, volunteer nature of the Amateur Satellite Service, DOVE remained out of service until November 1993. What is important are the procedures that returned it to service and what has been accomplished since then to realize DOVE's planned mission.

During the time DOVE was out of service, work was being done in parallel on three different software components. First, a simplified RAM-based boot loader was being developed as an intermediate step to loading the operating system kernel. The motivation was to load the smallest amount of software possible to get into a half-duplex load mode and thus minimize contending with the failed S-band modulator. Second, it was clear that a more efficient way of developing phoneme strings for the speech synthesizer was needed. Moreover, improvements were needed in the 68HC11 software controlling the voice module. Finally, modifications were required in the operating system task used to communicate with and control the voice module.

The first item to be attacked was that of simplified speech synthesizer phrase construction. In the time since DOVE was designed and built, production of the speech synthesizer chip under the Votrax SC-02 designation had ceased with an equivalent now being produced by Artic Technologies under the designation 263A. An Artic Sonix speech development system consisting of an IBM-PC compatible card using the 263A and a speech file builder/editor was purchased. A program was then written to extract the phrases from the database built by the Sonix system and insert them in the 68HC11 program to run in the voice module. The resulting program was tested using a Motorola 68HC11EVB evaluation board interfaced to an Artic 263A chip in the same manner as done in the actual spacecraft. The 68HC11EVB allowed decoupling of much the initial software testing from using the full-blown ground-based simulator which was installed at another location. Once the program ran properly on the 68HC11EVB, it was reassembled for the proper load address and sent electronically for testing on the simulator. The spacecraft simulator includes a duplicate of the actual flight voice module.

With a method of building phrases and creating the proper 68HC11 programs more efficiently, attention was turned to better support for the voice module functions in the housekeeping task (PHTX). This programming was likewise tested on the ground-based simulator. Programming was begun to support the speaking of certain phrases based on telemetry system values. Implementation of this capability is consistent with the educational mission of DOVE and will eventually allow students, without any digital data decoding equipment, to know something about the spacecraft's condition. A method for testing the digital-to-analog converter for audio production has also been included in PHTX.

The last step toward returning DOVE to service was the completion of the RAM-based loader to allow half-duplex loading of the operating system kernel. This minimal-function loader required only 13 frames to be uplinked while listening for responses on S-band. For the most part, it would be unknown whether the responses were positive or negative acknowledgements. Therefore, the procedure was to be, load the RAM-based loader, then execute it and see if any telemetry was heard on the downlink. After testing on the simulator, the new loader was uploaded on October 31, 1993 (November 1 UTC) during an evening pass using the S-band receive facilities of Bill McCaa, K0RZ. The execute command was given and no telemetry was heard on the 2 m downlink. The assumption was that the code did not work as planned. However, on the evening of November 1 the U.S. east coast command station (WJ9F) reported that telemetry was being transmitted on the 2 m downlink. What had happened was that the telemetry interval had been set fairly long and there had not been enough time to hear the telemetry before LOS on the previous evening.

Attempts to load the operating system kernel failed but it was determined fairly quickly that the problem was timing between the half-duplex operation of the 2 m uplink and downlink at the spacecraft and the operation of the ground station command computer and its software. Changes were made to the RAM-based loader and several versions were tested on the ground. Once the desired timing had been achieved, the already running copy was used to load the new version. Loading of the operating system kernel and minimal housekeeping task (PHT) began on November 5, 1993 and was completed the following day. The loader in PHT was then used to load the production housekeeping task (PHTX). The satellite remained in continuous operation on 2 m until late May 1994 when testing of the voice module was resumed. The period between November 1993 and May 1994 allowed evaluation of the onboard systems which was necessary since the satellite had not been under autonomous control for well over a year.

During the period between May 24 and June 12, 1994 new operating system tasks were loaded in preparation for resuming the speech synthesizer tests and DOVE was intermittently out of service. After one unsuccessful test (garbled speech) and one unsatisfactory test (low transmitted audio level), a satisfactory test was initiated on June 11, 1994 with the satellite repeating the phrase, "Hi, this is DOVE in space" for one minute followed by transmission of digital packet telemetry. Besides the phrase itself being different from the tests run in 1992, the new speech software controls the rate, amplitude, and inflection attributes on a phoneme-by-phoneme basis. The old software set these attributes once for the entire phrase.

Once the new speech synthesizer test was running, attention turned to checkout of the digital-to-analog converter (DAC) chip. For this test an existing single-tone DAC test program was modified to transmit a sequence of tones stepping from a high frequency down to a low frequency and then back up again. While the DAC test was being readied, work was being done to add a communications path from the

68HC11 in the speech module back to the housekeeping task (PHTX). While the physical path had always existed, it had not been used in any previous tests because no software support for it existed. One of the many possible uses for this communications path would be to allow the speech synthesizer test program to tell PHTX how many times the test phrase had been spoken.

After considerable ground testing of the new software, controllers uploaded the new PHTX and started its execution on August 8, 1994. Everything worked as planned with telemetry, voice, and tones being transmitted in sequence on the downlink. Followers of DOVE will remember that the test phrase being transmitted prior to August 8 would usually be cut off in mid sentence whereas, with the new software, it is completed an integral number of times. This is due to the communications from the speech module processor back to the housekeeping task (PHTX). As this paper is being prepared, programming to produce different speech sentences based on real-time telemetry values is continuing.

FUTURE PLANS

Programming to support speech generation based on telemetry values is scheduled for completion in the last quarter of 1994. The next major programming effort will be implementing the ability to upload files of digitized speech for transmission using the digital-to-analog converter (DAC). Several components of this software project have been identified. First, control of the speech module will be removed from the housekeeping task (PHTX) and placed in a separate module. Second, a slightly more complex loader will have to be written for the 68HC11 processor in the speech module. The new loader must be able to: report status and error conditions to the speech control task; allow the loading of more than one program in RAM; select which program to run based on information received from the speech control task; and perform some type of memory wash procedure on its own data and program storage RAM. Finally, a variant of the Pacsat broadcast file system must be implemented.

Since DOVE has the same 8 Mbyte message storage area as the other Microsats, files containing digitized messages could be stored there and then transferred to the speech module as needed. The plan is to generate the files using a readily available system such as the Sound Blaster board. The internal functions of the file system would be almost identical to AO-16 and LO-19, but since only command stations would be uploading messages, there would be no user interface like PB/PG. It may well be that a broadcast, rather than connected mode, upload will be implemented. While no time schedule has been set for implementation of the speech upload facility, there has been some discussion of not disrupting DOVE's operation during times when school is normally in session. Of course, such a plan would not affect development and ground-based simulator testing.

SUMMARY

The DOVE recovery plan established in 1993 has been reviewed and a detailed description of the past year's activities resulting in the recovery of the DOVE mission has been presented. Since the return of DOVE to service on 2 m on November 6, 1993, it has been transmitting on 2 m for about 95 percent of the time. The few days of downtime were, of course, associated with loading of new software. Software to generate speech based on telemetry values is to be completed soon. Future plans presented include support for uploading files containing digitized speech. It is particularly gratifying to see coverage of DOVE reappear in the various amateur radio publications, the most recent of which is Steve Ford's article in September 1994 *QST* [2]. Moreover, it is hoped that educators who have used DOVE in the past can resume their use of this excellent educational resource [3]. The recovery of the DOVE mission is especially significant because it makes the 1990 AMSAT Microsat mission 100 percent successful.

ACKNOWLEDGEMENTS

Two people deserve recognition for their assistance in preparing this paper. Thanks go to Jim White, WD0E and Harold Price, NK6K who provided many pieces of information and reviewed parts of the manuscript. It has been my pleasure to work with them as well as command team members Russ Platt, WJ9F, and Richard Howlett, VK7ZBX to bring DOVE back to routine operation.

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A SAREX Case Study
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SAREX, the Shuttle Amateur Radio Experiment, is flown primarily as part of NASA's education program. Any school or educational group can submit a proposal for a prescheduled SAREX contact. It's hoped that schools will get interested in the space program and amateur radio, and make these activities part of the normal curriculum. Sometimes a SAREX contact is incredibly exciting, but forgotten soon after the shuttle mission is over. But in many cases SAREX does leave a lasting impression on the students and teachers. Co-author Joan Freeman is a teacher at South Seminole Middle School in Casselberry Florida. Three years ago she watched television and read the newspaper to find out about the space program. Now she uses amateur radio every day in her class and completed a SAREX educational contact with the shuttle during the STS-65 mission. This paper will show what has been done, and suggestions for how to increase awareness about ham radio, SAREX, and the shuttle program in schools.

SAREX, the Shuttle Amateur Radio EXperiment, is one of the most enjoyable ways of getting students involved in ham radio and the space program. It has flown on the shuttle over a dozen times and has become one of the most popular shuttle experiments.

Three years ago co-author Joan Freeman was a typical middle school teacher, with little special interest in amateur radio or the space program. Another local teacher, Joe Laughlin KC4VBY, got her interested in SAREX and an upcoming school contact. During the STS-45 shuttle mission in March 1992 a handful of central Florida schools were linked together via the Lake Monroe 147.285 repeater. Lyman High School was the primary contact point. A student at Lyman got to ask a question to shuttle astronaut Brian Duffy N5WQW. The next student from Ventura Elementary got to ask a question, followed by students from Galaxy Middle, Trinity Prep, and Rock Lake Middle Schools. Unfortunately time ran out before South Seminole Middle School,

Lyman High School SAREX team members for the STS-45 mission - Photo by KC4YER

Joan's school, got to ask their question.

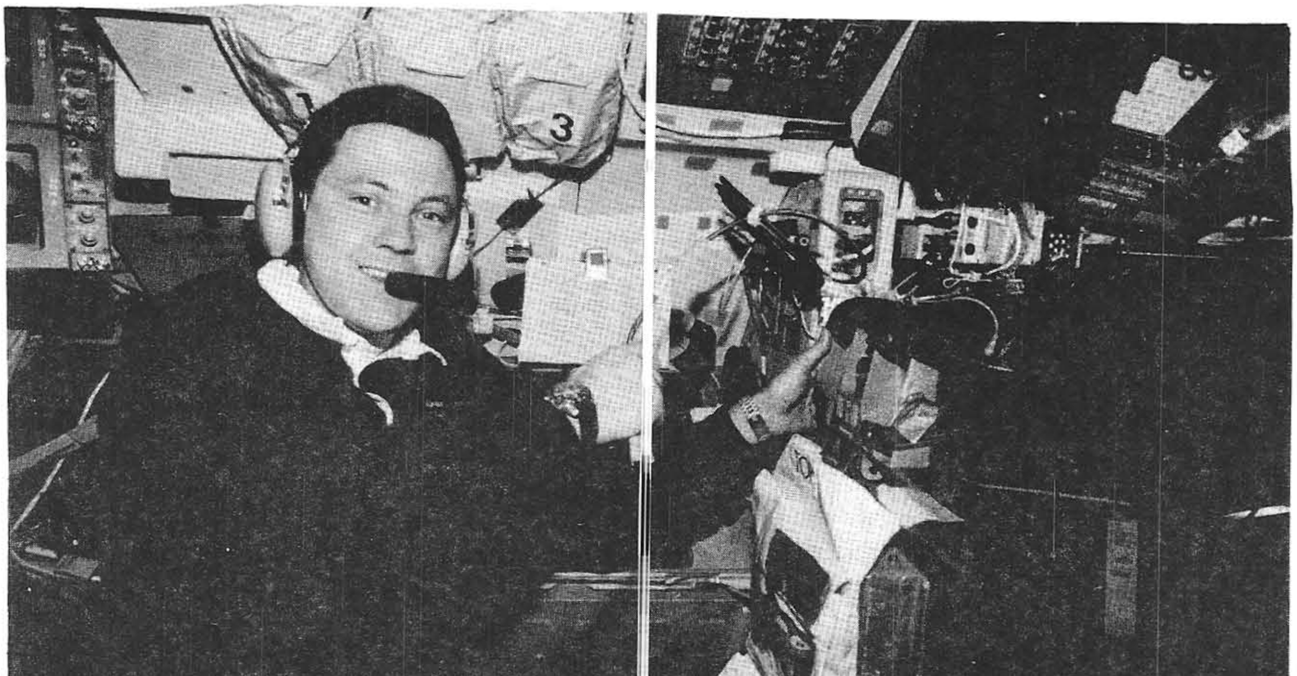
Linking several schools together on a net had many advantages - most significantly getting many more schools involved than with a typical contact, but was much more difficult logistically - in addition to being frustrating for schools which didn't get the opportunity to talk to the astronaut in space.

Still, preparing for the contact got Joan excited. Of all of the teachers involved in the STS-45 SAREX contact, Joan decided to get her amateur radio license and uses amateur radio in regular day-to-day classes. Her classroom includes many radios, donated by local hams, and a computer donated by a local business. In addition Joan runs an education net on the local repeater. Eleven schools in three counties, ranging from elementary through high school level participate in classes during the net. But the most frustrating part for Joan was not getting to talk to an astronaut in space. So Joan decided to put in her own application. It took two years before an appropriate opportunity came up. South Seminole Middle School got selected for the STS-65 mission as one of commander Bob Cabana KC5VBH's many school contacts.

The contact was scheduled for July 13th at 10:09 am EDT at a mission elapsed time of 4 days 21 hours and 15 minutes. Most of the hams involved with the Lyman contact a couple of years earlier donated their time and expertise to making Joan's contact a success, including Joe Singer N4IPV, Ed Cox W0RAO, and John Rothert KC4IYO.

Everything went smoothly, with Joan acting as the control operator for the contact. Appropriately the first student to get to ask a question was one who had earned his ham license in Joan's class. Eight students got to ask questions to Bob Cabana. There was additional time available and three of the adults also asked questions. As a bonus benefit Joan got special permission to visit the Kennedy Space Center and got to see Bob Cabana up close.

All together the contact lasted just six minutes, but the experience will last a lifetime. "Something to tell my grandkids about" as one student told a local reporter.



NASA Photo STS65-44-014

Bob Cabana KC5VBH using SAREX during the STS-65 mission for a school contact

For a ham who wants to get involved in SAREX it's extremely simple. Just contact a local school and talk to the education coordinator or head of the science department. It can be the school you graduated from, the school your kids go to, or just the school closest to where you live or work. Ask them if they'd be interested - and it would be difficult to get a negative answer. Even with the amount of effort required the thrill of a successful contact makes it worth it. Contact the ARRL's educational department and ask for a SAREX application. This is a simple two-page form with basic information on the school, its location, and your equipment. Fill out the form with the school and send it in. The backlog of schools is slowly disappearing and hopefully you won't have as much of a wait as South Seminole Middle School did before its contact.

It's important to include all of the information specified - especially your school's location. The easiest way to get an accurate latitude / longitude for your location is to use a surveyor's map, or find a boater with a Global Positioning Receiver.

While you're waiting for your application to go through get your school interested in amateur radio and the space program. Optional (perhaps extra credit) classes are an excellent way to get kids interested in ham radio, and NASA's education department will be glad to provide generic materials on the shuttle and its activities. Unfortunately the SAREX information sheet is badly out of date, but it still has some good information.

The most important thing to remember is SAREX, like the shuttle program, is much more than just astronauts - it's people. The astronauts certainly have the most visibility and most envious jobs within NASA, but SAREX exists because of many different people performing different roles, including the JSC amateur radio club volunteers who prepare the hardware and train the astronauts, the ARRL and AMSAT folks who handle the paperwork and information distribution, and most importantly the hams and teachers at the schools who interact directly with the students.

For a ham getting involved in a school contact is a fantastic experience. You get to help out education in your community, and the excitement watching the looks of joy on students faces as they talk to the astronauts certainly makes it worth all of the effort.

Many months after you put in your application you will get a tentative flight assignment. This can easily change depending on the mission's requirements, changes to the crew's flight plan, and other factors. But it gives you a date to plan towards, and tells you that you've made it to the top of the pile.

Contact your local NASA education office. If you don't know which NASA center serves your region then ask the ARRL educational representative. The Johnson Space center's public affairs and education office is also an excellent source for information. Another excellent source, if you have a computer with a modem is to call NASA Marshall's Spacelink BBS at 205-895-0028. Spacelink will include press kits, astronaut biographies, and even scanned versions of the crew logo for the mission.

If you don't ask - you don't get. There is plenty of public information available for each mission, including press kits, crew biographies, descriptions of the mission's primary payloads, etc. etc. The NASA education office should be able to provide lithos of the ham astronauts, and the official crew photo. There are also commercial firms where you can purchase patches and pins with the crew logo. In addition the JSC Amateur Radio Club, W5RRR, has SAREX patches available for sale for $5. The proceeds go towards the SAREX operating fund.

Lessons learned:

Based on several SAREX contacts here's some recommendations we'd like to pass on to everybody planning a contact:

Keep asking NASA education for materials - if you don't ask - you don't get. If you just send in a letter to NASA asking for materials it usually goes to a special 'fan mail' area where it's processed, and occasionally you'll get a reply. But if you call the education office and speak to a specialist and explain that you're involved with a SAREX contact there will be much more information available to you.

When you get your flight assignment get all of the information you can on that flight, its objectives, and other information. The Goddard Spaceflight Center's ham club WA3NAN coordinates the school contacts and they will be glad to get you the specifics on your particular mission.

If you don't get NASA Select in your school make arrangements to get it temporarily at least for your mission. NASA Select is a publicly available satellite transponder (Spacenet 2 69 degrees West channel 9) which provides full-time coverage of shuttle missions. In between missions important press conferences and other events are broadcast. Around two weeks before each mission there are a series of press conferences where the mission's details are explained. If you can get copies of these press conferences they are excellent teaching materials.

One of the best ways to get NASA Select is to contact a local dealer which sells satellite dishes. Convince the dealer it would be excellent publicity for the dealer to loan the school a dish for the duration of the mission, and promise that advertising literature will be made available to anybody interested. Alternately you may be able to convince a local cable company to provide the NASA Select signal.

If you can't get live NASA Select at the school arrange for it to be taped. Hopefully you can find somebody in your area who has access to NASA Select, possibly somebody who has a home satellite dish. If a satellite dish dealer isn't willing to loan the school a dish, perhaps it might be possible to make arrangements to videotape important activities at the dealership showroom? The best system is to videotape all of the press conferences and each day's mission highlights. If you can't get the schedule for the press conferences when they first air, the preflight press conferences are replayed on the day before the planned launch.

Contact all of the local press in your area ahead of time, about a week or so before the mission. Include newspapers, television stations, radio, etc. Tell them about your contact and when it's scheduled. Don't be shy to ask for the news director, or somebody you've seen on the air who does stories in your local area. It doesn't hurt to have a prewritten press release which you can fax or mail to each of the media. After launch call back with the planned time and date for the contact based on the actual mission elapsed time. While you're going to be extremely busy the day before the contact getting everything together it wouldn't hurt to call again with a reminder. Other good people to invite include local VIPs, like the school's principal, school board members, and even local politicians - anybody who would like to see how hams and teachers are working together to help educate students.

The day before the contact make arrangements for several different people to record each of the day's newscasts. Have at least two people record each of the local television stations to make sure you don't accidentally miss getting copies of yourself on the air. It wouldn't hurt to monitor CNN either. We've heard a rumor that our contact was covered on CNN, but still haven't been able to get a copy of it on tape.

Set up a computer running a satellite tracking program with accurate keps ahead of time. A large television set with NASA Select certainly helps. There's no guarantee, but if the shuttle's facing the right direction and the video channels are not in use for other purposes you may actually see video from the flight deck of the shuttle of the astronaut using the ham transceiver talking to you!

Make a list of the students names, in the order they will ask questions ahead of time. Also include the names of the hams and teachers involved and the astronaut's name and call sign. Give this to the press immediately after the contact. This will make it easier for the press to spell everybody's name correctly.

Make audio and high-quality video recordings of the contact. Start your recorders by the time the shuttle goes above the horizon. If possible hook up a tape recorder directly to your rig for the best quality audio. Alternately have the tape recorder on the same table as the radio, but not where its mike will pick up noise from fans or other interference.

Assign specific people, not directly involved with the contact, the responsibility of videotaping the event and taking photographs. Good choices would be other hams or teachers.

Make sure that your radio's controls are well protected to prevent somebody from accidentally shutting it off or turning it off frequency.

Do *NOT* let the press take over the contact. I remember one case where a local radio reporter wanted to be the one to ask the astronaut a question!

Most importantly - do NOT let the press bug the students until AFTER the contact is completed. The students will be extremely nervous, it's a high stress situation and you don't want the extra distractions. Afterwards make the students, teachers, and key hams available for interviews. Explain everything in simple terms - not ham jargon. A good rule of being interviewed on TV is to talk directly to the reporter as if he/she was an intelligent 12-year-old. Do not talk down to the audience, but explain everything in simple terms. For the Lyman contact one of the TV reports claimed that our computer with the satellite tracking program was connected directly to the Goddard Spaceflight Center!

Make sure you pick up copies of the next day's newspapers with your story. For our contact we were told that the "Orlando Sentinel" was going to put the story on the front page of the Local/State section, but it turned out that we appeared on the front page of the main section instead!

The SAREX team, especially the JSC and Goddard amateur radio clubs, and ARRL love to get feedback on how everything worked out, and what kind of coverage you received. Videotapes, audio tapes and newspaper clippings are always appreciated. But when you send copies of the audio tapes - please cue them to the right point just before the contact starts. The JSC club listened to our tape during their meeting, but only heard the preparations ahead of time because the tape was rewound!

One thing every school group would like to do is get the astronaut to visit the school after the mission has been completed. After each mission the astronauts perform many public relations functions, visiting the NASA benefits the local community by get students interested in science and education - there really is a purpose for all of those classes which students have been sleeping through. For the amateur radio community there are many tangible benefits. A SAREX contact is a high visibility project which shows how amateur radio benefits the public at large, something which will hopefully be remembered the next time some zoning board wants to restrict outdoor antennas! It also helps introduce teachers and students to amateur radio. On a more personal level participating in a SAREX contact is an excellent way for a ham to help out in your local community. If you've helped at least one student choose to stay in school instead of dropping out, or gave a nudge to a student interested in a technical career then it's worth the effort.

UoSAT-3: Lessons Learned from Three Years of Serving the Development Community

by
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The Pacsat Communications Experiment mission, sponsored by Volunteers In Technical Assistance, and which evolved into the UoSAT-3 spacecraft, was planned in the late 1980's following the success of the Digital Communications Experiment on UoSAT-2.

This paper reviews the original mission design, options considered, selected or discarded, and the results and lessons learned during the on-going non-amateur radio operations of the UoSAT-3 Pacsat Communications Experiment payload since its commissioning in early 1991.

Since the early 1980's, Volunteers In Technical Assistance (VITA), a private voluntary non-government organization based in metropolitan Washington, DC (USA), has spent substantial resources and time developing and testing easy-to-implement communications systems in the developing world. Although VITA's immediate goal was to solve communications problems with its own projects in the developing world, we felt that the entire development community could benefit from our work. Our success is due, in large part, to a common interest shared by Martin Sweeting and Jeff Ward, their co-workers at the University of Surrey and later Surrey Satellite Technology Ltd., and Harold Price, who devoted a great deal of their time and expertise towards helping us reach our goal.

While the telephone (both wired and wireless) and resultant facsimile machine have become ubiquitous in the developed world, the penetration of these devices in the developing world has been minuscule. According to the International Telecommunications Union, there are an average of almost 50 main telephone lines per 100 people in the "high income" world (Europe, USA) and only 0.8 per 100 people in the "low income" world, which is almost exclusively centered on Africa.

VITA's initial involvement with store-and-forward communications systems began in the early 1980's with the Digital Communications Experiment (DCE) payload on the University of Surrey (UK) UoSAT-2 satellite. A limited number of stations operating on frequencies in the amateur satellite service proved that non-government (particularly non-military) store-and-forward satellite communications could take place using relatively simple technology. While the DCE service operated on UoSAT-2's amateur radio frequencies, and all of the users held amateur radio licenses, they often times represented organizations that expressed interest in using this service on a regular basis should VITA continue work in the low earth orbiting (LEO) satellite field ("little" LEOs operating below 1 Ghz).

The success of the DCE project, along with this expressed interest, encouraged VITA to formalize its interest in LEOs into a three-phase program. The first phase was the *proof of concept*, and included the development and operation of a store-and forward communications payload on amateur radio frequencies. The second phase, still ongoing, is the *demonstration*, using a communications payload operating on non-amateur frequencies implementing protocols that are easy to implement and more closely resemble that which might be implemented in an operational system. The third, or *operational* phase of the program would integrate the lessons learned and into a fully operational satellite communications system.

Phase one was accomplished with the operation of the DCE on UoSAT-2, and effectively ended with the launch of the UoSAT-3 satellite in early 1990. The demonstration (or beta test) was be undertaken with the use of the Pacsat Communications Experiment on the Surrey Satellite Technology Ltd. UoSAT-3 satellite, launched in January 1990, and made available to VITA on non-amateur radio frequencies in March 1991.

With the PCE communications payload we had a communications system that out-performed that of the DCE. The protocols, developed by Jeff Ward and Harold Price, were formalized as the Pacsat Protocol Suite, and the communications hardware both on the satellite and ground stations was standardized. The system was designed to facilitate unattended operation, while permitting maximum flexibility in use.

This flexibility and ease of use resulted in a fundamental change in ground station operating philosophy. Where the DCE was serviced by gateways feeding other terrestrial networks (see table 1 for a list of gateway stations), the PCE allowed individuals and groups the opportunity to have their own station to contact the satellite directly. It was VITA's intent when we started this phase of the VITASAT program in 1990 -- before the massive growth and proliferation of computer networks -- that unique groups of users could be developed where the "home office" in the developed world would have its own station to talk directly to its fellow stations in the field. Our hope in this phase was to field enough stations in developing countries that would use the satellite regularly, but for a wider range of applications other than simply passing message traffic. With funding from the State of Virginia, we decided to develop our own hardware and software that we felt would be particularly sensitive to our user community overseas.

While our goals and objectives were intentionally broad, we learned many lessons quickly.

♦ *The user's perception affects his expectations and use of the system.*

One of the most significant problems we encountered was the user's perception of what exactly the system is. While VITA stressed that operations of the UoSAT-3 PCE were for demonstration purposes, users often perceived that since the service was up and running (in some form) when their station was installed, the system must be an operational one. This put an undue amount of pressure on all participants, including VITA and SSTL, to keep the system running when the time might have been better used to develop a better ground station, or in optimizing the protocols.

Although this changed over time, it was not uncommon for the program or mis/computer department at an organization's home office to decide that the VITA satellite link would solve all of their communications difficulties with their field offices. The decision to install a satellite station was made by the home office, often without consultation. The cost of the equipment and work to obtain a license was left to the field office. If there is no incentive to use the system in the field, and no directive or program that requires it, it will not be used. Generally speaking, field workers accept their communications predicament more so than their home office counterpart, and if at all possible, would rather not change procedures.

♦ *The overall effectiveness of a communications system is determined by its simplicity to the end user.*

Development work is difficult, and by its nature does not allow for much latitude with regard to staffing and budget. Therefore, operating the communications equipment, whether it is a satellite station, 2-way voice radio, or computer and fax machine is generally delegated to an individual or group of individuals who have many other assignments. This in itself is not bad, but it presents a unique challenge to the communications service provider. The system must be easy to install and operate, require little maintenance, and be capable of restarting itself after long periods of dormancy. While the former two items can possibly be overcome by sending a technician to install and train in the operation of the equipment, the later item becomes a significant issue. The system VITA developed, similar to that used in the amateur radio world, is based on a mains-powered desktop computer. The operator was required check and adjust the ground station's system clock, check that the satellite's orbital elements are current (or within 6 weeks) and create a table of tracking data on a near daily-basis. If the system clock has drifted, the radio will be mistuned, and the throughput will drop to the point where the system doesn't work. This requires a certain amount of time and attention to detail that is often hard to find. If the operator, as was the case in one instance, decides that he has no personal stake in the success of the system, and is overworked to begin with, the system will -- and in this case did -- fail.

♦ *Obtaining ground station licenses in developing countries is difficult.*

Because the PCE was designed as an experiment, the licensing in the United States was experimental, and easy to obtain. The frequencies allocated to VITA were in a band that was not yet allocated world-wide for this use. Licensing became a matter of haggling and horse-trading, and had to be done on a one-on-one basis. Reactions varied from countries where no fee was charged, to countries that charged an annual license fee based on the percentage of the external telecommunications services that might be used, to the one country which inspected the ground station twice to verify that the material being sent was truly of a scientific and technical nature. And where some countries would issuea license immediatly upon application, others would take as long as six months to review an application.

With the creation of the Non-Voice, Non-Geostationary Mobile Satellite Service along with a world-wide allocation at the 1992 World Administrative Radio Conference, licensing should be significantly more straightforward.

♦ *The amateur radio community, while a tremendous resource, does not accurately represent the interest and capabilities of users of the system in the developing world.*

The principals of this program at VITA are, to varying degrees, active amateur radio operators. Being an amateur radio operator is a double-edged sword. While understanding how the system operates on both a practical and theoretical level has been easy to come by, this had an impact in two different ways. It limited our perspective to available amateur radio equipment and software, and more unfortunately, distracted us from our goal of developing a easy-to-install and simple-to-use ground station and system.

We quickly learned that while our software was extremely flexible with respect to its capabilities, that flexibility did not necessarily translate itself to ease of use. We also learned that while the amateur radio equipment we were modifying for our service was quite powerful, it offered far more than we really needed.

VITA's reliance on amateur radio equipment made the ground station equipment package expensive, difficult to operate, and offered too great a variety of different pieces. While there are few complaints regarding the equipment, there were instances where the item selected offered far more capability -- and resultant complexity -- than necessary for our purpose. In most instances, the quality of the amateur radio equipment was equal to the quality of commercial radio equipment. However, while amateurs enjoy turning knobs and pushing buttons, these two simple acts can, and did, take VITA satellite stations off the air.

♦ *The lack of an overall network architecture results in a plateau in the number of station serviced.*

VITA's agreement with SSTL limited the number of stations to 35. While that number of stations was never attained (See table 2 for a listing of the stations installed by VITA), SatelLife, with whom the satellite has been shared since 1993, has installed a number of stations in similar footprints that have been a good model for a larger number of users.

Since the initial system was envisioned as being user-to-user, little thought or planning was given to the network architecture. It was assumed that remotely located users would send messages directly to recipients operating their own earth stations in either the developed or developing world. Without gateways, traffic would be limited to only those who own and operate ground stations. The VITA Ground Station Software (VGS) that was developed was based on that assumption.

When it became obvious, for a variety of reasons, that this scenario would not hold true, a decision was made to turn VITA's ground station in Virginia into a gateway station that would facilitate the movement of traffic between the satellite and FidoNet. The VGS software was modified to accommodate this added feature. The increased traffic load, however, has pointed out the need for a possible second gateway. The addition of this gateway and others would require a separate network management software package to be developed to manage the gateways.

♦ *The lack of a software design and review process made user software and user base development difficult.*

As previously mentioned, the communications system as conceived by VITA was based on the lessons learned from the operation of the DCE and, to a certain degree, based on the operating skills and habits of the amateur radio community. The requirements for VGS software, which was developed by Virginia Polytechnic University through a grants from the Virginia Center for Innovative Technology and VITA, were based on certain assumptions regarding the user's competence as part of a wish-list of features that VITA felt would make the software user-friendly. However, there was no written specification document that described the technical or user/network interface requirements. Nor was there a document describing how the system would evolve. This lack of documentation resulted in a significant slowing down of the software development.

Each version of the software delivered to VITA had to be tested for its technical capabilities and usability. Changes would be done as part of a single track, as modifications to the satellite communications code might affect the user interface portions and vice versa. Similarly, the requirement for non-english language and non-latin character support could not be accommodated.

♦ *The evolution and growth of related technologies is hard to predict.*

Of the assumptions VITA made regarding the user community, one that could not be predicted was the wild growth of the Internet and other electronic data networks. In the three years since the commissioning of the PCE payload, growth in terrestrial data networks has been so significant as to make the basic scenario of users in the developed world having their own individual earth stations unnecessary. Reverting back to the DCE strategy of having gateway hubs from existing networks to the satellite is more practical, and now relatively simple to implement.

These lessons and others have allowed us to come to some significant conclusions regarding the implementation of Phase Three, an operational satellite system.

♦ *The specific mission of the satellite must be determined before the satellite is designed and built.*

The goal of the VITASAT mission in its operational phase (phase three of the VITASAT program) is to efficiently and effectively carry electronic mail and other message data between developed and under-developed parts of the world using store-and-forward low-earth-orbit satellite technologies.

♦ *The architecture of the entire, completed network must be determined before any satellite is built.*

The VITASAT system will consist of one or more satellites that will directly serve individual users or user groups in remote areas, and users and user groups in the developed world via a network of strategically located gateway stations that can be accessed via existing electronic data networks.

♦ *The design of user hardware and software must be part of the system development, and must be designed for ease of installation, maintenance and use.*

A potential customers for this service are not purchasing hardware. Instead, they are purchasing a robust and reliable communications service that is easy to use, operates in a wide range of conditions and can be adapted to a diverse set of applications.

Antarctica	McMurdo Sound
Australia	Adelaide
New Zealand	Auckland
Nicaragua	Managua
Pakistan	Karachi
	Islamabad
South Africa	Johannesburg
United Kingdom	Surrey
United States	Arlington, VA
	Los Altos, CA
	Redondo Beach, CA
	Dallas, TX
	Phoenix, AZ

Table 1: Digital Communications Experiment Stations [13]

Antarctica	McMurdo Station
Australia	Melbourne
Canada	Prince George, BC
Djibouti	Djibouti
Ghana	Accra
Indonesia	Jakarta [2]
	Bandung
	Bali
	Sumbawa
Ireland	Letterkenny, Co. Donegal
	Dublin
Pakistan	Peshawar
Philippines	Leyte
	Los Banos
Sierra Leone	Freetown
Somalia	Garowe
Tanzania	Kibidula
Thailand	Bangkok
United States	Arlington, VA
	Albuquerque, NM
	Woods Hole, MA
Zaire	Kinshasa

Table 2: VITA-sponsored Pacsat Communications Experiment Stations [23]

A LONG-TERM EXAMINATION OF AO-16 AND UO-22 ACTIVITY LOGS

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ABSTRACT

Tabular and graphical summaries of broadcast and connected mode activity for AO-16 for the period October 1991 to August 1994 are given. Summaries are also given for UO-22 for the period July 1992 to August 1994. The summaries are derived from data sets that are at least 95 percent complete for AO-16 and 90 percent complete for UO-22. The missing data is primarily from the earlier dates and a detailed list of missing data is included. As a matter of secondary interest, a two-week activity period from LO-19 is compared with the same period for AO-16.

INTRODUCTION

For nearly five years, amateur radio satellite enthusiasts around the world, have been using the Microsat and/or UoSAT class digital communications satellites on a daily basis. Most users of satellites like AO-16 and UO-22 probably do not realize that they represent a distinctly different type of communications resource. A recent issue of *IEEE Spectrum* has recognized the development work done in the Amateur Satellite Service as pioneering [1].

Since the launch of AO-16 and UO-22, software in the spacecraft and at the ground station has continued to evolve and improve. The present implementation of the Pacsat Broadcast Protocol (PBP) allows automatic maintenance of the ground station's directory of files available from the satellite and provides an automated mechanism for downloading files. The directory maintenance and downloading functions are implemented using the AX.25 protocol in a connectionless mode. File uploading is done using AX.25 connected mode and the FTL0 Protocol. Since the operation of satellites like AO-16 and UO-22 has become very stable, it is important to document the level of activity taking place. This paper provides a summary of AO-16 activity logs from October 1991 to May 1994 and UO-22 logs from July 1992 to May 1994.

DATA COLLECTION

Since July 1992, this author, along with Richard Howlett (VK7ZBX), have been responsible for collecting the activity log files from AO-16 for use by command and operations personnel. Richard was also involved in the collection of log files prior to July 1992. The author started the collection of UO-22 log files at about the same

Table 1
Summary of 1991-92 Log Files Analyzed for AO-16 and UO-22

Log	AO-16 Days Complete	AO-16 Days Missing	UO-22 Days Complete	UO-22 Days Missing
AL9110	14	17		
AL9111	13	17		
AL9112	13	18		
AL9201	14	17		
AL9202	24	5		
AL9203	30	1		
AL9204	30	0		
AL9205	30	0		
AL9206	30	0		
AL9207	25	0	31	0
BL9207	--	--	31	0
AL9208	0	0	31	0
BL9208	--	--	31	0
AL9209	0	0	25	5
BL9209	--	--	25	5
AL9210	15	0	22	9
BL9210	15	0	23	8
AL9211	30	0	30	0
BL9211	30	0	30	0
AL9212	31	0	28	3
BL9212	31	0	27	4
Totals	375	75	334	34

Notes: PBP not running on AO-16 after 07-25-92.
New PBP running on AO-16 starting 10-16-92.
No BL files produced for AO-16 until new PBP installed.

time primarily to allow comparison of activity between a satellite with 1200 bps communications links (AO-16) and one with 9600 bps links (UO-22). Maintaining a complete collection of UO-22 log files is much more difficult than keeping a collection for AO-16 because the lifetime of the files on UO-22 is much shorter.

Tables 1 and 2 show the relative completeness of the AO-16 and UO-22 data sets. For AO-16, the 1991 and early 1992 data is only about fifty percent complete. Consequently, only averages are reported for these early AO-16 data. A break in the AO-16 data occurs between July and October 1992. Prior to July 26, 1992, AO-16 was running the initial version of the Pacsat Broadcast Protocol (PBP) which did not support automatic hole filling in directories and downloaded files. On October 16, 1992, AO-16 began running the new version of the PBP that does support automatic hole filling. Users of AO-16 will recall this as the time when it was necessary to switch from the "old" to the "new" version of the PB ground station computer program. The new version of the PBP had already been running in UO-22 for quite some time.

Table 2
Summary of 1993-94 Log Files Analyzed for AO-16 and UO-22

	AO-16		UO-22	
Log	Days Complete	Days Missing	Days Complete	Days Missing
AL9301	31	0	30	1
BL9301	31	0	30	1
AL9302	28	0	26	2
BL9302	28	0	27	1
AL9303	31	0	27	4
BL9303	31	0	22	9
AL9304	30	0	30	0
BL9304	30	0	30	0
AL9305	31	0	25	6
BL9305	31	0	25	6
AL9306	30	0	25	5
BL9306	30	0	26	4
AL9307	31	0	31	0
BL9307	31	0	31	0
AL9308	31	0	29	2
BL9308	31	0	26	5
AL9309	30	0	30	0
BL9309	30	0	30	0
AL9310	30	1	28	3
BL9310	31	0	29	2
AL9311	30	0	29	1
BL9311	30	0	28	2
AL9312	31	0	31	0
BL9312	31	0	31	0
AL9401	31	0	31	0
BL9401	31	0	31	0
AL9402	28	0	26	2
BL9402	28	0	26	2
AL9403	31	0	19	12
BL9403	31	0	19	12
AL9404	29	1	29	1
BL9404	29	1	29	1
AL9405	31	0	31	0
BL9405	31	0	31	0
AL9406	30	0	30	0
BL9406	30	0	30	0
AL9407	31	0	31	0
BL9407	31	0	31	0
AL9408	31	0	28	3
BL9408	31	0	28	3
Total	1,213	3	1,216	90

Tables 1 and 2 show many more days of missing data for UO-22 than AO-16. For both AO-16 and UO-22, two different methods of dealing with the missing data have been employed. In cases, where only one or two days were missing, the missing values were replaced with the average values of the nearby days. When many days were missing, the averages reported are computed using only the available days. As is the case with the early AO-16 data, only averages are reported for UO-22 due to the larger number of missing days.

AMSAT-OSCAR-16 (PACSAT-1)

The primary mission of AO-16 and LO-19 is that of providing a store-and-forward communications facility in low earth orbit. During approximately the first 2 1/2 years in orbit, the application software required to realize this mission, evolved through several distinct stages of development. For about the first year of operation, AO-16 and LO-19 provided what is called digipeater service. With this mode of operation, two stations within the satellite's footprint could connect to each other using the satellite as a relay. The amount of data transferred was, of course, limited by the time of co-visibility and the typing speed and proficiency of the ground station operators.

In late 1990, testing of the first version of the file server system began. This system allowed a suitably-equipped ground station to establish a connection with the satellite and upload and download files as well as download directories of files stored in the satellite's RAM disk. In addition to the connected mode of operation, the file server system also supported a broadcast mode of operation. With broadcast mode, a ground station could request the transmission of a specific file without establishing a dedicated connection.

The important difference in the two modes is that with connected mode, data transmitted on the downlink can only be used by the station establishing the connection, even though the downlink data is being heard by all stations in the satellite's footprint. On the other hand, downlink data resulting from a broadcast mode request can be utilized by any station in the footprint needing the information. Consequently, if several stations in the footprint need a particular file stored in the satellite, one broadcast request can potentially satisfy the requirements of all three stations.

Another advantage of the broadcast mode is that, while AX.25 protocol used for connected mode has a sliding window size limit of 7, the broadcast mode has an infinite window. Each packet or group of packets need not be acknowledged, even by the original requestor. As a result, no uplink load is generated by the broadcast download which can then run at full downlink speed.

Even though the first implementation of the broadcast mode provided the best method of operation in terms of potential downlink data reusability, there were still some improvements required before use of the broadcast mode would supplant connected mode, especially for directory data downloading.

After nearly a year of uninterrupted operation, AO-16 suffered an onboard software crash on July 26, 1992. The crash was caused by the interaction between the spacecraft software and a user-written ground station program. Of course, if there was a single "factory supplied" program, these types of software failures would be much less likely. However, a unique aspect of the Amateur Satellite Service is to allow users, who are so inclined, to write their own ground station software.

Table 3
Connected Mode Statistics for AO-16 While Running the Initial Version of the File Server System

	1991 Oct to Dec	1992 up to 07-25
Average Byte Count/Day		
Downloads	71,982	82,067
Uploads	48,281	27,893
Directories	256,092	139,273
Average Byte Count/Month		
Downloads	959,764	2,157,199
Uploads	643,740	733,187
Directories	3,414,557	3,660,882

AO-16 was returned to operation quickly but the file server system was not returned to service again until October 16, 1992. The intervening time was used to run engineering tests and ready a new version of the file server software with enhanced broadcast mode capabilities. The most important of these new features were the transmission of directory information in broadcast mode and the capability of the satellite and ground station software to cooperate to automatically fill holes in broadcast files and directories. The software implementing the new broadcast mode facilities has been in continuous operation since it was started in October 1992. With the exception of file uploading, almost all access to the store-and-forward facilities is by the broadcast mode. Although the timeline has been slightly different, a similar progression of software installation has occurred on LO-19.

Table 3 gives AO-16 connected mode statistics for October 1991 thru July 25, 1992--the time of the software crash. The averages for October 1991 thru February 1992 are computed from data sets containing about 15 days worth of data per month. From March 1992 to the present date, the data sets are virtually complete with only about three or four days worth of logs missing for the 2 1/2-year period. Note the amount of directory and download activity for 1992 and recall that in connected mode operation, none of this downlink traffic could be used by any station other than the one establishing the connection. Table 4 shows connected mode statistics after the installation of the enhanced broadcast mode support. Notice that file and directory downloading is decreasing while file uploading now constitutes the majority of connected mode traffic as desired.

Table 5 gives the broadcast mode statistics starting at the time of the new software installation. Note that the total transmitted byte count for 1993 is about 650 Mbytes. At 1200 bps, about 4.75 Gbytes could be transmitted in a year. Consequently, 650 Mbytes represents about 15 percent downlink utilization excluding HDLC overhead, telemetry transmissions, and other types of downlink data. Of course, much of the time AO-16's footprint does not include any

Table 4
Connected Mode Statistics for AO-16 Since Installation of the Current Version of the File Server System

	1992 from 10-17	1993 complete	1994 thru 08-31
Average Byte Count/Day			
Downloads	14,170	2,387	351
Uploads	26,932	18,232	19,235
Directories	2,811	1,003	696
Average Byte Count/Month			
Downloads	372,647	72,594	10,673
Uploads	682,287	554,559	584,261
Directories	71,211	30,497	21,141
Total Byte Count[1]			
Downloads	1,117,940	871,127	85,382
Uploads	2,046,861	6,654,712	4,674,089
Directories	213,633	365,965	169,125

[1]Note that 1992 and 1994 totals are not for an entire year.

populated areas, so 100 percent utilization is not possible. On the other hand, effective utilization would be higher than 15 percent if one could estimate the data reuse factor. Remember that many stations can be utilizing the broadcast mode data as a result of another station's request for a needed file or directory. If the monthly averages for the first eight months of 1994 are used to project a yearly total, the total byte count would be about the same as 1993. This will be interesting to watch because it will mean that the usage of AO-16 has remained fairly level in spite of several new digital store-and-forward amateur radio satellites being launched since 1992.

Finally, Figs. 1 thru 4 give a month-by-month account of AO-16 usage for 1993 and Figs. 5 thru 8 show the same summaries for 1994. In the broadcast mode charts (Figs. 1, 2, 5, and 6), the left-hand bar of the pair is the transaction count and is read on the left-hand Y axis while the right-hand bar is the byte count and is read on the right-hand Y axis. Figs. 1 and 2 for 1993 clearly show a decrease in activity in the summer months while a corresponding trend is not obvious for 1994. Figs. 3, 4, 7, and 8 show that almost all connected-mode activity results from file uploading which is exactly what is desired.

UOSAT-OSCAR-22 (UOSAT-5)

Tables 6 and 7 for UO-22 correspond to Tables 4 and 5 for AO-16. Table 6 gives the connected mode statistics, while Table 7 shows the broadcast mode statistics. While the averages shown in these tables should be reasonably accurate, please remember the totals are understated due to the missing log files listed in Tables 1 and 2. An

Table 5
Broadcast Mode Statistics for AO-16 Since Installation of the Current Version of the File Server System

	1992 from 10-17	1993 complete	1994 thru 08-31
Average Transactions/Day			
Start+Fill Requests	794	646	699
Directory Requests	259	268	365
Average Byte Count/Day			
File Bytes	1,860,244	1,260,069	1,188,418
Directory Bytes	419,080	501,573	655,863
Average Transactions/Month			
Start+Fill Requests	20,104	19,649	21,232
Directory Requests	6,551	8,142	11,087
Average Byte Count/Month			
File Bytes	47,126,172	38,327,111	36,869,661
Directory Bytes	10,616,681	15,256,183	19,921,848
Total Transactions[1]			
Start+Fill Requests	60,313	235,792	169,857
Directory Requests	19,653	97,698	88,697
Total Byte Count[1]			
File Bytes	141,378,516	459,925,333	288,785,550
Directory Bytes	31,850,043	183,074,192	159,374,780

[1]Note that 1992 and 1994 totals are not for an entire year.

observation about the total byte count for 1993 is that it is within 10 percent of being 8 times the total byte count for AO-16. This is interesting because the UO-22's downlink bit rate is 8 times that of AO-16 (9600 bps vs. 1200 bps). It will be interesting to see if the same relationship appears when the 1994 data is complete.

Figs. 9 thru 14 summarize UO-22 (UoSAT-5) activity from July 1992 to May 1994. As was mentioned earlier, UO-22 data were collected to allow a comparison between AO-16 operating with 1200 bps links and UO-22 operating with 9600 bps links. Readers who are satellite operators will realize that the orbits of AO-16 and UO-22 are similar enough that any differences noted will primarily be a result of the greater capacity of the communication links and the number of active users.

Unlike AO-16, whose activity level has remained fairly constant, UO-22 activity has decreased slowly. Fig. 9 shows a daily average broadcast mode transaction count of about 9,000 and daily average byte count of around 17 Mbytes. By 1994, shown in Fig. 13, the average daily activity has levelled out at about 4,000 transactions and 12 Mbytes. One possible and likely explanation for this is the availability of KITSAT-OSCAR-23 (KO-23) launched in 1992 and KITSAT-OSCAR-25 (KO-25) launched in 1993. Both KO-23 and KO-25 have 9600 bps

Table 6
Connected Mode Statistics for UO-22

	1992 from 07-01	1993 complete	1994 thru 08-31
Average Byte Count/Day			
Downloads	121,082	5,325	276
Uploads	704,447	810,302	921,622
Directories	116,301	34,952	1,526
Average Byte Count/Month			
Downloads	586,779	151,758	7,756
Uploads	19,607,107	23,093,598	25,920,626
Directories	3,237,047	996,143	42,916
Total Byte Count[1]			
Downloads	3,520,676	1,821,098	62,048
Uploads	117,642,643	277,123,180	207,365,009
Directories	19,422,284	11,953,719	343,326

[1]See missing data report in Tables 1 and 2.

links and use the same PBP has AO-16 and UO-22. Daily averages for connected mode transactions are shown in Figs. 10, 12, and 14. Fig. 14 depicts a similar situation as Fig. 8 for AO-16 in that connected mode directory requests and downloads have all but disappeared.

LUSAT-OSCAR-19 (LUSAT-1)

As a final matter of interest, a very cursory examination of LO-19 activity logs was made. Since long-term records have not been kept for LO-19, data collection was started in April 1994. Unfortunately, after nearly 1,000 days of uninterrupted operation, LO-19 suffered a system failure of unknown origin on May 15, 1994. As a result, very little data was available for analysis. Since LO-19 had been in stable operation for quite some time, it was decided to compare the period of May 1 to 14, 1994 (the two weeks immediately preceding the failure) to the same period for AO-16. The two daily charts for AO-16 and LO-19 can be seen in Figs. 15 and 16 respectively. While care should be exercised when drawing conclusions from such a small data set, it appears that LO-19 handles about a third less traffic than AO-16.

SUMMARY

The results of a long-term analysis of AO-16 and UO-22 activity logs has been presented. The analysis has shown that AO-16 handled an average of 27,000 transactions per month resulting in the transmission of an average of 50 Mbytes of user data per month in 1993. If the trend set during the first eight months of 1994 continues, AO-16 will

Table 7
Broadcast Mode Statistics for UO-22

	1992 from 07-01	1993 complete	1994 thru 08-31
Average Transactions/Day			
Start+Fill Requests	6,834	3,870	2,369
Directory Requests	2,462	2,198	1,670
Average Byte Count/Day			
File Bytes	16,684,801	8,980,556	6,262,349
Directory Bytes	6,329,034	7,380,378	7,257,014
Average Transactions/Month			
Start+Fill Requests	190,216	110,286	66,625
Directory Requests	68,535	62,650	46,965
Average Byte Count/Month			
File Bytes	464,378,215	255,945,846	176,128,562
Directory Bytes	176,158,117	210,340,783	204,103,505
Total Transactions[1]			
Start+Fill Requests	1,141,294	1,323,436	533,003
Directory Requests	411,209	751,798	375,720
Total Byte Count[1]			
File Bytes	2,786,269,290	3,071,350,151	1,409,028,497
Directory Bytes	1,056,948,703	2,524,089,399	1,632,828,040

[1]See missing data report in Tables 1 and 2.

handle a slightly larger amount of traffic by the close of the year. In contrast to AO-16, UO-22 with its 9600 bps links, was found to average about 175,000 transactions per month resulting in the transmission of an average of 466 Mbytes per month in 1993. Based on the first eight months of 1994 logs, UO-22 will handle slightly less traffic in 1994 than in 1993.

During the analysis of the data summarized in this paper, a number of items for future investigation were identified. First, as work intensive as it might be, it would be interesting to compare activity on UO-22 with KO-23 and KO-25 and to do a long-term comparison of AO-16 and LO-19. It would also be informative to characterize the geographical distribution of users on AO-16, LO-19, UO-22, KO-23, and KO-25. Finally, the amount of activity attributed to terrestrial packet network gateway stations could be studied. Of these and other possibilities for future work, a detailed and long-term analysis of user characteristics seems to be the most interesting.

REFERENCES

[1] Trudy E. Bell, "Technology 1994: Telecommunications," *IEEE Spectrum*, vol. 31, no. 1, January 1994, pp. 22-25.

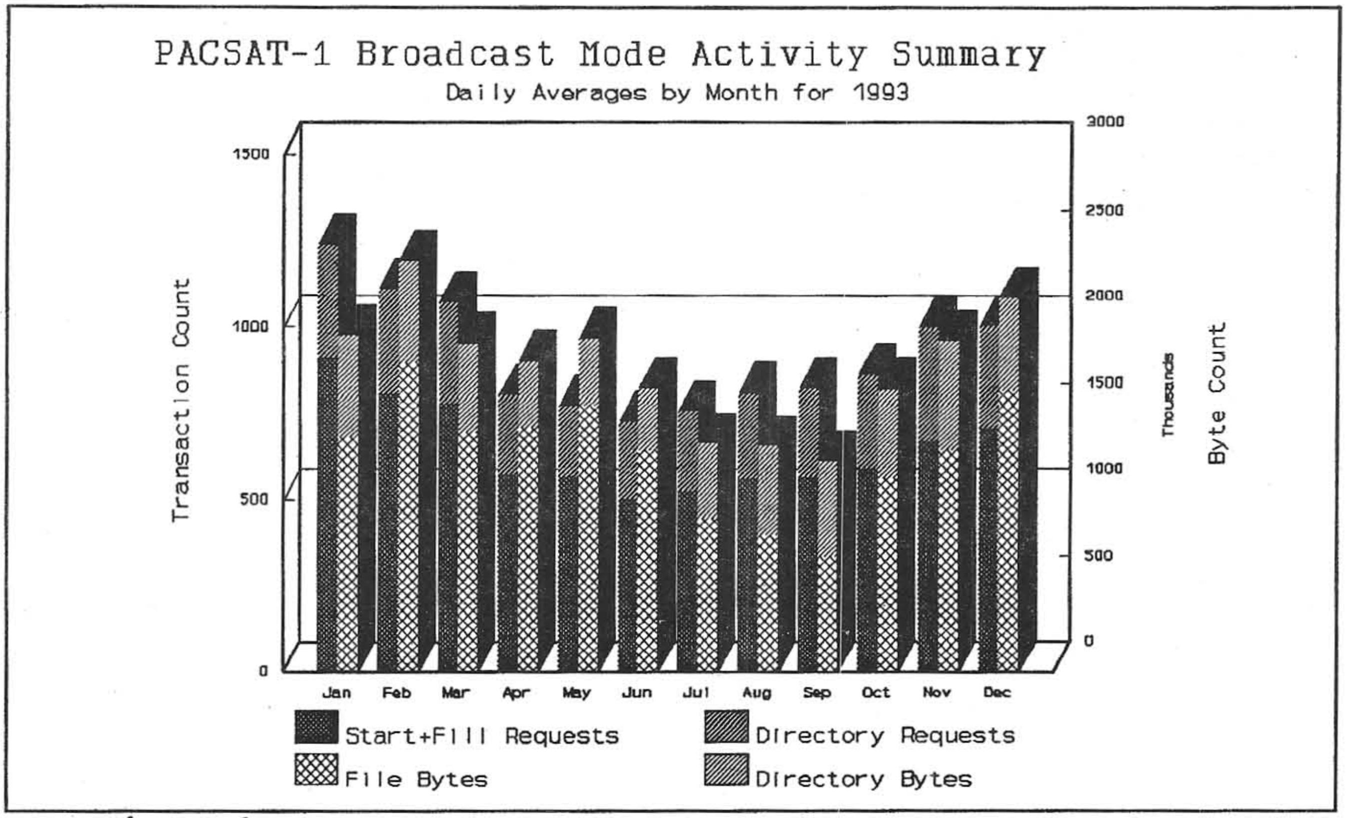
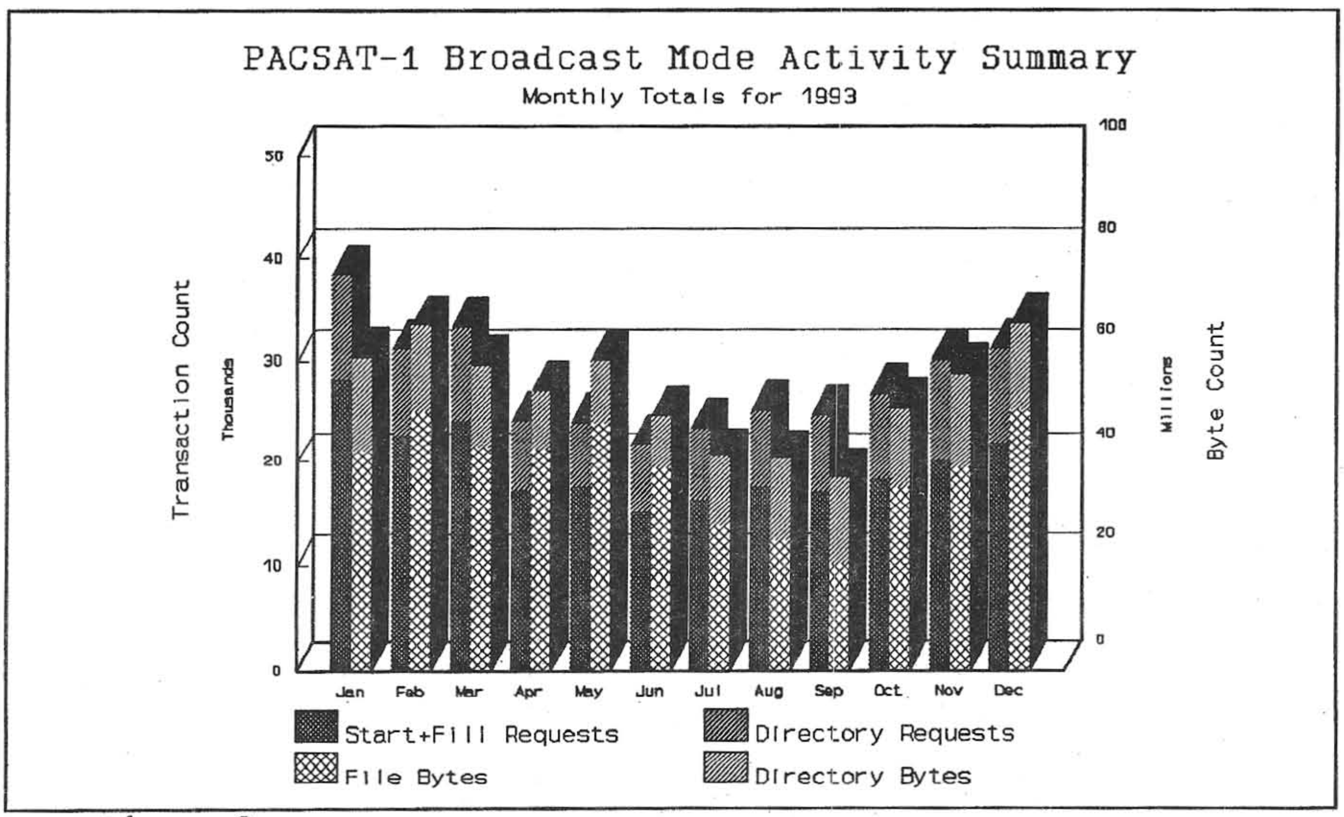


Figure 1.



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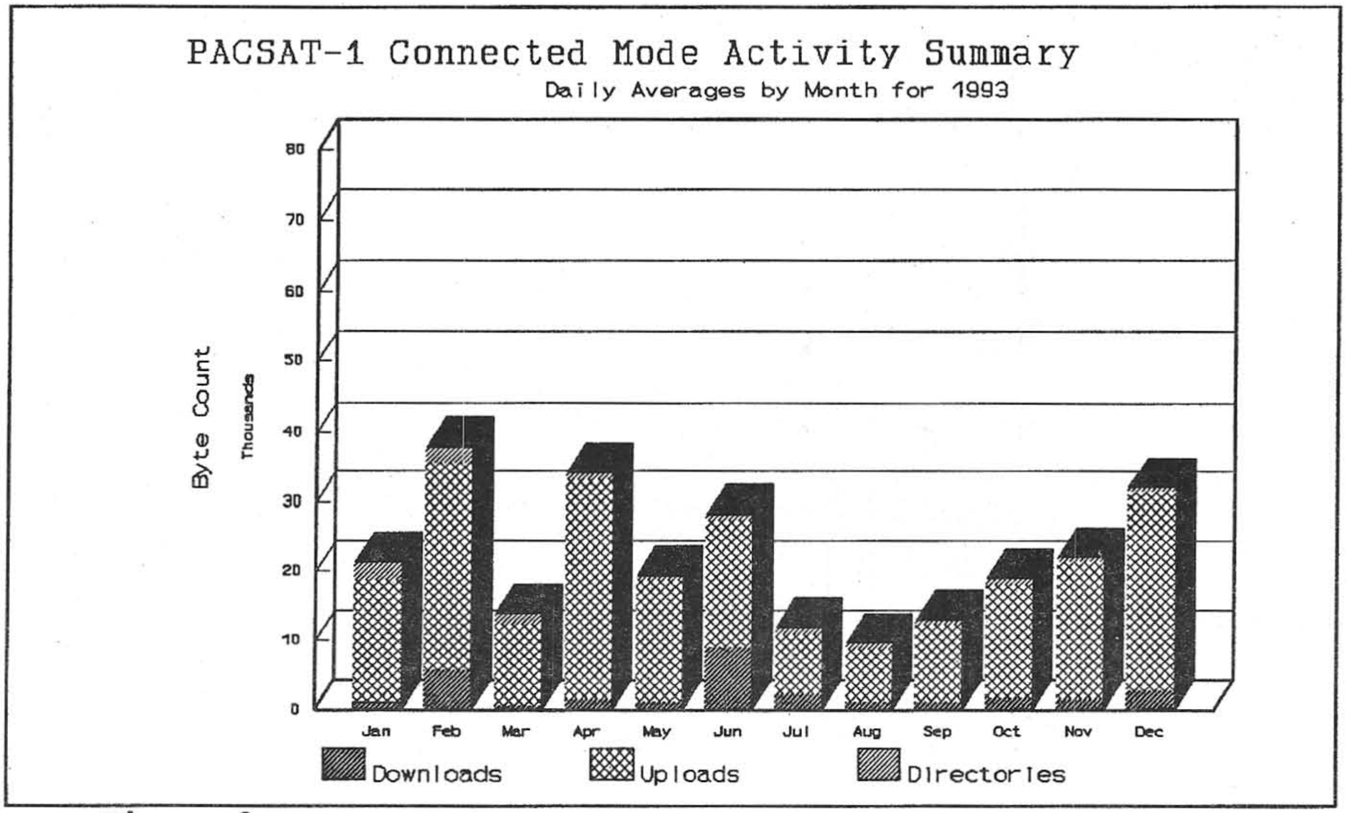

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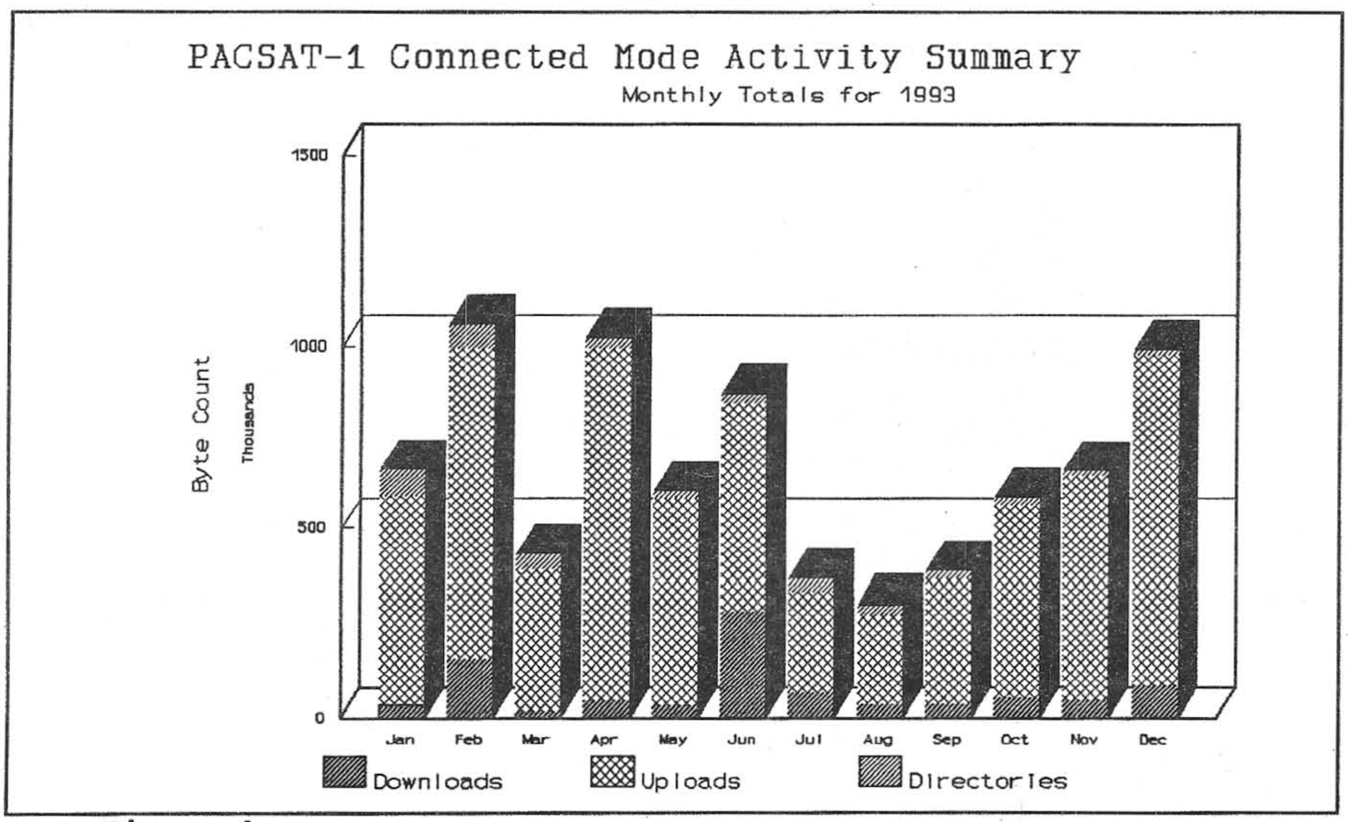

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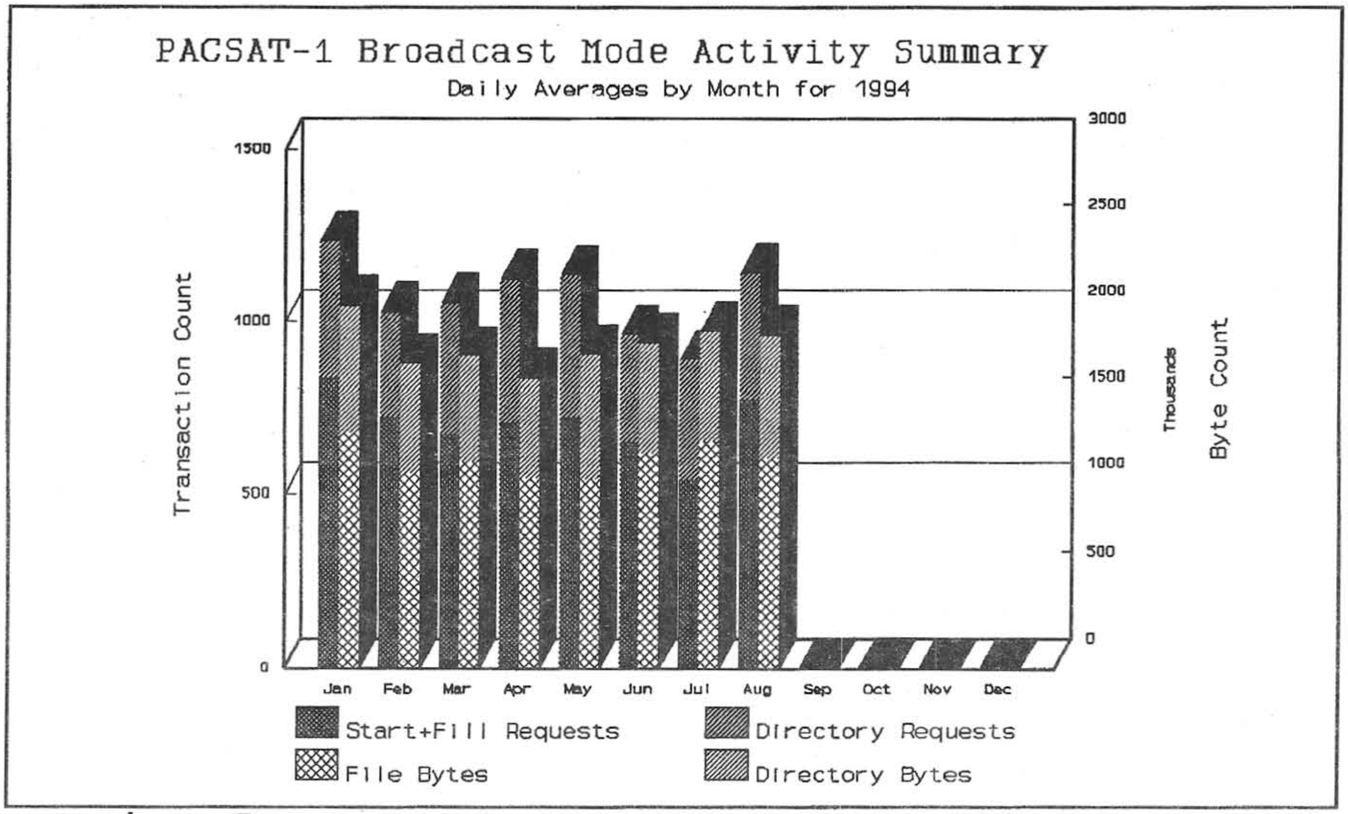

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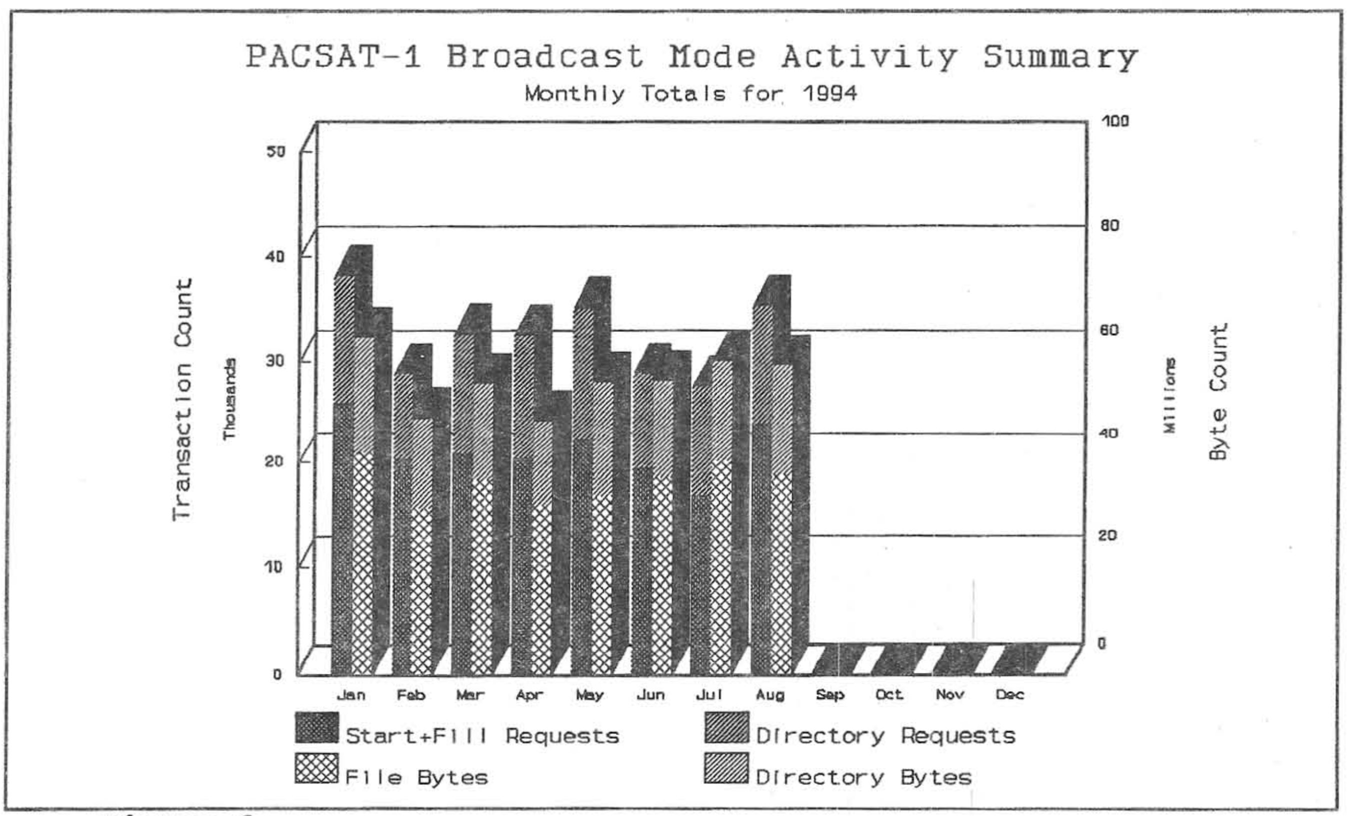

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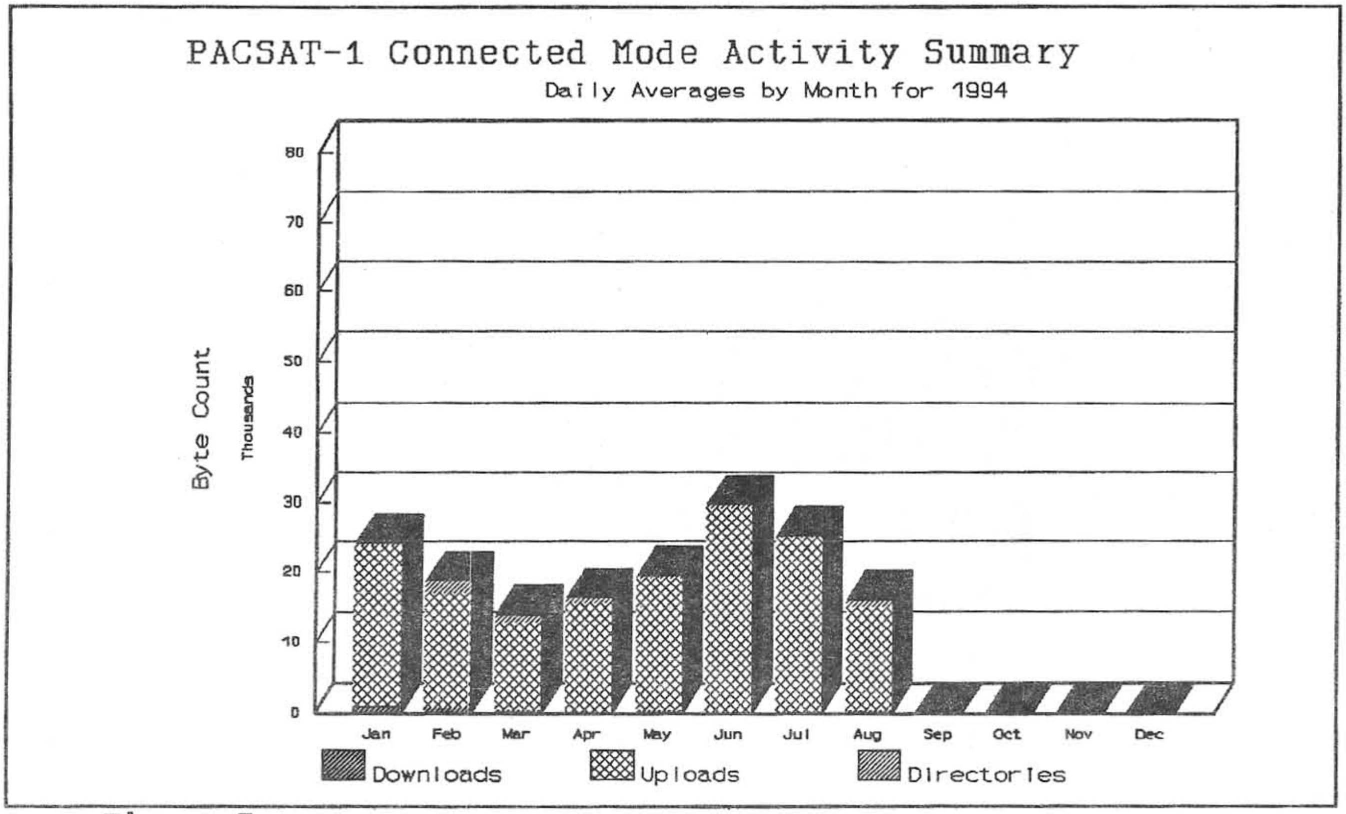


Figure 7.

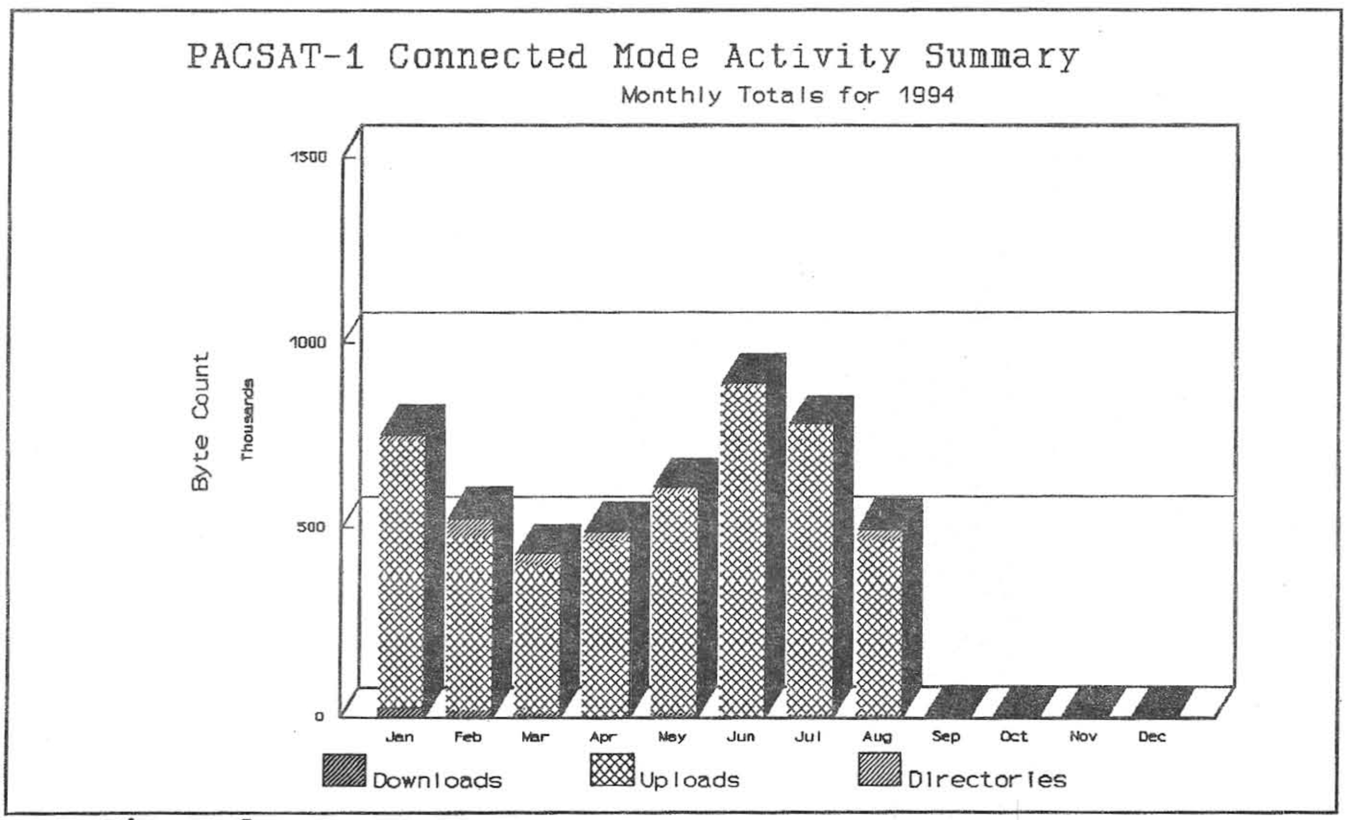


Figure 8.

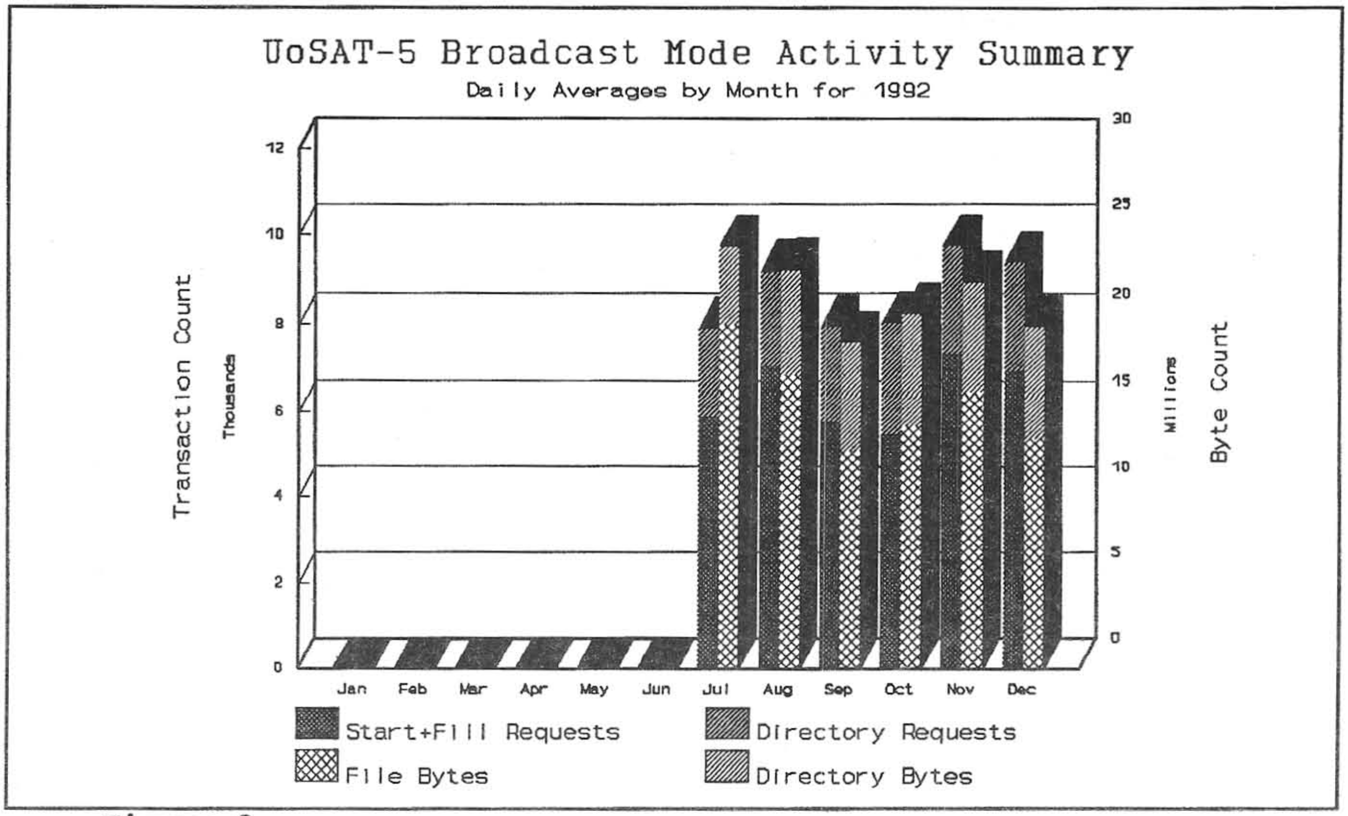


Figure 9.

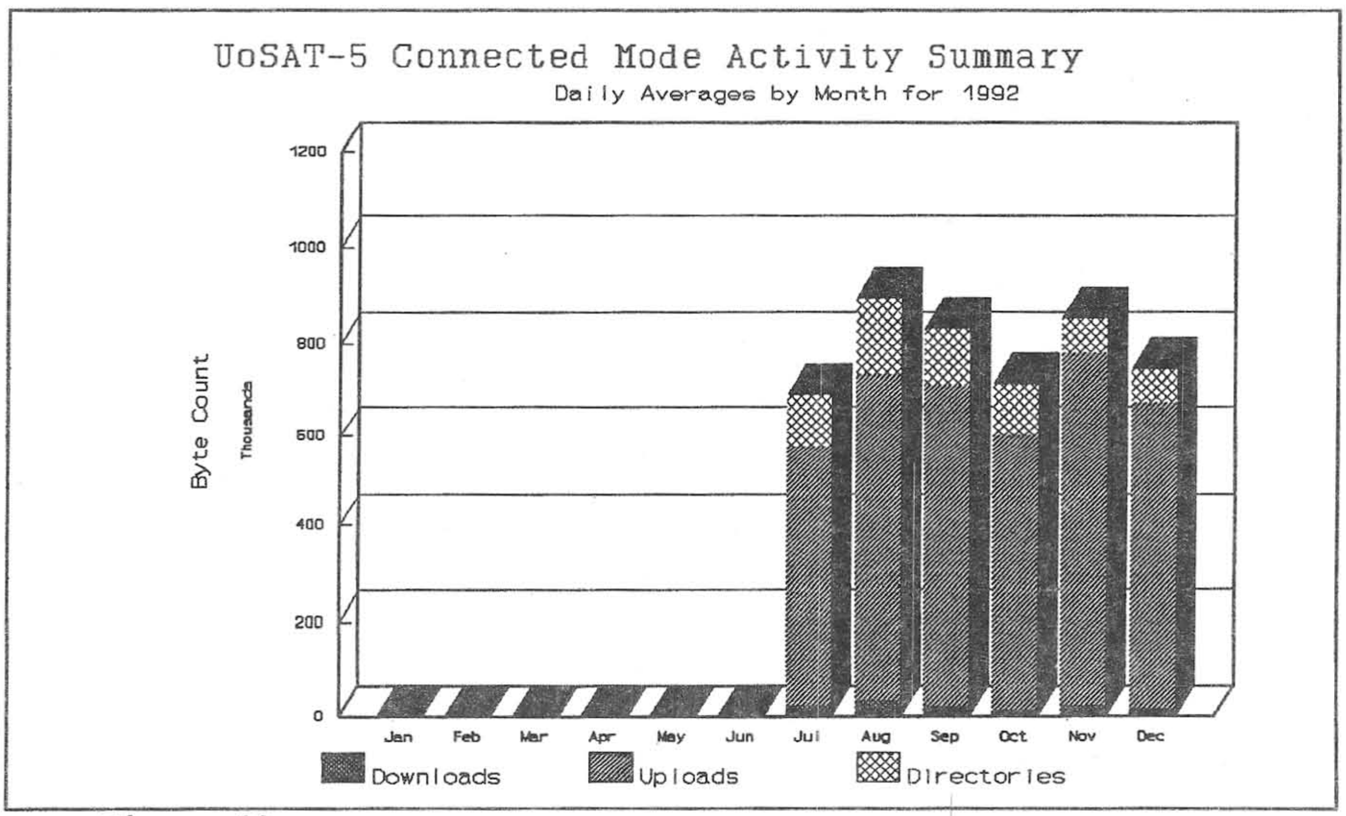
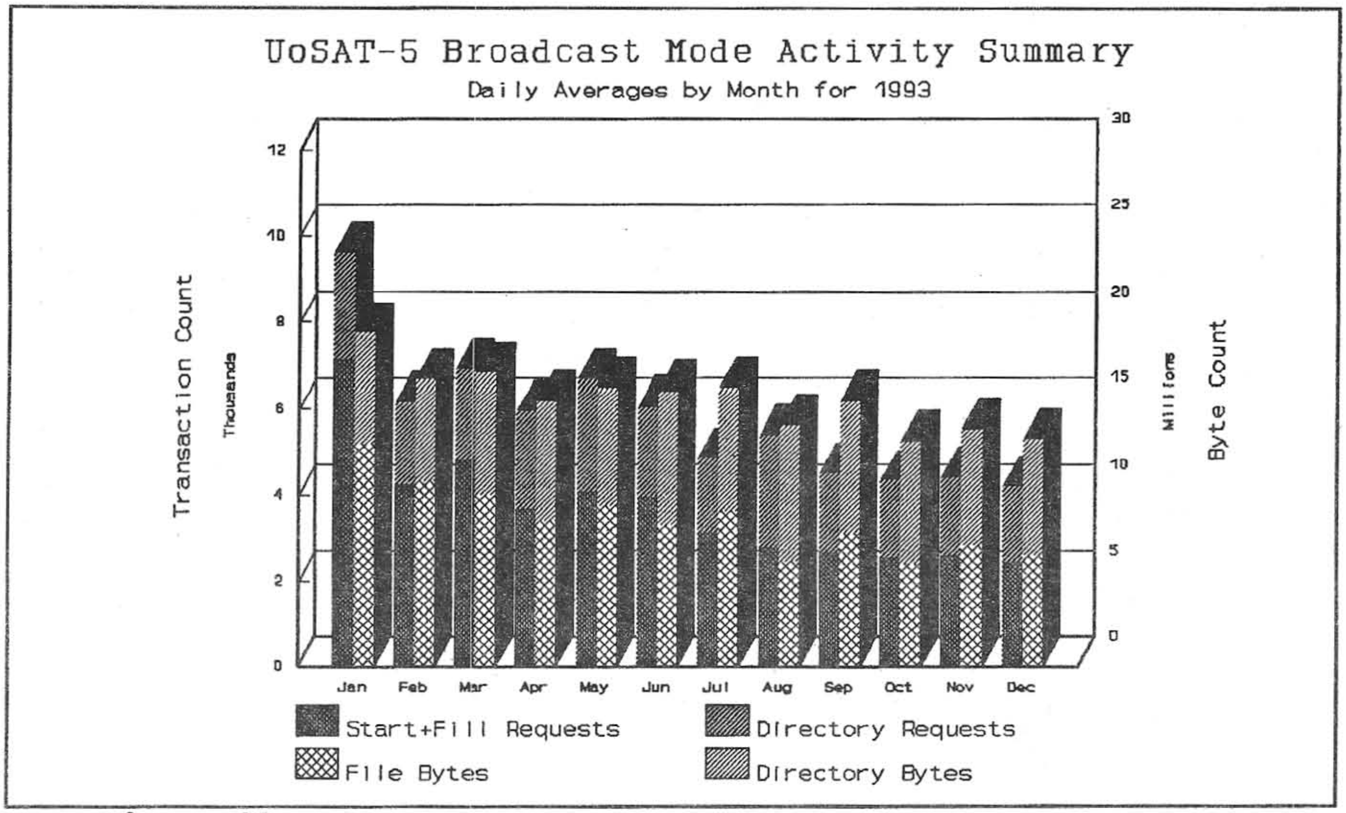


Figure 10.



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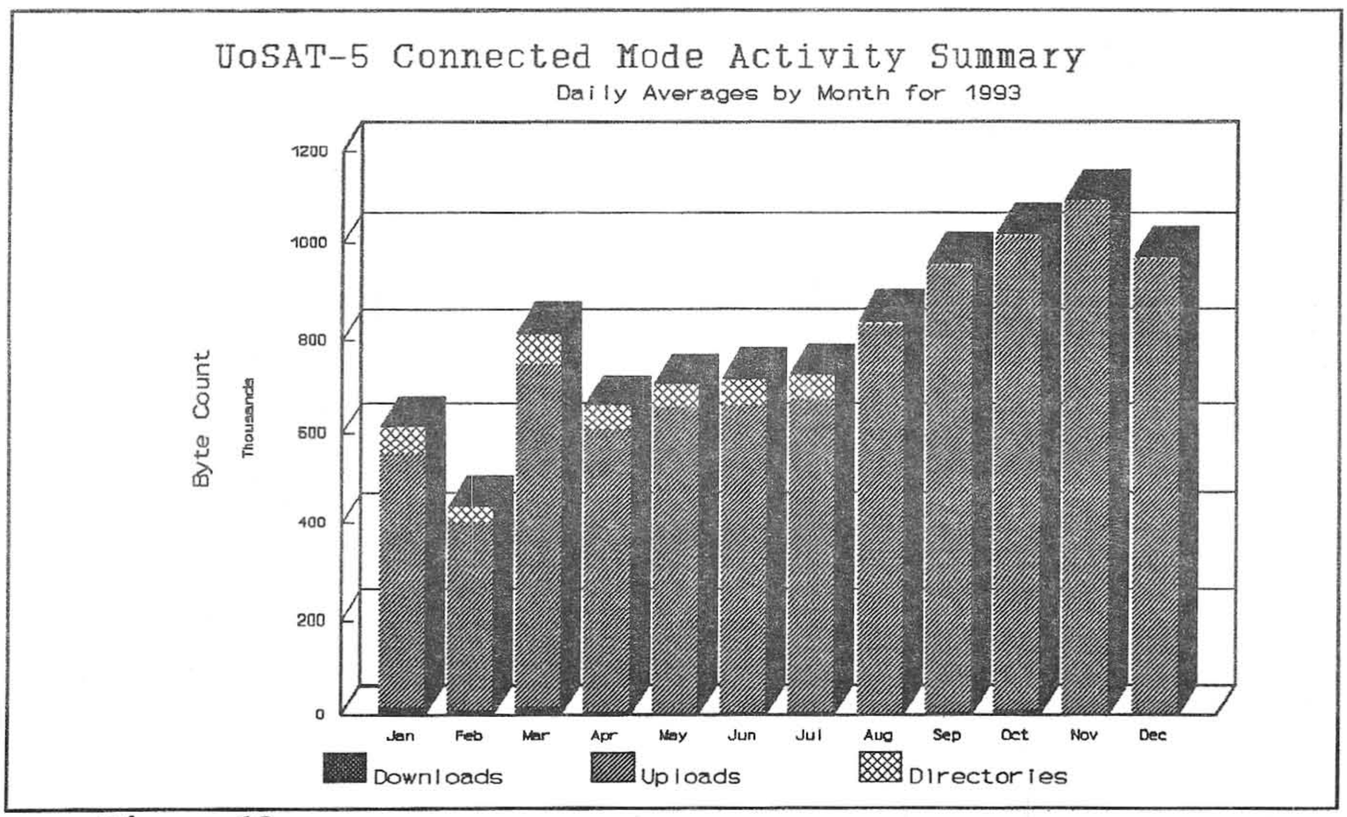

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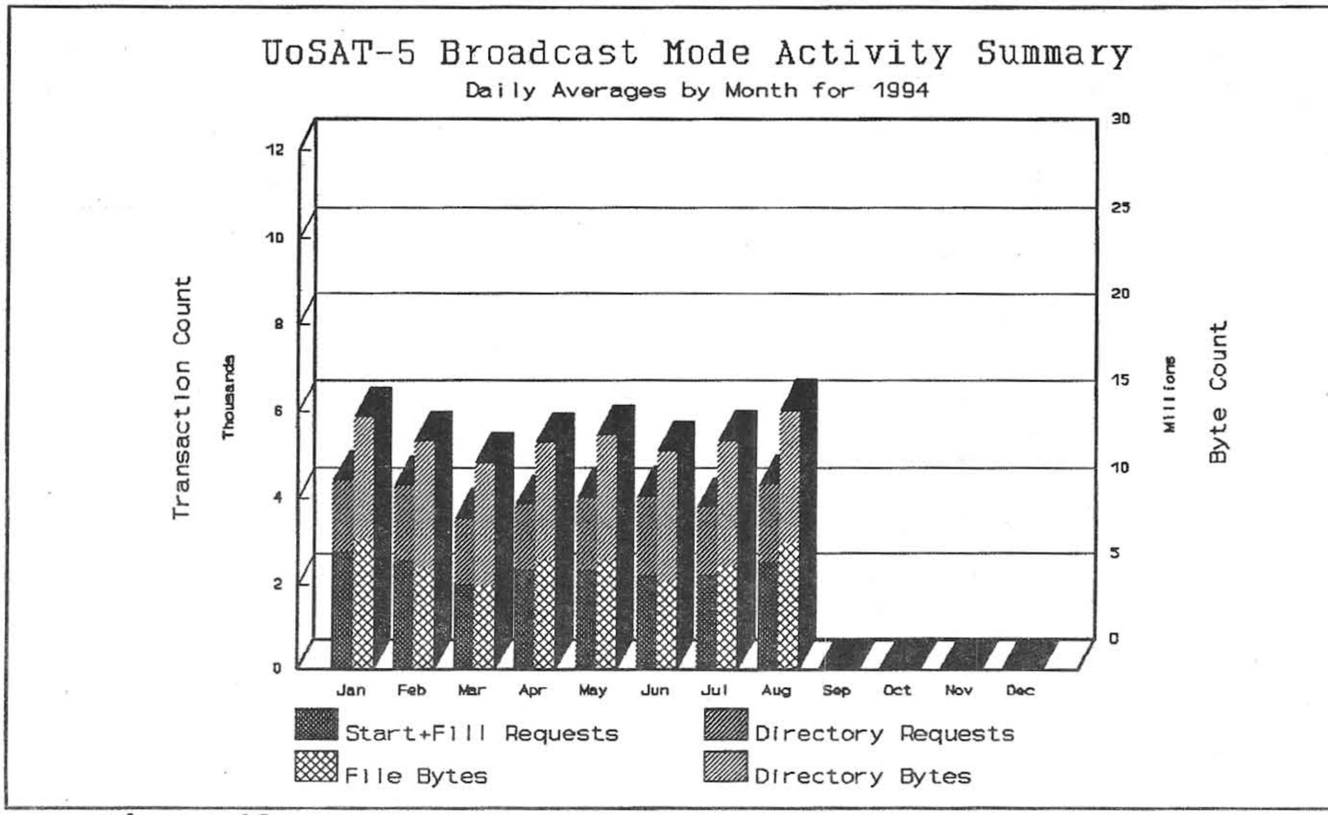

Figure 13.

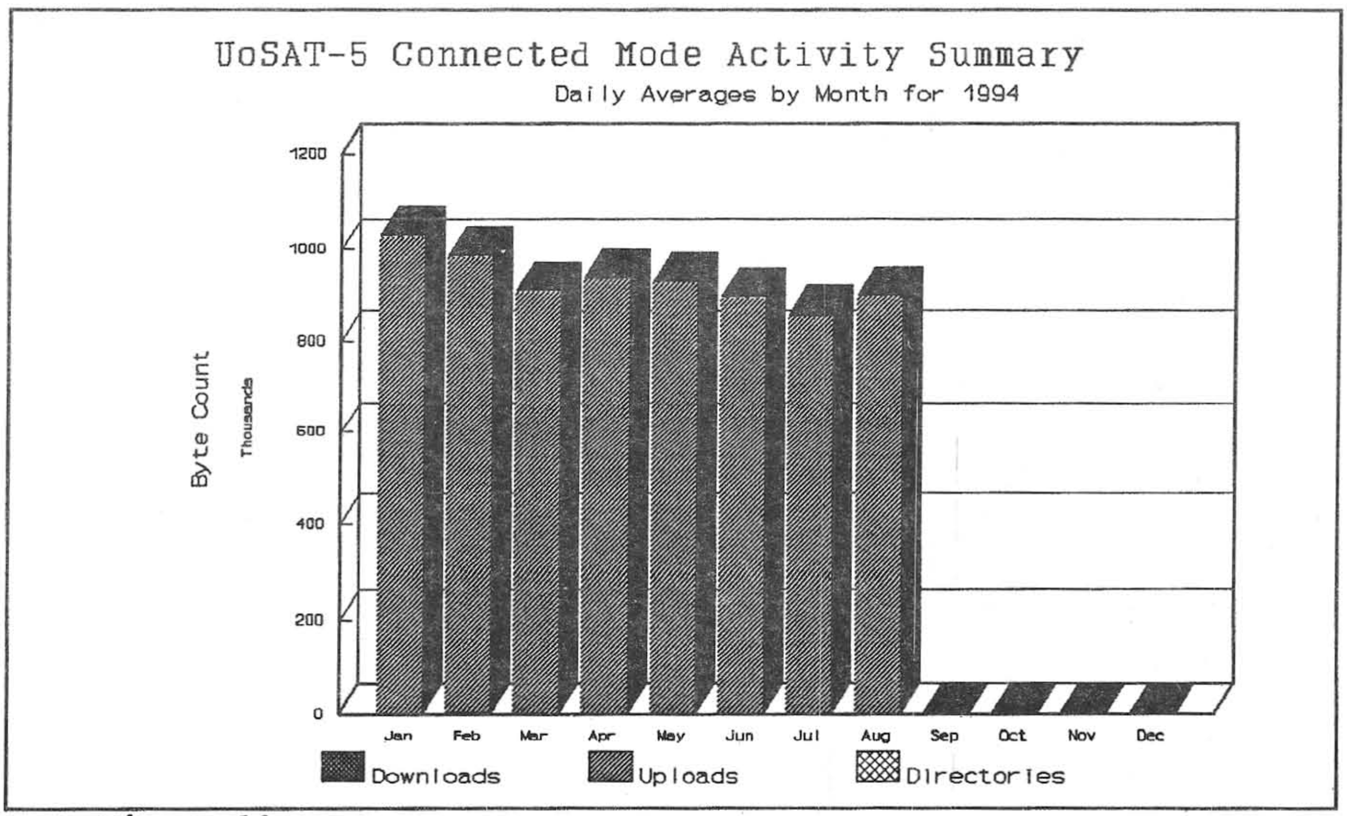

Figure 14.

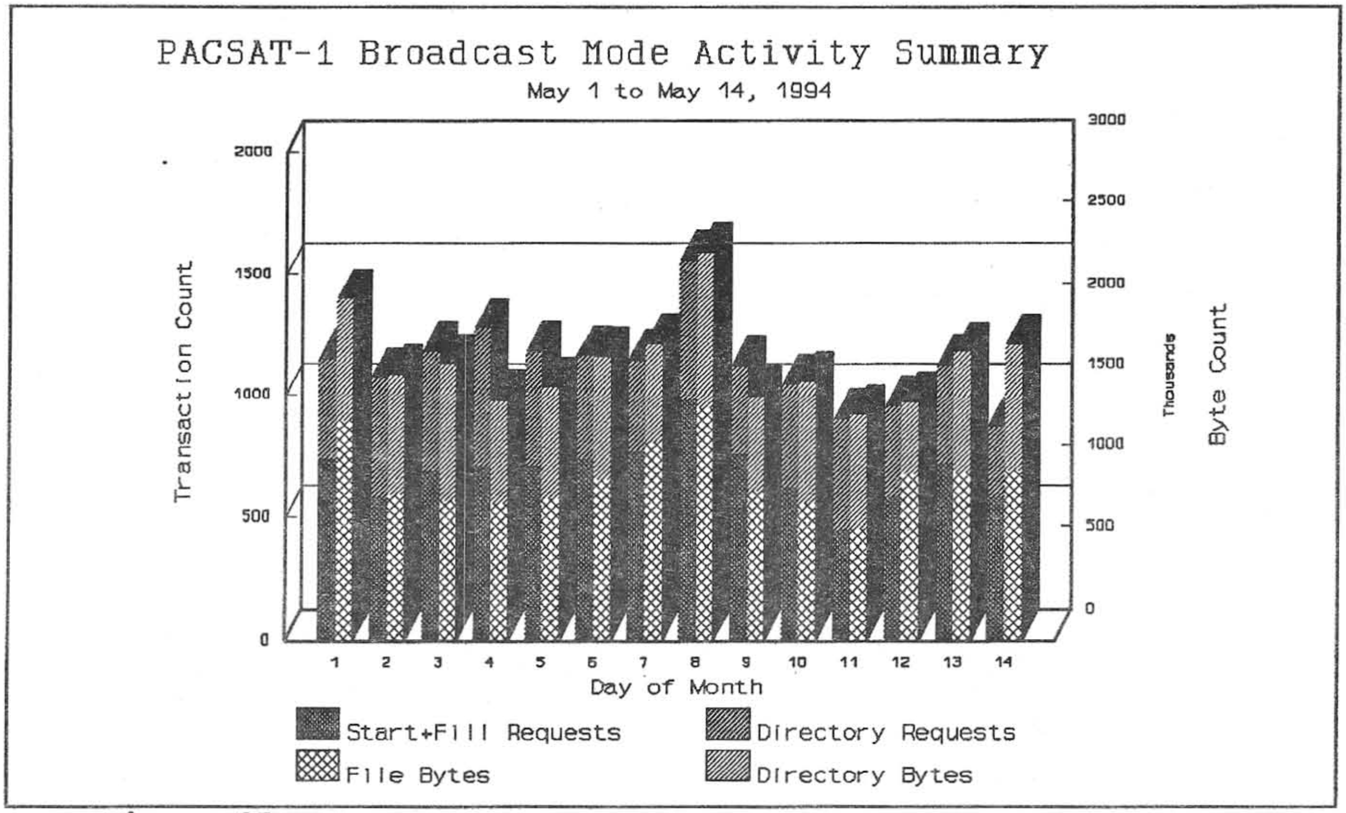

Figure 15.

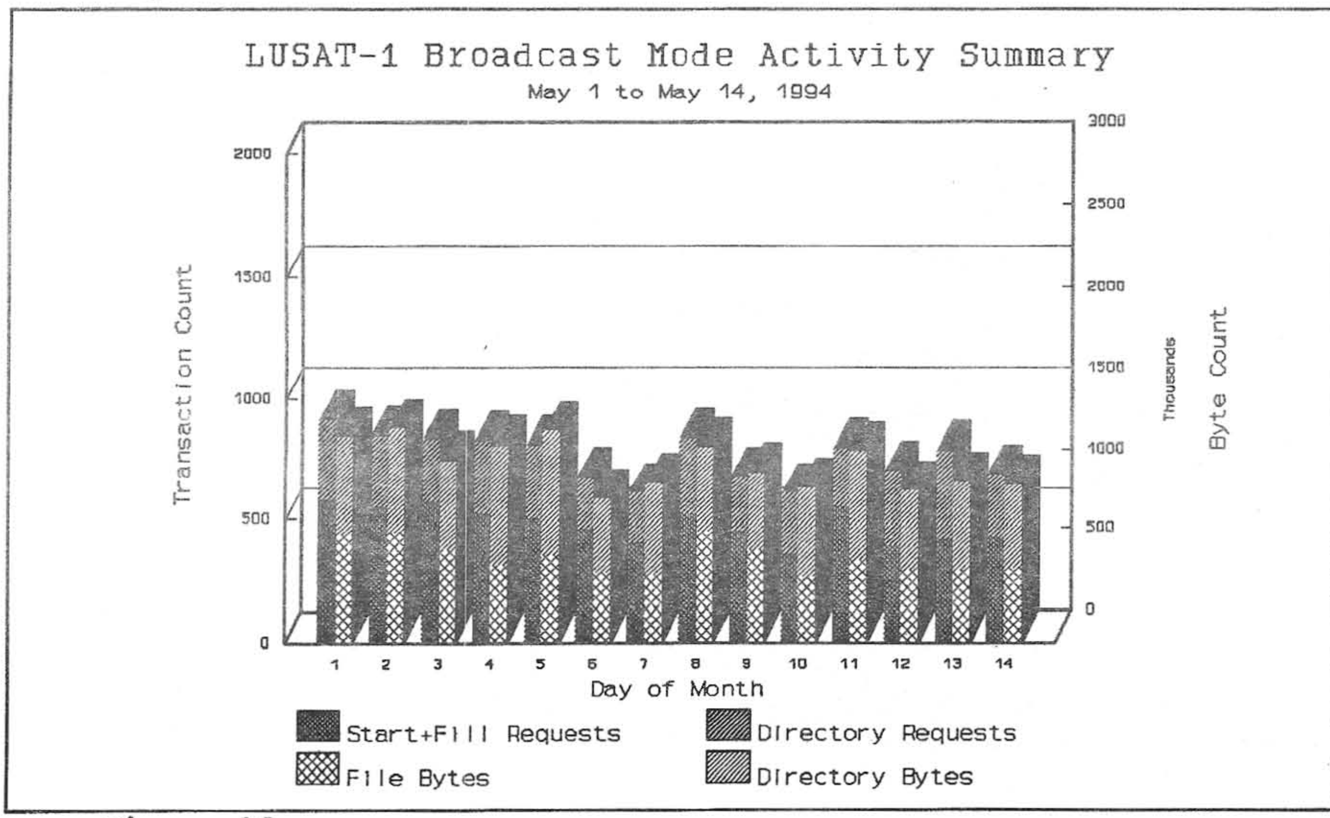

Figure 16.

UNAMSAT-1 : AN OPERATIONS GUIDE.

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INTRODUCTION

UNAMSAT-1 is a Microsat spacecraft sponsored and built by the Universidad Nacional Autonoma de Mexico (UNAM). Based on the highly successful Microsat bus configuration, UNAMSAT-1 is planned for launch aboard a Russian booster in September 1994. Recall that all microsats consist of common transmitter, receiver, computer and power conditioning modules. These provide for the orbiting store-and-forward digital payload activities we have become accustomed to. In addition, each spacecraft contains a unique TSFR (This Space For Rent) module. The unique and truly novel experiment to be carried aboard UNAMSAT-1 is an instrument designed to detect and characterize meteor trails in the outer atmosphere. While awaiting an invitation for vehicle integration, the development team has been busy completing this TSFR payload.

The UNAMSAT-1 team conducted a calibration of the TSFR module during the Perseids meteor shower at the beginning of August. While doing this, we realized that it would be useful to advance as complete a guide as possible to all future users of UNAMSAT-1.

STATUS UPDATE

In the last few weeks, UNAMSAT-1 has been going through a complete and very intensive set of tests to certify that all on-board systems are operating according to expectation. The last pieces of software required to establish communication between the TSFR and the main CPU were finally written and tested and all seems to be working well. Special thanks is due to Harold Price NK6K for his great help in achieving this goal. As described earlier[1], the TSFR has an HC05 micro controller to control the experiment on board. The residing software in the HC05 will be re-programmable from the ground via the main CPU. The "Trail echoes" detected from the meteors will be digitized and transmitted to the main CPU by the HC05 where they will become available to all ground stations via the BBS.

BBS OPERATION:

As expected, UNAMSAT-1 will be operating a BBS. It is identical to that used in AO-16 and LU-19. The same software (PB/PG) is required to upload or download files. The meteorite "Trail Echo" files will also be available to all via the BBS.

The required equipment is exactly the same as that used for Pacsat AO-16 or LU-19. Nothing additional is required to download the meteorite information gathered by UNAMSAT-1. The unique pre launch operating frequencies excluding Doppler are as follows:

TX1	BPSK	1200 baud	437.180 MHz.
TX2	BPSK	1200 baud	437.135 MHz.
RXA	MAN.	1200 baud	145.922 MHz.
RXB	MAN.	1200 baud	145.942 MHz.
RXC	MAN.	1200 baud	145.962 MHz.
PULSED RF		6 to 16 msec.	40.997 MHz.

Table 1. OPERATING FREQUENCIES

TSFR TECHNICAL DATA:

The operation of the TSFR requires that we be able to re-program the HC05 micro controller so as to fine tune the experiment. This implies the ability to upload to the main CPU a program that will be transferred to the HC05 at 9600 bps via one dedicated bus line (originally receive D). The HC05 will ACK each instruction via the HDLC2 line at 9600 bps. The CPU will, at pre-established times, give a GO to the HC05 to start execution. Two additional parameters, the pulse duration (from 1 to 16 ms) and the pulse repetition rate (from 1 to 16sec) are input via the AART.

The pulse transmitter (70W) and the echo receiver with a sensitivity of-110 dBm. are connected to the same antenna (a canted dipole). Isolation between them is very high. Hence, when they are both on the same frequency, the receiver is not desensitized by the transmitter. More than 40 dB isolation is achieved. The HC05 has an A/D converter and a serial output port, so it will open a window to digitize the receiver output and send the information via its serial port at 32kbps to the main CPU. The CPU in turn will process the received data, performing a Digital Fast Fourier Transform (DFFT). In the main CPU there will be two buffers, one from the previous echo and one for the present. If a Doppler shift is detected and it matches some criteria, the CPU will give an order to the HC05 to change the pulse repetition rate to 1 pulse per second with a maximum duration pre-established in the HC05 software (12 sec is our first trial). Afterwards, it will resume the 6 sec pulse repetition rate looking for more meteorites.

The CPU will put all the 12x2 sets of digitized and DFFT'ed data in a file, give the file a name and make it available on the BBS.

The achieved threshold sensitivity of UNAMSAT-1 is about 10^14 ions per meter. This is a result of two serendipitous "accidents" during the design phase. The power of the pulse transmitter was specified to be 70 W peak but the student in charge of building it (it took him about 4 months) forgot the specs and by the time he finished, had achieved 70 W rms giving an additional gain factor of 1.4. The receiver is a single conversion design with SSB detectors for both USB and LSB and a passband of 10 KHz in each side band (which is the maximum Doppler expected). The student in charge of the echo receiver specified a sensitivity of -100 dBm but ended up with -110 dBm giving an additional gain of 10 dB to the system. We are very happy these two "accidents" occurred.

To give you an idea of the sensitivity of the system, an ionized trail of about 10^14 ions per meter of trajectory is produced by a meteor with a mass of 1 gr. at a speed of 25 Km/s. This is considered a superdense trail and for the reflection of radio waves it behaves as a solid copper conductor of a few hundred meters in diameter.

In order to avoid the problem of normalizing the frequency of the echo it was decided to sample the crystal oscillator of the exciter of the pulse transmitter and apply that for the conversion oscillator at the receiver. By doing this we can determine the Doppler shift without having to normalize the frequencies between transmitter and receiver.

DATA FORMAT

The files of each digitized meteorite will appear in the BBS using a coded name as follows:

Mmmddxx

where M means "meteorite",

mm stands for the month,

dd for the day,

xx is a progressive number going from 00 to 99 for the sequence of meteor on each day.

Inside the file, the first line will have a copy of the date and time at which the observation started, so it will be easy to know where the satellite was at the moment the meteor was observed. Another number will indicate the pulse repetition rate in ms. The rest of the file will be a table that contains 12 samples of 2304 bytes taken at the indicated interval that contain all the spectrum information of the echo. Half of the 2304 bytes belong to the USB and the other half to the LSB. By comparing each of the successive sets of spectrums in each sideband, you will be able to estimate the Doppler shift of the echo and calculate the velocity of the meteor relative to UNAMSAT-1 at the moment of observation. A special piece of software is being prepared to do this and will be available to all interested stations.

TELEMETRY:

The telemetry coming down from UNAMSAT-1 is very similar to the telemetry of the microsats presently in orbit. It will show some additional parameters related to the experiment in the TSFR, like the temperature of the 70W power amplifier, the temperature of the capacitors of the 40V switching power supply for the pulse transmitter, the temperature of the switching transistor on the power supply and the output voltage.

The decoding of this telemetry can be done using one of the already existing programs. We will supply upon request the table of parameters required to correctly decode the telemetry and as soon as available, we will publish it.

PLANNED ORBIT:

As of this moment, we have the basic keplerian data for the orbit. The orbit is targeted to have an inclination of 72 degrees and 700km. altitude. The eccentricity will be 0.000.

As soon as we know the exact keplerian elements, they will be published through the normal channels so everybody can use them in the orbital prediction programs.

ON ORBIT TESTING

Do not expect to use the satellite immediately after launch. As is typical for all microsats, the passive stabilization system will require some time to settle out. We are going to stabilize the satellite in orbit and test all the systems before commissioning the spacecraft for general use. Initial testing will start immediately after launch thanks to the great help of Jim White WD0E. The UNAMSAT-1 launch crew will continue the checkout as soon as we return from Moscow. Once the satellite is released for general use, the BBS will be started on an experimental basis to see if it is fully compatible with the meteorite trail echo (TSFR) experiment operation.

INTERNET:

From this moment on there is an account in INTERNET were you can send requests for information, comments and all other mail. The address is :

unamsat@aleph.cinstrum.unam.mx

All reports will certainly be appreciated.

CONCLUSION

The detection and characterization of meteorite Trail Echoes represents a novel scientific application of the Amateur Satellite Service. The data should provide an insight into the origins and effects of matter in space. A good additional project will be to build a converter to be able to receive the pulses from UNAMSAT-1 at 40.997 MHz +/- Doppler and use these signals to investigate a variety of propagation phenomena. It is hoped that the information presented here will provide an introduction to the future operation of the UNAMSAT-1 and encourage additional scientific investigation.

References:

1. Liberman, David, "UNAMSAT-1 Experiment Module TSFR," *The AMSAT Journal*, Vol. 17, No.3, May/June 1994, p5.

LUSAT-1 CW BEACON TRANSMITTER

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There is an area in the LUSAT (LO-19) satellite originally planned to hold memory. Due to changes to larger scale integrated circuits, (miniature monolithic circuits), all the memory was moved into the second satellite module, thus freeing the TSFR ("This Space For Rent") module for other experiments. This circumstance was exploited to install a CW beacon, whose design and construction was made in Argentina.

The beacon consists of a transmitter of 600 mW and a miniature intelligent controller that will give telemetry data independent of the satellite onboard computer. The computer controller consists of an MC146805 CPU and C-MOS auxiliary CI's to get a low energy consumption. It has eight digital analog input/output gates for taking the data for transmit. The circuit added a Watchdog for reset the controller in a fault case. The telemetry program was loaded in available EPROM space. Transmit data is in MORSE code. This program was loaded seven times with a different number version for each load. Furthermore a control program was loaded (worm), to detect any anomaly caused by radiation in the program memory. In the case of a fault, the EPROM changes to a new version.

The specification for the CW transmitter was to operate at 437.125 MHz with an overall efficiency equal to or better than 65 %. This is calculated by dividing the final output power by the total D.C. power consumption (oscillator, multipliers and final amplifier included). For the transmitter, the design taken was based on the exciter of the main transmitter in the microsats. That design has a conventional oscillator with a 54.8 MHz crystal using a 2N4957. The oscillator is multiplied to 109 MHz. Two additional multiplier stages convert to 218 and finally 437 MHz. The power output in this range is 1mW.

The final amplifier has two stages. The first uses an MRF 571 transistor. This stage is switched on/off by the signal in Morse code made by the controller, using a 2N2907 switching transistor. A 2N2222 transistor in the base circuit stabilizes its polarization. This stage was modified to obtain 35 mW of RF in place of the original 100 mW to increase the overall efficiency. The output amplifier consists of an MRF 559 working in class C. The power provided by this stage was near 900 mW. A final adjustment was made to improve the overall efficiency that resulted in an output power of 750 mW with a total efficiency of 55 %. The output filter was designed to obtain the correct impedance matching and decrease the harmonic output. Laboratory test results were -45 dB of harmonic suppression.

The beacon's antenna connection was made with a special latching relay to avoid extra load. This relay stays in a given position until a transfer pulse is received. This relay switches between the HELAPS, secondary packet transmitter, or the CW Beacon. The beacon's tests were made in CITEFA, (Argentina Technological Research Center), before sending it to the USA to be placed in the satellite. We made vacuum tests, thermal tests between -30 and +60 degrees. C.,and vibration tests at 7.3 G. All OSCAR satellites experience very low temperatures at the moment of orbit entry. Thus the module was made to run on the worst expected and unfavorable conditions.

A good performance was obtained working from -35 degrees. C. This beacon sends CW telemetry at 12 WPM at 437.125 MHz in reduced Morse codification allowing energy savings of 44 %. The beacon has one status channel and eight data channels. The following is the data of each channel and the formula necessary to obtain the correct value.

CH 1 +5 voltage
636/N1 = Volts
CH 2 +10 voltage
.064*n2 = Volts
CH 3 CW temp
.354*(134.7-N3) = Deg. C.
CH 4 TX power
((10.9+N)^2)/40.1= mWatts
CH 5 : Box #4 temperature
.356*(136-N5) = Deg. C.
CH 6 +10 V current
.7*N6 = mA.
CH 7 +Z voltage panel
.15*N7 = Volts.
CH 8 +8.5 voltage
.056*N8 = Volts.

Calibrated Telemetry Factors

The message format is the following:

LUSAT HI HI VL N1 N2 N3 N4 N5 N6 N7 N8

V = is the letter of the EPROM's program version.

The program was repeated seven times, to avoid crash's for radiation degradation. If the first version is out of service, the second will be loaded and executed.

L= is the ram MC146805 microprocessor result test. If L=O the ram is okay. If L=E there has been an error detected.

N1 to N8 are the telemetry data of each channel. For the numeric values, there has been adopted a compact codification, thus allowing for a more effective power usage, this codification is as follows:

1: .-
2: ..-
3: ...-
5: .
6: -....
7: -...
8: -..
9: -.
0: -

Numeric Telemetry Codification

VOXSAT Review

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ABSTRACT

This paper contains a report on the efforts to finish the first all Argentinean-made ham satellite. The original designs are reviewed, like the SoundUnit, and the On board Computer.

Argentina has very little aerospace professional activity, so there are a lot of problems getting useful information about space materials. These difficulties have delayed the completion of the project. The help of many AMSAT members around the world and some Argentinean scientific institutes will make it possible to finish very soon.

MISSION REVIEW

The VOXSAT satellite is aimed at educational and research problems. Signals from the satellite are to be received as short audio messages on the Earth by VHF-FM receivers. The satellite will also include an FM crossband Repeater, with an uplink in the 70 cm band and a downlink in 2 meter band. The satellite is to be put in orbit inside a big Russian satellite. Its active existence depends of the power supply resources available.

The satellite is being developed by AMSAT ARGENTINA with the help of AMSAT RUSSIA, The Centre of Space Communication of the House of Science and Technical Creative Work of Youth, The Adventure Club and Compas-R company of RUSSIA.

STRUCTURE

VOXSAT consists of a common modular structure that has the purpose of containing the different functional blocks. The structure is made of thin aluminum that makes it strong and light and provides effective shielding of the RF signals. All the frames are similar, having a rectangular form of 23 cm x 18 cm x 2.5 cm with a bottom and upper cover and a hole for a DB25 connector. The different aluminum parts were painted to prevent corrosion during the manipulation and transport.

Like the MICROSATS and soon P3-D, each VOXSAT module has a unique external communication port via a DB25 connector. All modules are interconnected via a common bus. This simplifies the removal of any module for test or change.

The structure has five modules :

1.- Switching Power Supply.
2.- RF Linear Amp.
3.- RF Exciters.
4.- OBC.
5.- Receivers.

ON BOARD COMPUTER, TELEMETRY AND DIGITAL BLOCK.

The command and telemetry section consists of two little microprocessor units. An MC68705K1 receives and interprets the ground commands. When a command is accepted, the order is sent via a serial interface to the main computer, an MC146805. This microprocessor executes and then sends a confirmation via a telemetry frame in AX.25 format. For control and measurement, there are eight analog inputs and eight digital outputs. Furthermore, there are six digital I/O ports, eight kbytes of ROM and eight kbytes of RAM for control of the experiments.

A watchdog timer resets the microprocessor in case of a fault. The telemetry and status frames are sent via a Packet Radio beacon using UI frames that do not need ground station acknowledgment. Since the spacecraft control and environment is supplied by the principal mission, the need for telemetry is very small. Only a small amount of telemetry will be transmitted about the operational parameters.,

For Record and Play audio, we are using a new generation of chips designed by ISD Inc. Each chip has the capability of loading audio signals for one minute inside a EEPROM of 500 kb and retaining the information for ten years.

The command and telemetry section was constructed on three small boards and stacked in one of the standard frames.

POWER SUPPLY

All the elements within the payload such as the on board computer and other systems require regulated voltages for their proper operation. To meet these needs, the satellite contains a switching regulator that converts the voltage supplied by the main mission.

The switching regulator converts the +28 V of the Russian satellite into the payload needs of +10 V and +5 V. In order to convert the +28 V from the main mission to +10 V, we use an MC34167. The +10 V is supplied to the rf parts. The current required is nearly 1 Ampere. The + 5 V regulator uses a 7805. The + 5 V supplies a well regulated voltage to all the digital systems. Since all digital components are C-MOS, very little current is required from this regulator. The switching regulator was constructed on a small printed circuit board and assembled in one of the standard frames of the satellite.

TRANSMITTERS

The VOXSAT has two high efficiency transmitters for the 2 meter band. The power output is near 4 W. The final transmitter efficiency achieved was better than 50 % while maintaining good harmonic suppression and overall frequency stability.

The transmitters consist of a pair of Exciters and RF Amplifiers. The exciters provide about 5 mW of rf drive at the output frequency to the rf amp. An MRF652 VHF power transistor is used for the amplifier. It was selected for its high operating efficiency. One transmitter is used as a beacon for telemetry, status and back up downlink. The other is used as the primary repeater downlink and audio broadcast transmitter. The only control is to turn it on or off.

Each exciter and rf amp was made on a double sided printed circuit board. Each pair of exciters and rf amps were assembled on a pair of standard frames. The beacon transmitter frequency will be on 145.995 MHz and the downlink repeater and audio broadcast frequency is 145.825 MHz.

RECEIVERS

Two FM receivers for 432 MHz are used for control and repeater uplink. The heart of these receivers is the MC3359 chip. Each receiver has a GaAsFET pre-amplifier and helical filters. Each receiver is made on double sided printed circuit board and staked on a standard frame. The uplink repeater frequency will be 435.100 MHz.

ACKNOWLEDGMENT

We are thankful to all AMSAT members around the world that in one way or another have helped. We especially thank Leonid Labutin, UA3CR and Eugeni Labutin, RA3APR for their great patience with our group.

The Stanford SQUIRT Micro Satellite Program

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June 7, 1994

Abstract

Stanford University's Department of Aeronautics and Astronautics is currently cooperating with the amateur satellite community in the full scale development of a new micro satellite initiative. Known as the Satellite Quick Research Testbed (SQUIRT) program, the project's goal is to produce student engineered satellites capable of servicing state-of-the-art research payloads on a yearly basis. Additionally, SQUIRT vehicles will carry interesting and educational payloads for scholastic and amateur satellite operators.

The first spacecraft in the SQUIRT series is the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE). The payloads for this mission include an experimental infrared (IR) sensor, a digital camera, and a voice synthesizer. The bus consists of a 25 pound, 9 inch tall, 16 inch diameter hexagonal structure with complete processor, communications, power, thermal, and attitude control subsystems. Through student participation, voluntary mentoring from the academic and industrial communities, and the extensive use of off-the-shelf components, the cash outlay target for each SQUIRT class vehicle is $50,000.

This paper discusses the educational and research issues surrounding the development of the SQUIRT program, and the progress of the current SAPPHIRE vehicle. Additionally, the involvement of amateur radio mentors is discussed and future payload concepts are outlined.

1. Introduction

Modern engineering curricula tend to emphasize understanding, research, and optimization of specific technical disciplines. Although interdisciplinary engineering is fostered through system technology projects and courseware, these approaches traditionally conclude with a conceptual design report. Based on a vocal industry request for exposure to a more realistic systems engineering environment, many academic engineering programs have now initiated formalized methods to teach detailed system design, fabrication, integration, test, and operation. Successful programs provide students with an authentic design education by introducing the real world issues of program management, system requirements formulation, and subsystem technology trades. The most fortunate students graduate with hands-on experience in all aspects of the system design life cycle and a technical grasp of the detailed design and operation of a variety of subsystems.

With respect to the satellite design field, the challenges to provide such an educational experience are magnified tremendously. This is due to the technically complex scope and multiyear timelines associated with most spacecraft projects. In addition, these factors greatly complicate the researcher's desire to use the rapid prototyping and iterative techniques typically employed in other scientific and technical fields.

The many space flight successes of the amateur satellite community, however, show that such goals are not impossible. In particular, the tens of Orbiting Satellite Carrying Amateur Radio (OSCAR) projects have proved that quick, small, and simple projects can reap significant rewards in terms of supporting researchers, educators, and hobbyists.

In response to these issues, Stanford University's Department of Aeronautics and Astronautics has recently expanded the scope of its traditional spacecraft design curriculum. The new center for these activities is the Satellite Systems Development Laboratory.

2. The Satellite Systems Development Laboratory

Officially inaugurated in January 1994, the Satellite Systems Development Laboratory (SSDL) is the focal point of Stanford University's spacecraft design program. The SSDL charter is to provide world class education and research in the field of spacecraft design, technology, and operation. Accordingly, its personnel create and instruct a comprehensive academic program as well as guide and manage a state-of-the-art research agenda. The specific execution of these tasks is accomplished through classroom instruction, research work, and project experience.

In order to provide a comprehensive spacecraft design experience, the SSDL has initiated development of a new micro satellite platform, the Satellite Quick Research Testbed. Scientific and engineering partners in this project include a variety of academic research centers, government laboratories, and industrial corporations. In addition, the assistance of radio amateurs and satellite experimenters is actively sought. It is hoped that radio amateur mentors can expand the hands-on experience of graduate students.

3. The Satellite Quick Research Testbed (SQUIRT) Program

The goal of the SQUIRT program is to produce student engineered satellites capable of servicing state-of-the-art research payloads on a yearly basis. To limit the scope of the program and to provide direction in the yearly academic setting, a number of design guidelines are stressed.

SQUIRT vehicle mission and environmental lifetimes are set at approximately one year, and relatively small cash budgets of $50,000 are targeted. The physical requirement is loosely specified as a highly modular bus weighing 25 pounds and having a 9 inch high by 16 inch diameter hexagonal form as depicted in Figure 1. Continuous development of alternate processor, communications, power, thermal, attitude control, and detailed structural options serves to populate the satellite design toolbox available to future SQUIRT teams. Additionally, guidelines require that all employed design tools, facilities, and technologies be available within the Stanford community and its academic, governmental, and industrial affiliates.

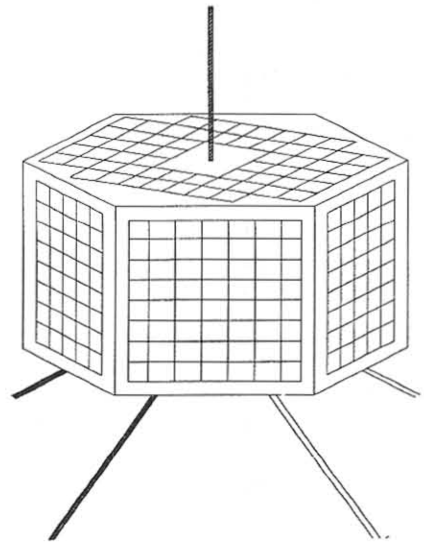

Figure 1 *- SQUIRT Physical Form.*

Design teams are also urged to consider the use of amateur satellite radio standards in order to foster a cooperative and mutually beneficial relationship with that community. The SSDL would like to establish a working arrangement that would grant satellite experimenters access and eventual ownership of new satellites. The SSDL would benefit by working with experienced designers and operators and by gaining access to amateur radio frequencies for communication with the satellites. Under consultation with numerous amateur radio mentors, current plans call for flight operations to commence with emphasis placed on payload research and educational activities. During this initial period, moderate access would be granted to satellite experimenters and would include command ability for the educational payloads. With research and educational activities finished, complete operational authority of the vehicles would be transferred to the amateur satellite community.

Because of the program's time and monetary considerations, much of the design process involves the modification of off-the-shelf non-space-rated consumer products. Once a particular component model has been selected, engineering studies are executed in order to determine the hardware, electronic, and software modifications required for space environment operation. These steps are documented in modification plans that are then submitted for review to the SSDL's mentors and the component's vendor. Once approved, the modifications are implemented, and the components are tested through hardware, software, and electrical diagnostic checks. Through cooperation with local industrial affiliates, these checks include structural vibration, acoustic, and thermal vacuum tests.

Educationally, the SQUIRT program exposes graduate engineering students to satellite design by providing hands-on technical and managerial experience in the following: conceptual design, requirements formulation, subsystem analysis, detailed design, fabrication, integration, test, launch, and operations. With respect to research, SQUIRT vehicles serve as a generic space based platform for a variety of low power, volume, and mass experiments currently under development by the SSDL and its affiliates. Yearly cycles permit rapid access for state-of-the-art space research and unique opportunities for low cost payload iteration.

Philosophically, SQUIRT satellites are intended to be excellent examples of simple, fast, cheap, flexible, and intelligent micro satellite design. Simplicity permits success in the allotted time and allows students to gain technical insight into the entire design and operation of the satellite. Speed allows the student to witness the entire life cycle of the satellite design process. It also provides rapid access to space and focuses efforts towards incremental and iterative technical upgrades. Low cost design satisfies the practical monetary constraints of the SSDL and provides an attractive platform alternative to potential researchers. Flexibility in the design allows the satellite to interface with a variety of potential payloads, to be launched on an assortment of launch vehicles, and to operate in a wide range of orbits. It also permits the design to withstand the uncertainties and technical evolution inherent in a student activity. Intelligence compensates for the operational inefficiencies that typically result from the above philosophical considerations.

Given this philosophical direction, the SQUIRT program accepts a number of characteristics typically denounced in commercial spacecraft development. These include acceptance of high risk, little component redundancy, low precision control, non-optimal designs, and inefficient spacecraft operations.

4. The Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE)

Based on student interest and the capabilities of the SSDL's affiliated researchers, the selected missions for the SAPPHIRE spacecraft, the first SQUIRT vehicle, include 1) assessing the performance of experimental IR sensors, 2) performing digital space photography, and 3) broadcasting voice synthesized messages. The IR sensor package is the result of micro machinery research performed by Stanford Professor Tom Kenny and the Jet Propulsion Laboratory. Digital black and white photography is achieved through the modification of a Fotoman camera in cooperation with the engineering staff at Logitech. Digital voice synthesis is obtained through the modification of a commercially available synthesizer board. Broadcasts are transmitted so that they may be received on an FM hand held radio.

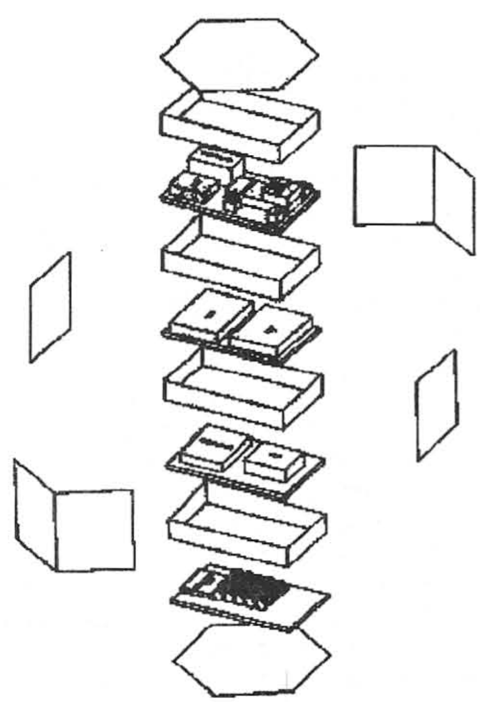

***Figure 2** - SAPPHIRE Structural Configuration*

Given these objectives, as well as the SQUIRT program goals previously outlined, students commenced the formal design of the SAPPHIRE satellite by formulating the applicable system requirements and flowing them down to the respective subsystems. Design alternatives were then generated and analyzed through software simulation and hardware modeling. Finally, a series of formal trade-off studies led to the selection of a baseline spacecraft and component configuration.

An exploded view of the selected hardware configuration is displayed in Figure 2. The heart of the system is a four tray interior structure that carries the predominant launch loads and supports the satellite components. The majority of the power, communications, processing, and payload subsystems are housed in trays 1 through 4, respectively, numbered from the bottom to the top. Component wiring, attitude control magnets, and hysteresis rods are placed in the lateral spaces between the interior structure and the solar array panels. Attitude determination sensors, solar cells, and required antennae are mounted on the exterior panels.

With respect to the spacecraft subsystems, the selected baseline consists of a Motorola 68332 based computer board that monitors and controls component activity, processes command inputs, and formats telemetry outputs. The power subsystem generates over eight watts of average power via the external solar panels. It is augmented by battery storage capability and regulated to provide both 5 and 12 volt lines. Orbit and attitude determination are provided by a GPS receiver, student manufactured Earth sensors, and a virtual sun sensor based upon relative solar panel current magnitudes. Passive attitude control is achieved with stationary magnets and radiometers. This orients the slowly spinning spacecraft for northern hemispheric imaging and smooths the radiant load on the passive thermal subsystem. Figure 3 displays the functional electrical interfacing of the active components.

The baseline communications system provides two-way data packet transmission as well as downlink analog output. Composed of one receiver and two transmitters, the system offers Mode J operations with a 2 meter uplink

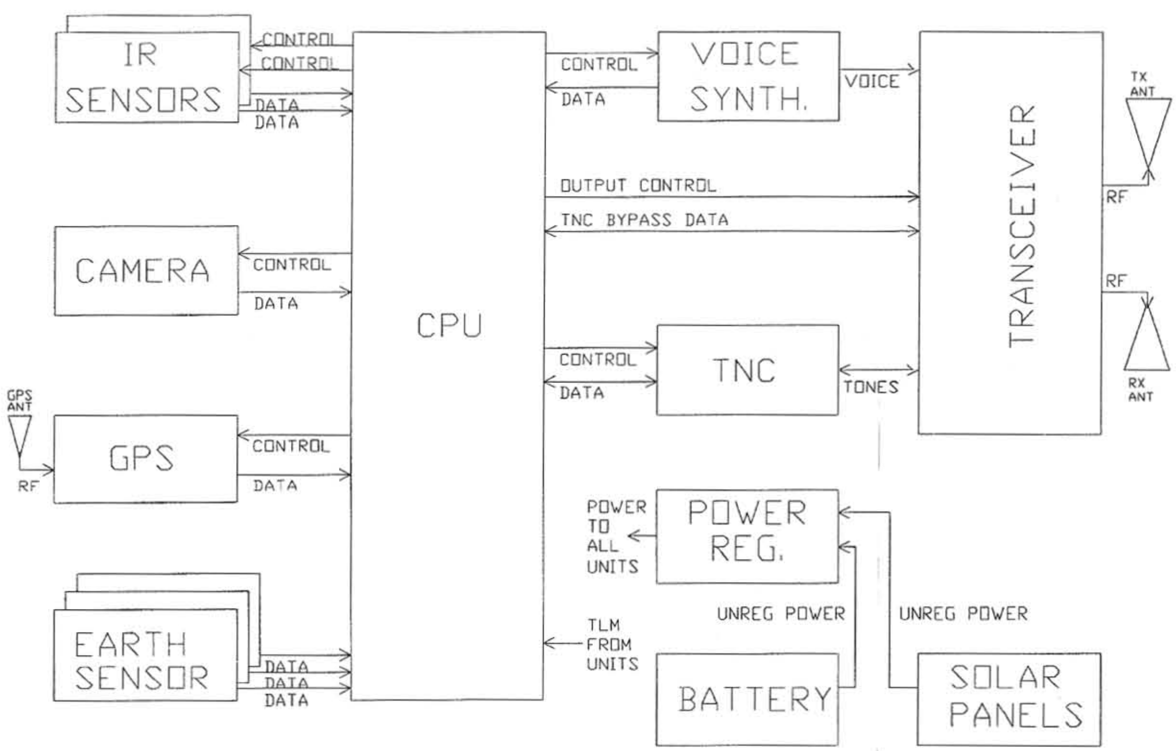

Figure 3 - SAPPHIRE Functional Interfaces

band (145 MHz) and a 70 centimeter downlink band (437 MHz). The transmitters and receiver are designed, built, and tested by the student design team under the strong mentoring of amateur satellite volunteers.

The narrow band FM receiver captures uplink signals via a single vertical 1/4 wave whip antenna located on top of the spacecraft. After acquisition, low noise amplification, downconversion, and conditioning are performed, a Motorola MC3363 chip extracts baseband information. The downconverter uses a 99 MHz Butler oscillator for the local oscillator with a 2 ppm crystal for temperature stability. Many of the components, including the bandpass filters, are off-the-shelf.

The data transmitter, TX1, downlinks photographic data and satellite state-of-health information. The link utilizes AX.25 packet protocols and operates at 1200 baud. Two modulation modes are planned: two-way terrestrial AFSK modulation via a hardware TNC, and Manchester AFSK uplink and BPSK downlink through software TNC and a separate

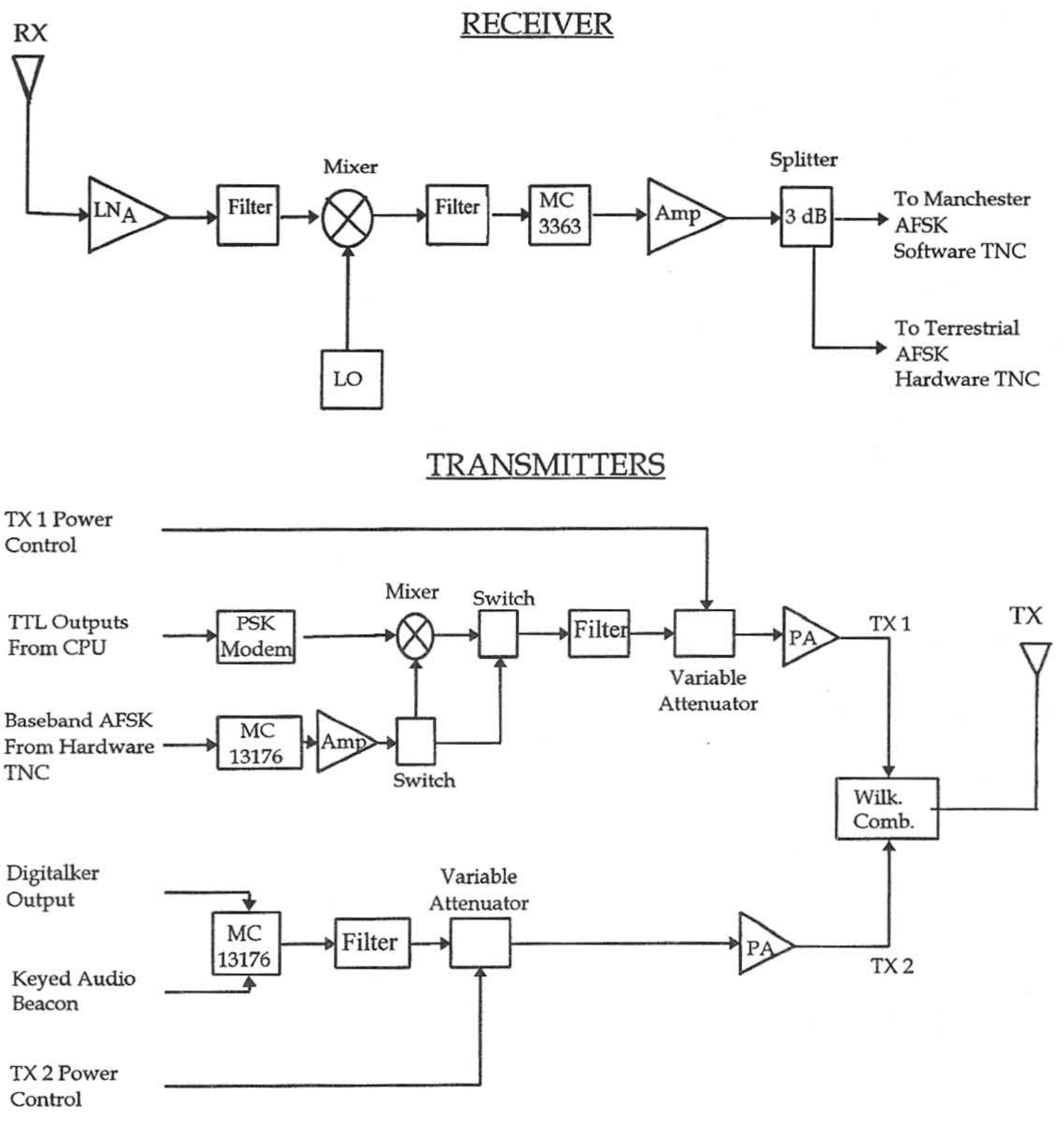

***Figure 4** - SAPPHIRE Transceiver Diagram*

PSK modem. For the AFSK/AFSK mode, hardware TNC output is modulated with a Motorola MC13176 chip and then amplified. For the AFSK/BPSK mode, software TNC output is routed to the PSK modem. The resulting signal is mixed with the stable 437 MHz carrier generated by the MC13176 and then amplified. A CPU commanded 8 bit serial current mode D/A converter varies the input attenuation to the transmitter amplifier chain. The downlink power is thereby selectively controlled between 0 and 5 Watts.

The analog transmitter, TX2, FM broadcasts synthesized voice or, in the absence of a voice input, a Morse code keyed beacon signal. The voice signals are FM modulated by a MC13176 chip and amplified by another commandable 0-5 Watt variable power chain. The Morse code beacon is broadcast at 200 mW to conserve satellite power resources. The output of both transmitters is impedance matched and combined in a Wilkinson combiner. Four 1/4 wave transmission antennae are mounted below the spacecraft in a symmetrical pattern to provide pseudo circular polarization. Figure 4 displays a functional diagram of the SAPPHIRE transceiver.

Managerial and systems level control is established through weekly student organized design reviews and subsystem manager meetings. System and subsystem specifications are maintained in a formal requirements document, and all component hardware, electrical, and software interfaces are published and reviewed on a weekly basis. Additionally, students regularly update a computerized design log that documents all relevant design information including trade-off justifications, component modification plans, and subsystem continuity data.

Without question, as the first SSDL mission and SQUIRT vehicle, the SAPPHIRE satellite project is challenged with considerations above and beyond the scope of what is planned for future SQUIRT design efforts. These challenges include the nonexistence of a formulated design toolbox, the lack of startup funding, and the difficulty of developing a suitable laboratory environment in parallel with this satellite design effort. Accordingly, SSDL personnel are prepared to delay the first vehicle's one year time line as necessary in order to produce a suitable technical design and academic experience.

5. Future Missions and Initiatives

In addition to developing the SAPPHIRE spacecraft, the SSDL has commenced with preliminary mission conceptualization and payload feasibility studies for future SQUIRT vehicles. In the category of student interest, payloads include higher resolution color digital cameras, analog television transmitters, micro meteorite sensors, and radiation sensors. Research payload studies include a miniaturized arc jet thruster, a space environment plasma analysis package, an autonomously coordinated constellation experiment involving multiple SQUIRT vehicles, a number of spacecraft navigation and attitude control investigations, a spectroscopic imagery package, and a series of component space qualification tests.

In order to broaden the organizational scope of the SQUIRT program, the SSDL is promoting the formation of an international SQUIRT community geared specifically towards the rapid production of SQUIRT class micro satellites for the purposes of education and research. Along these lines, design cooperation and discussions have commenced with the University of Umea in Sweden and with Weber State University. In addition, input from amateur satellite experimenters is continuously sought in order to generate new mission ideas and to develop current designs. To promote this cause and to further overall educational objectives, the SSDL plans to make all SAPPHIRE and future SQUIRT design information available to the public via an Internet Mosaic link and through specific requests for documentation.

6. Conclusions

Stanford's Satellite Systems Development Laboratory was formed due to an increasing demand for graduate students with a mature background in satellite systems engineering. The SQUIRT program specifically caters to the educational needs of graduate students through a judicious blend of systems engineering exposure and hands-on technical experience with a limited size, scope, and timeline. It appeals to researchers with low power, volume, and mass payloads as an inexpensive, rapid access testbed opportunity.

With respect to the first SQUIRT project, the SAPPHIRE design team has built a strong foundation for the future of the SQUIRT program by developing a flexible structural configuration, by investigating and developing a wide range of viable bus components, and by establishing strong mentoring relationships with its affiliates.

The particular assistance of the amateur radio community has been instrumental in framing the technical and operational scope of the SQUIRT program. In addition, the design guidance and configuration reviews provided by satellite experimenters has directly advanced the development of the SAPPHIRE spacecraft. This relationship serves to enhance the educational experience of the project's students, and it reinvests the skills and experiences of the mentors in a new generation of engineering designers.

Acknowledgments

The authors wish to express their sincere appreciation to the SSDL Director, Professor Robert Twiggs, for his leadership, direction, and encouragement in Stanford's spacecraft design program. In addition, the following students are commended for their outstanding work and commitment as members of the SAPPHIRE design team: Eric Abbott, Sung Ahn, Birdy Amrutur, Raj Batra, Jeff Chan, Helene Cochelin, Louie Demmel, Michel Iagolnitzer, Beth Kader, Will Kim, Sangho Kim, Dave Lauben, Alex Luebke, Mori Ohara, Jeff Ota, Kevin Stattenfield, and Michael Swartwout.

Also, special thanks is given to all of the individuals and companies that have donated their time and resources to this design effort. Particular gratitude is expressed to the following design mentors for their dedicated assistance: Mr. John Ellis, Mr. Kitt Blanke, Mr. Tim Panczak, Mr. Kevin Freund, Dr. Frank McLaughlin, Mr. Bill Rausch, Professor Tom Kenny, and Mr. Kevin Mackey.

Investigating the Integrated Control of Payloads with Amateur Satellites

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3 June 1994

Abstract

The Stanford Satellite Systems Development Laboratory (SSDL) is currently investigating advanced satellite control technologies aimed at improved spacecraft system operations. One technique involves a unique real-time payload control strategy for satellites operating within a crosslinked constellation. This strategy effectively merges payload scheduling, traditionally considered a high level planning problem, with low level actuator control. The developed method utilizes attractive artificial potential fields of varying strength to exert 'planning' forces on the payload. As the payload nears a particular goal, it is critically damped to that specific position.

This approach has been simulated for the simple repositioning of a mechanically actuated space telescope. Applied to constellation operations, this strategy provides the basis for simple, efficient, and robust satellite cooperation in dynamic environments. This paper describes the strategy under consideration and discusses preliminary plans for its flight testing through the use of a small constellation of Satellite Quick Research Testbed (SQUIRT) micro satellites.

1. Introduction

Conventional satellite control techniques rely heavily on the use of an operator centered 'fly-by-wire' architecture. In this scheme, commands are planned and issued from a ground station based upon operator knowledge, mission documentation, and basic computerized prompts and manipulations. Similarly, telemetry is transmitted to the ground for analysis based upon the same factors. Typical functions of this nature include payload scheduling, state of health monitoring, fault detection and resolution, orbit control, communication configuration control, and most subsystem failure mode control functions.

Because a substantial segment of satellite activity is operator centered, a considerable control network is commonly required for mission essential operations and maintenance. Compounding this, the growth in the size and complexity of modern satellite systems serves to increase the number as well as the technical and procedural scope of these nodes. As a result, industrial, governmental, and military satellite operating agencies are finding that their control architectures are extremely time and resource intensive, costly, vulnerable, and error prone. Additionally, large organizations of highly skilled operators are generally required, and architectures are rarely oriented for direct tasking by the operational field user. Beyond the obvious inefficiencies, these problems are so cumbersome that they can actually jeopardize the initiation of new and the continuation of current space programs.

Given these challenges, the industry is investigating a variety of methods to mitigate the costs of operating spacecraft. This can be achieved partially through the elimination of system and organizational inefficiencies within the operator centered architecture. But to achieve order of magnitude gains, researchers are attempting to migrate from a human-based to a computerized locus of control and from a ground to spacecraft locale of control.

To achieve these steps, a wide range of technologies are being researched. These include expert systems, model based diagnostics, neural networks, fuzzy logic, planning optimization, human-computer interfaces, and cooperative intelligent agents. Although the computational capability required for the ground execution of these strategies has been available for quite some time, it is the recent development of high performance, radiation hardened, flight quality processors that now makes these options viable on board the spacecraft.

The success of these technologies in automating the prescribed tasks would satisfy many of the problems encountered in the operator centered architecture. Computerizing the locus of control can result in smaller operator organizations with fewer training requirements. Likewise, moving the control locale to the spacecraft results in reduced contact times, less dependence on ground stations, and quick response to changing satellite conditions.

2. Spacecraft Autonomy and Cooperation

Without question, the ability to automate the execution of basic tasks is critical to the migration of the locus and locale of control of spacecraft duties. But beyond automation, system 'autonomy' must be adopted in order to achieve a higher level of control ability. In particular, an 'autonomous' space system includes the necessary intelligence in order to be self-governing. In addition to processing ability, autonomy requires a system to sense and interact, both explicitly and implicitly, with its environment in order to determine what sequence and combination of task execution is appropriate. So while automation permits the mechanization of basic tasks, it is autonomy that allows the resolution of conflicting tasks and the sense of when to switch from one task to another during unexpected or unplanned situations.

The notion of orbiting a constellation of spacecraft that unite to perform a single mission elevates the topic of spacecraft autonomy. In this conception, individual satellites become intelligent agents that attempt to optimize their contribution to system objectives. To do this, an individual satellite interacts, or 'cooperates', with its partner satellites through the exchange of control directives and sensed data.

One of the most crucial spacecraft tasks is payload planning and control. The conventional approach to this problem, both for single and multiple satellite systems, is to plan and coordinate payload activity at a centralized ground control center. Activity schedules and configurations are then uplinked to the individual satellites and stored in memory. To achieve low level payload control, the appropriate preplanned parameters are accessed and the payload is reconfigured. This style of operation is based upon mere satellite automation in the sense that satellites have no knowledge of system goals. For this reason, all task planning must be performed on the ground. Additionally, the architecture limits the satellites to the use of 'local information'. This means that the satellite is unaware of how well other system resources are doing in the quest to meet system goals. It also means that potentially helpful information collected by other system resources is not passed along.

Unfortunately, this architecture poorly addresses the dynamic demands of the highly interactive, low Earth orbit (LEO) satellite constellations of the future. Examples of such networks include several widely publicized cellular telephone communications space systems as well as conceptual plans for a fleet of space based telescopes. In particular, these systems will depend heavily upon two-way data exchange between operational system users and the individual satellites. They may also rely on satellite crosslink communication in order to coordinate and perform mission tasks. Both of these concepts include a level of real-time payload tasking that is unachievable in an operator centered architecture. In addition, the orbital dynamics of such constellations requires continuous reassessment of visibilities, crosslink communication paths, and field user request routings.

A potential solution to this challenge is to achieve higher levels of satellite autonomy through the migration of control and higher levels of constellation autonomy through the incorporation of cooperative behavior. A variety of research efforts are currently engaged in developing new architectural approaches along these lines. Among the most widely publicized are strategies based upon behavioral analysis, contract negotiation, and genetic evolution.

3. The Integrated Control Strategy

A new payload control paradigm, termed Integrated Control, is currently under development in the SSDL. Requiring satellite knowledge of system level goals, this model constructs artificial potential fields in order to attract the payload to its next configuration. One field is associated with each possible payload destination. The attractive strength of each field is a function of that destination's priority and the phenomenological conditions between the payload and the object of interest.** With this framework, payload planning becomes a real-time task implemented through the actual application of joint space forces upon the payload. As the payload gets 'close enough' to a particular configuration, it is critically damped to its final position.

One of the elegant features of this approach is its ability to merge the conventionally distinct tasks of high level planning and low level control. Such integration permits the payload to quickly and more efficiently respond to unplanned local effects such as corrupted interaction with previous objects and a roving field of regard (FOR). For example, assume that a constellation of telescopes has the mission of tracking space objects. With centralized ground control, the rescheduling of a poor sighting is ignored until the next wave of constellation planning and schedule commanding. Rapid response to such poor sightings requires a high duty rate of ground planning and commanding that severely taxes the system's infrastructure. With respect to a roving field of regard, this certainly occurs for low precision spacecraft. It is also a consideration for multi-mission platforms during operating modes in which the payload of interest does not dictate spacecraft attitude.

Another remarkable quality of this technique is the ease with which global information can be integrated into the tasking of the payload. Quite simply, information concerning a partner satellite's performance and status is factored into the attractive strength function of each relevant payload destination. Thus, the incorporation of both a payload's past performance as well as the cooperative inputs of other payloads is achieved in the same way. Consider again the example constellation of telescopic payloads. Satellite A applies an attractive force to the payload for each object in its FOR. The strength of each field is based upon the current ephemeris quality, the viewing conditions, and the importance of each object. Now assume that Satellite B collects high quality tracking data for a particular object. Satellite B forwards this information to Satellite A. In turn, Satellite A substantially reduces the strength of the attractive force exerted upon its payload by this object. This process reduces redundant viewings and therefore increases overall system efficiency.

Current research into the Integrated Control technique is concentrated on gaining a better understanding of payload movement due to the artificial potential fields and damping function. Once this is accomplished, focus will turn to the heuristics involved in determining appropriate attractive strengths for various local conditions and cooperative inputs.

4. Initial Implementation and Simulation

Simulation of the Integrated Control technique is currently underway for a single payload in the constellation of space telescopes previously mentioned. In order to concentrate on and learn about the fundamental issues involved in the control strategy, a simple two-gimbal, mechanically actuated telescope was assumed for initial study. The formulation and results of its simulation are presented here in order to detail the essential aspects of the Integrated Control technique.

Figure 1 shows the simple physical model that was adopted for this initial study. The telescope rotates through joint angles θ_1 and θ_2 about the X and Y axes, respectively. This model assumes idealized physical properties and uses the values J_x, J_y, and J_z for the three telescope principal moments of inertia; the value I_x is used for the gimbal's principal moment of inertia. From this model, the Lagrangian function was formulated and manipulated in order to derive the model's equations of motion.

** Such conditions commonly include range and interference. Telescopic payloads must also consider illumination angles, target emissive and reflective parameters, etc. Communication payloads also consider link quality.

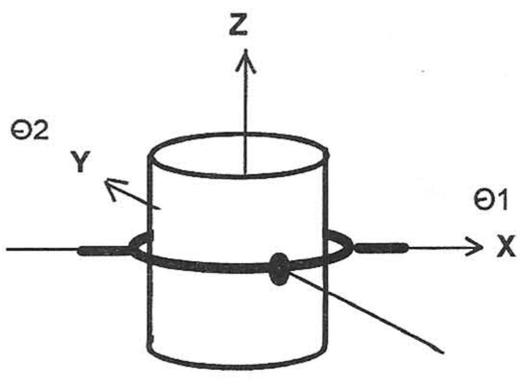

Figure 1 - Telescope Physical Model.

The Integrated Control block diagram used for initial implementation is displayed in Figure 2. As can be seen, a computed torque structure is employed in order to reduce telescope control to a unit mass problem. This was done in order to decouple the specific physical model from the study of the artificial attraction field concept. Any practical implementation of such a scheme would require the use of a very accurate plant model and/or the addition of a system identification algorithm.

For this first implementation, the control algorithm was sectioned into distinct laws for artificial potential field 'planning' forces and final positioning forces. With this demarcation, the payload is subjected first to the superposition of attractive forces from each possible object in the telescope's FOR. Each attractive force function is simply the inverse of the distance to the object's joint coordinates multiplied by a constant (Force = Constant / Distance). The constant is a function of object range, illumination, priority, and disparity between the desired and actual ephemeris accuracy. It is calculated by a heuristic algorithm that has not yet been defined.

The resulting motion can be visualized by imagining a ball rolling across a terrain that is distorted by potential wells. These wells move due to the relative orbital motion of the space objects. They may also translate within the FOR due to varying spacecraft attitude conditions. The ball rolls along the resulting terrain until it is 'captured' by a specific well corresponding to the 'winning' space object. At this point, the control algorithm switches to a standard proportional derivative (PD) controller. The PD controller capture radius is calculated for the value at which the attractive forces of nearby wells become equal. This law is tuned to critically damp the payload to the object's joint space location.

This specific implementation of the Integrated Control technique has been modeled using MATLAB simulation software for a 0.1 m diameter, 0.5 m long, 10 kg telescope, and a 0.15 m diameter, 1 kg gimbal assembly. Joint friction coefficients were specified at 1 kg·m^2/sec. To showcase the effects of the potential well attraction, the trial was limited to two stationary space objects with equal attractive strengths. The attractive constants were sized to produce a control effort equivalent to the joint torques required for a conventional PD controller. The joint space coordinates of these objects were set at (-0.5, 0) and (0.5, 0) radians. The initial

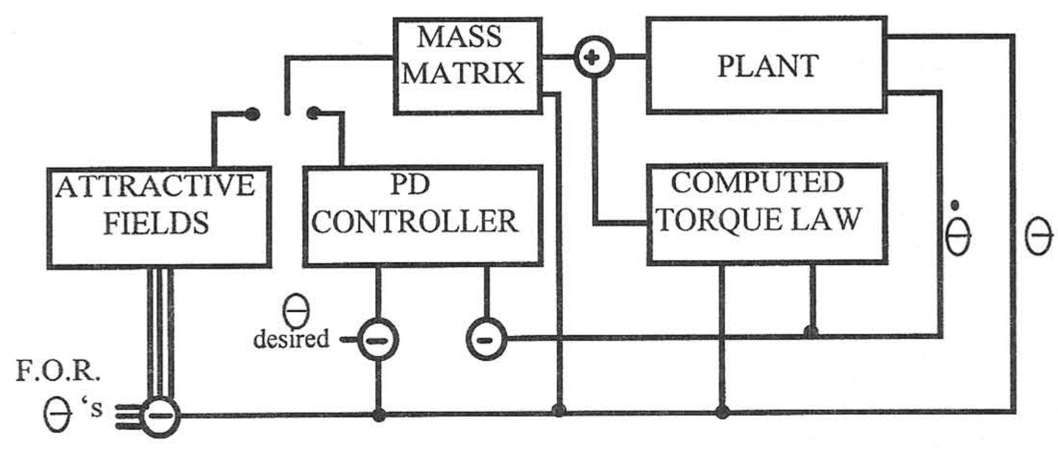

Figure 2 - Integrated Control Block Diagram.

payload joint space position was placed at (0.07, 0.47) radians, a position with a nearly equal distance to each object.

The resulting motion is summarized in Figure 3. Figure 3a shows a view of the payload's joint space motion. As can be seen, the payload initially moves between the two objects until it is distinctly captured by the object on the right. Figure 3b shows the terrain visualization of this same effect for the unit mass ball rolling across the potential field. Figures 3c and 3d show the individual joint time responses.

Strict comparison of these results with the performance of a more conventional architecture, assumed to be a ground executed planning algorithm and a spacecraft sequenced PD controller, is difficult without focusing on specific planning optimization algorithms and system efficiency metrics. In general, however, it is obvious that the time required for payload movement in the Integrated Control technique is greater than for a conventional strategy. But it should be noted that the Integrated Control technique commences this initial movement in what is equivalent to the planning phase. In addition, by using a fairly simple algorithm, the Integrated Control technique eliminates the need for the substantial resources required for ground planning and schedule commanding. Finally, as has been previously noted, the prospects for simple integration of real-time performance analysis and cooperative inputs from partner satellites serve to distinguish the Integrated Control technique as a worthwhile research pursuit.

With respect to the modularity of the simulation framework, the MATLAB code is divided into distinct functional algorithms corresponding to physical parameters, equations of motion, attractive potential field functions, numerical integration, and time response plotting. This permits simple and quick changes in physical plants and attractive functions. It should also be noted that the Integrated Control technique can be applied equally as well to both mechanically and electronically actuated payloads.

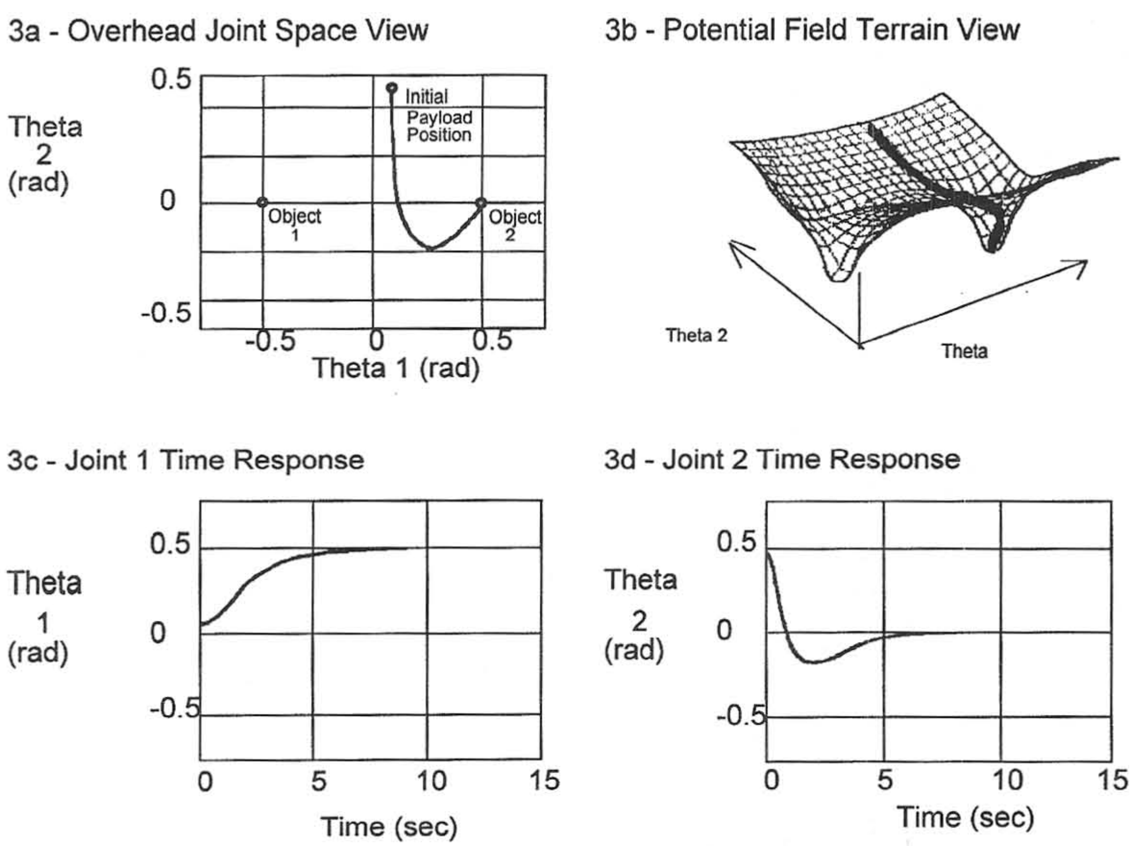

***Figure 3** - Simulation Results.*

5. Future Research and Flight Demonstration

Initial implementation and simulation of the Integrated Control technique has provided encouraging results. Future work consists of a combination of software simulation, hardware experimentation, and space flight demonstration.

The next stage of software simulation will permit model refinement through experimentation with more objects and moving potential wells. Different potential functions will be investigated in an attempt to fully unify the planning and final positioning of the payload. Formulation work will then commence on the appropriate form of the attractive strength calculation based upon system goals, local conditions and performance, and the global information acquired through cooperative inputs.

Hardware experimentation plans currently call for several microprocessor controlled 'payloads' linked with each other through a relatively low rate communication channel. Various promising implementations from the software simulation research program will be tested to determine their ability to withstand a non-idealized environment. Specific attention will be focused on the adaptive nature of the system's behavior and its performance under the influence of degraded crosslinks.

Finally, a flight demonstration of this technique is currently in the conceptual design stage. This research objective would utilize a small constellation of the SSDL's SQUIRT micro satellites in order to validate the system operation aspects of the Integrated Control strategy. SQUIRT vehicles are student engineered satellites capable of servicing state-of-the-art research payloads. These spacecraft typically consist of a 25 pound, 9 inch high by 16 inch diameter hexagonal bus as pictured in Figure 4. Complete processor, communications, power, thermal, and attitude subsystems support low power, volume, and mass payloads for missions of up to a year. Through student participation, voluntary mentoring from the academic and industrial communities, and the extensive use of off-the-shelf components, the cash outlay target for each SQUIRT class vehicle is $50,000.

A potential flight package would consist of a variable field of view camera and a low power omnidirectional crosslink communication package. Two to four vehicles would be launched together, injected into nearly identical orbits, and given the goal of photographing various objects at particular frequencies. Current SQUIRT vehicle development suggests that additional unrelated payloads could be included on each satellite in order to maximize the investment in a space launch. Potential payloads include an analog television transmitter, an amateur radio experimental frequency communications package, and a variety of other SSDL research experiments. The constellation configuration of this mission could provide unique opportunities for satellite experimenters to communicate with each other via spacecraft crosslink transmissions.

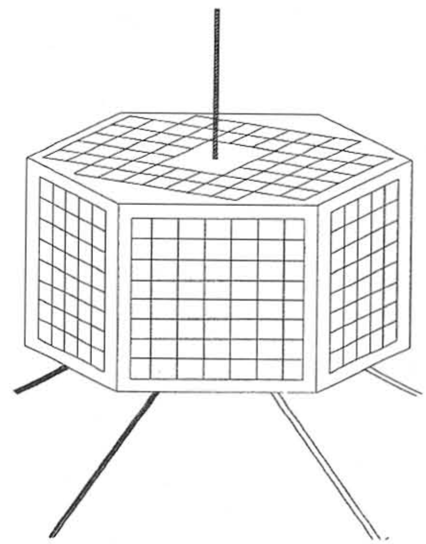

***Figure 4** - SQUIRT Physical Form.*

6. Conclusions

The myriad costs associated with conventional satellite control techniques serve as an impetus for migrating both the locale and locus of space system control. The development of multi satellite constellations reinforces the need for such action and is stimulating concentrated research efforts to advance satellite system autonomy and cooperation technologies.

Stanford's Satellite System Development Laboratory is actively engaged in such efforts. Its researchers are investigating a particularly encouraging satellite control paradigm formulated to meet the specific demands of highly interactive LEO constellations. This Integrated Control strategy uses analytically produced attractive potential fields to exert payload positioning forces while also effectively planning the appropriate sequence of payload activity. Benefits of this technique include merging the planning and positioning tasks as well as simply incorporating cooperative inputs from partner satellites.

A simplified implementation of this technique has been simulated in software for a mechanically actuated telescopic payload. Future development of the model will include refining the potential field's form as well as defining the heuristics involved in determining the field's attractive strength. These enhancements will be supported and validated through more detailed software simulation, hardware experimentation, and space flight demonstration through a constellation of SQUIRT class micro satellites.

Acknowledgments

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Use of Star Cameras for Attitude Determination of Amateur Radio Satellites

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Satellite cameras can be used to capture sky images. If the stars in such images are matched with catalog entries, spacecraft attitude can be computed. An algebraic technique for attitude determination using two star observations is described in this paper and demonstrated using an image from the Clementine spacecraft. Potential applications of imagers on board current and future amateur radio satellites as star cameras are discussed.

Introduction

Numerous spacecraft use star observations for attitude determination. While star sensors have usually been used on large spacecraft, the technology has matured to the point that star cameras on small satellites are feasible. For example, some amateur radio spacecraft have imagers that could be used as star sensors.

In this paper, "attitude" refers to orientation with respect to distant stars. An inertially-pointed spacecraft must accurately determine attitude in order to point solar panels at the Sun, a telescope at a planet, or an antenna at a ground station. Once attitude has been computed, the information can be used by the attitude control system of the spacecraft to maintain the proper orientation. In some applications, a star sensor is not used by the control system but simply for determining where the spacecraft was pointing at a particular time.

Star Sensors

Any instrument that provides star observations for use as attitude references can be called a star sensor. The three major types are star scanners, star cameras, and star trackers. Star scanners are used on spinning spacecraft to determine the orientation of the spin axis. Star cameras and star trackers are imaging devices installed on non-spinning satellites.

There is a subtle but important difference between star cameras and star trackers. Any camera can be used to record star images, but those images must be processed by the spacecraft computer or downlinked to the ground. By comparison, a solid-state star tracker has a microprocessor in addition to a CCD array detector. The microprocessor continuously scans the CCD array for star images and computes positions and magnitudes of those stars. Current star trackers are complex devices that typically cost in excess of US$1 million.

Coordinate Frames

When spacecraft attitude is referenced to an inertial frame, the Earth Centered Inertial (ECI) or Geocentric Inertial (GCI) coordinate frame is used [1]. The ECI frame is also used for defining orbital elements. In the ECI frame, North is defined as the Z axis while the X axis points in the vernal equinox direction. The Y axis is chosen to complete the right-handed system.

A star sensor is attached to the spacecraft body, so the measurements are considered to be in the "body" frame. Inertial axes are labelled with capital letters (XYZ) while body axes are labelled with lowercase letters (xyz). A star camera might be located such that it is aligned with the z axis of a spacecraft (see Figure 1). Typically, the field of view of the camera would be ±5° in both x and y directions. Note that the image will be inverted by the optics, but the position values can be inverted algebraically in order to preserve the geometry shown in the figure.

A star is located in the CCD array by row and column pixel numbers. The focal length of the camera is known, so the vector that points towards the star is

$$\mathbf{u} = d*r\ \mathbf{i} + d*c\ \mathbf{j} + f\ \mathbf{k}$$

where r is the row pixel number, c is the column pixel number, d is the distance between pixels, and f is the focal length. Note that vectors are indicated by bold type and that **i**, **j**, and **k** are unit vectors in the x, y, and z directions. The row and column numbers can be converted into angles from the boresight using simple algebraic calibrations. In this example, the angles in the figure are

$$\alpha = \arctan(d*r/f)$$
$$\beta = \arctan(d*c/f)$$

where α is the angle due to x deflection and β is the angle due to y deflection. In practice, the calibration equations for these two angles are quite complicated in order to correct flat-field effects. An algebraic conversion from row and column numbers to α and β is easily done, so star trackers usually are programmed to output two angles per star. Once these angles are computed, the vector that points towards that star is:

$$\mathbf{u} = \tan(\alpha)\ \mathbf{i} + \tan(\beta)\ \mathbf{j} + \mathbf{k}$$

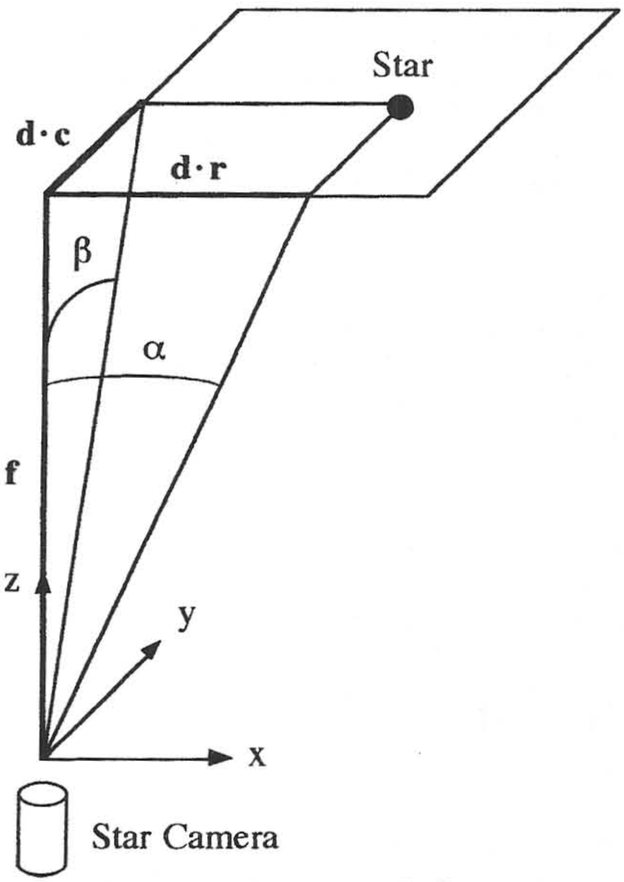

Figure 1. Star Camera Angle Definitions

Stellar Attitude Determination

There are three steps involved in determining attitude from a star camera image. First, the raw image must be processed to determine star positions and magnitudes. Next, the stars from that image must be matched to entries in a star catalog. Finally, the matched star observations must be converted into a mathematical representation of attitude.

The CCD detector of a star camera produces an image that is typically composed of 8-bit numbers. A human can view an image, distinguish rough magnitudes of stars, and recognize patterns such as constellations. For a computer to use this image, pixel location and magnitude for each star must be extracted from the raw data. A program might scan through the image line by line until high pixel values are encountered. The program would then examine several pixels in the vicinity to determine if a star image is present. For increased accuracy, the pixel values are used in a curve fitting algorithm. Location and magnitude of the star image are the parameters determined by the algorithm. In fact, location can be determined to within a fraction of a pixel. A larger star image improves the curve fit, so star sensor optics may be deliberately defocused.

Once star positions and magnitudes are extracted, these observations must be matched to star catalog entries. Pattern matching algorithms are often used, but extensive storage for the star catalog and intensive computation for matching are required. Algorithms such as the one by van Bezooijen [2] begin with one star, check magnitudes, then compute the angle to the next star. More observations are added until a threshold of certainty has been reached. An alternative to pattern matching is a direct match technique. If a reasonably accurate estimate of the attitude is known, a program can be directed to search for stars within small regions of the image. Direct matching is faster and requires less storage than pattern matching, but the simpler technique is not as flexible and robust.

After sufficient matches have been made, the observations are used with corresponding catalog entries to determine attitude. Numerous techniques for attitude determination using multiple star observations have been developed. One of the more direct though less accurate methods is the algebraic construction of an attitude matrix [3]. This method is sometimes termed "triad" after the three vectors computed from the two observations (see the Appendix). The attitude matrix is simply a direction cosine matrix for rotating vectors in the inertial frame into the spacecraft body frame. The transpose of the attitude matrix will rotate vectors from the body frame into the inertial frame.

When the attitude matrix is known, several important parameters can be computed. For example, a model of Sun position will produce a unit vector in the inertial frame that points towards the Sun; the attitude matrix can be used to rotate that vector into the body frame. The vector dot product between the Sun vector and the solar panel vector is the cosine of the angle between them. Another use would be for determining where a camera on the spacecraft is pointed. The camera boresight unit vector in body coordinates can be rotated into the inertial frame using the transpose of the attitude matrix. The components of the unit vector can then be used to compute right ascension and declination of the center of the image.

Clementine Star Camera Image Example

To illustrate the stellar attitude determination process, consider the image in Figure 2 that was taken by a star camera on board the Clementine spacecraft [4]. This device has a field of view of 29° by 43° and pixel format of 384 by 576. The image in Figure 2 is 384 by 288 pixels, so it was treated as the upper half of a complete image. The camera was assumed to point in the z direction of the spacecraft with y up and x to the left in the figure.

The image in Figure 2 is clearly of the Big Dipper as can be seen by comparing the image with SkyGlobe plot in Figure 3 [5]. The star in the upper left corner is named

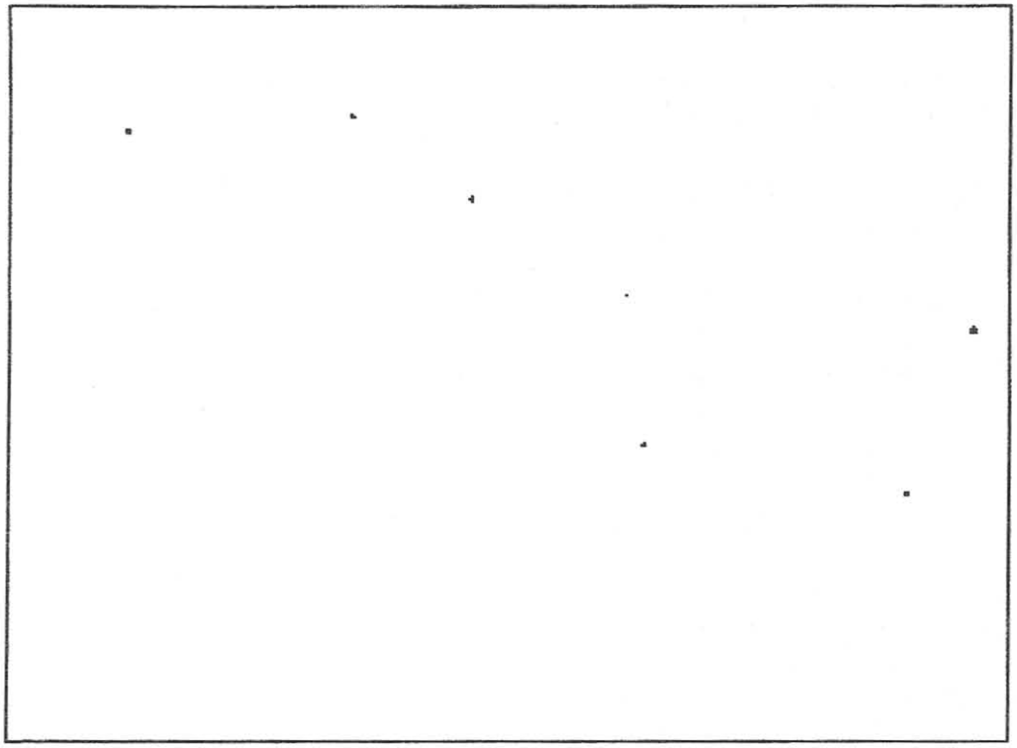

Figure 2. Clementine Star Camera Image (Inverted)

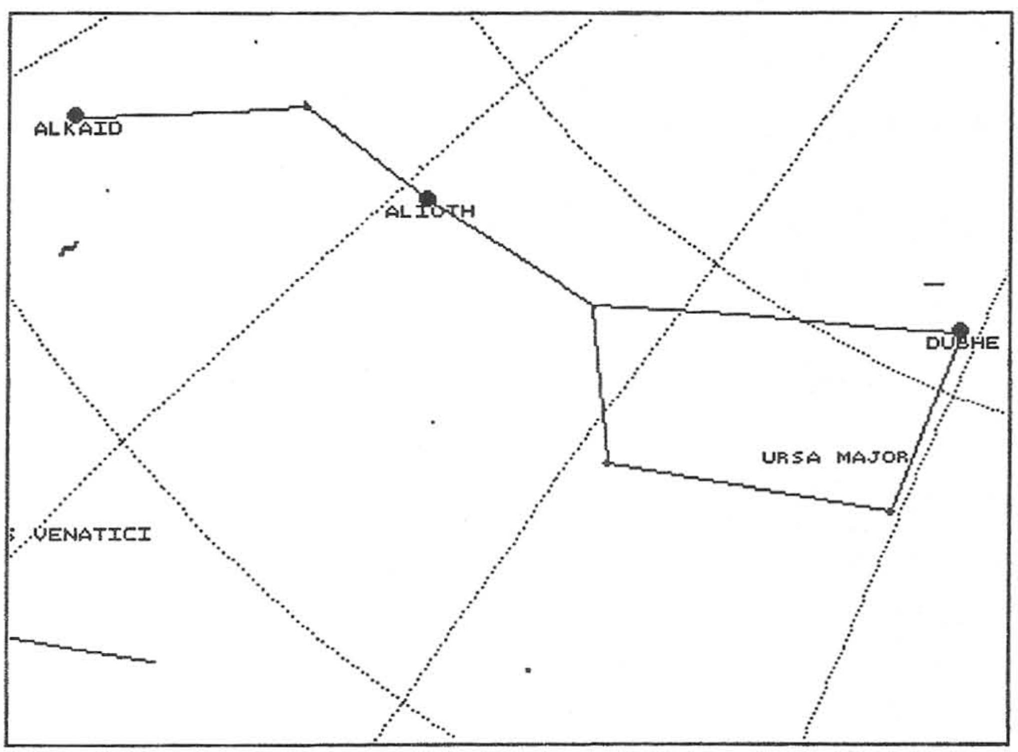

Figure 3. SkyGlobe Plot of the Big Dipper

Alkaid and was the first observation **u**. The star at the center of the right edge is named Dubhe and was the second observation **v**.

The first step was to determine the star positions and magnitudes. Magnitudes were not be used in this example since the pattern of stars was already know. The file was imported into NIH Image, a Macintosh image processing program, and the approximate centers of the two stars were located. The measured pixel locations were 147,238 for Alkaid and -181,161 for Dubhe.

The pixel locations must be converted to angles α and β. Since the angles of the field of view and number of pixels were given, these specifications were used to create approximate calibrations of 13.24 and 13.40 pixels per degree in x and y respectively. Dividing the pixel number by the calibration value resulted in angle pairs of 11.10°,17.76° for Alkaid and -13.67°, 12.01° for Dubhe. These angle pairs were converted into unit vectors as described earlier. The result was $\mathbf{u}_b$ and $\mathbf{v}_b$:

$$\mathbf{u}_b = 0.1837\ \mathbf{i} + 0.2998\ \mathbf{j} + 0.9361\ \mathbf{k}$$
$$\mathbf{v}_b = -\ 0.2314\ \mathbf{i} + 0.2024\ \mathbf{j} + 0.9516\ \mathbf{k}$$

The second step in the attitude determination process was to match the observations to a star catalog. The pattern was already matched visually, so the only details needed were unit vectors for the two stars in inertial coordinates. The right ascension and declination for these stars was recorded from the SkyGlobe display. Alkaid was at 13h47', 49°19' while Dubhe was at 11h03', 61°35'. After converting these angles to unit vectors [6], the result was $\mathbf{u}_R$ and $\mathbf{v}_R$:

$$\mathbf{u}_R = -\ 0.5821\ \mathbf{i} - 0.2934\ \mathbf{j} + 0.7583\ \mathbf{k}$$
$$\mathbf{v}_R = -\ 0.4612\ \mathbf{i} + 0.1171\ \mathbf{j} + 0.8795\ \mathbf{k}$$

The third and final step in the process was to construct the attitude matrix. The vectors for the two observations were used in the triad method to compute the direction cosine matrix that rotates vectors from the inertial frame into the body frame. The result is a square matrix:

$$\begin{matrix} -0.4303 & -0.8087 & -0.4009 \\ 0.5520 & -0.5872 & 0.5920 \\ -0.7142 & 0.0334 & 0.6990 \end{matrix}$$

For an example of the use of the attitude matrix, assume that the solar panels were aligned with the x-axis of the spacecraft and that the star image was taken at the winter solstice (22 December). The x-axis of the spacecraft in inertial coordinates is the first column of the transpose of the attitude matrix (the first row of the attitude matrix):

$$\mathbf{x}_{in} = 0.4303\ \mathbf{i} - 0.8087\ \mathbf{j} - 0.4009\ \mathbf{k}$$

The Sun vector at the winter solstice is [7]:

$$\mathbf{s_{in}} = 0.0\ \mathbf{i} - 0.917\ \mathbf{j} - 0.399\ \mathbf{k}$$

The dot product of $\mathbf{x_{in}}$ and $\mathbf{s_{in}}$ equals 0.902, so the solar panels are 90.2% illuminated. The arccosine of this value is 25.6°, the angle between the solar panel vector and the Sun.

Star Camera Design

A dedicated star camera design would be similar to a regular imager with a few modifications. A conceptual design is portrayed in Figure 4. The detector from an existing camera could be used; inclusion of a thermoelectric cooler would increase sensitivity but would not be necessary. The optics would be for a relatively wide field of view if attitude determination were to be accomplished with one sensor. The optics would be defocused slightly to increase the accuracy of the star image centroiding algorithm.

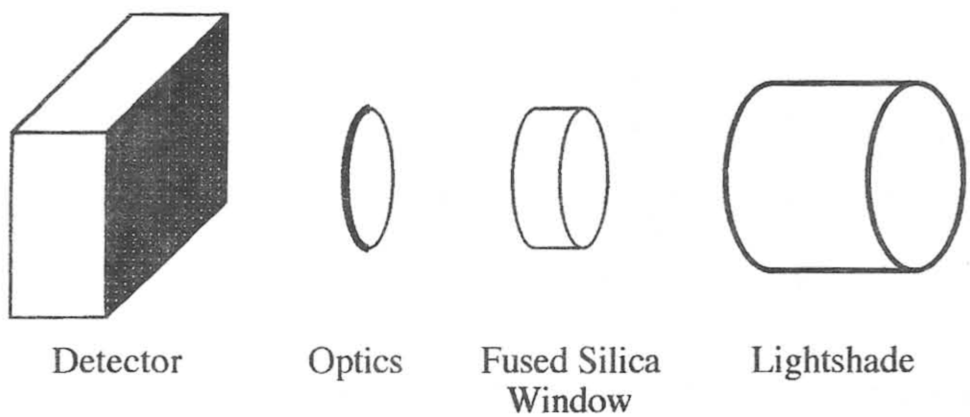

Figure 4. Expanded View of a Star Camera

A fused silica window could be used to protect the optics and detector from radiation. The camera would not have color filters that degrade with radiation, but detector pixels can be damaged and the glasses in the optics can fog after continued radiation exposure. The silica window might reduce the optical quality of the images, but that is not a concern for a dedicated star camera.

One of the more challenging aspects of building a useful sensor would be the calibrations for star magnitudes, pixel positions, and angle conversions. A CCD detector is more sensitive to red and infrared light than is the human eye, so visual magnitudes will not be sufficiently accurate for the star catalog. A straightforward way of calibrating the sensor would be to observe the night sky from the ground before the sensor is integrated on a spacecraft. Pixel positions must be carefully measured and detailed angle calibration equations must be developed to provide sufficient accuracy.

Experience with Existing and Future Amateur Radio Spacecraft

At least one dedicated star camera has been operated aboard a partly-amateur spacecraft. PoSat-1, built by the University of Surrey, has a dedicated star imager that points away from the Earth. This star sensor was adapted from the Earth imaging cameras that have previously flown on satellites such as UO-22 and KO-23. The pixel format is roughly 560 by 280 with a corresponding field of view of about 16° by 8°. The owners of PoSat-1 have not approved the release of star camera images to amateur users. Results of experiments with the camera were presented at the AMSAT-UK Colloquium but were not available when this paper was written [8].

Webersat (WO-18) was constructed at Weber State University in Utah and features an imager that was adapted from a CCD video camera. The camera was intended to image the Earth, but some sky images were taken early in the mission before controllers understood the attitude motion of the satellite [9]. This camera has a fixed integration time of less than 1/60 second, so only bright stars and planets can be detected. Planet positions and magnitudes can be computed at the time that a Webersat image was taken. If at least two bright stars or planets appear in an image, attitude can be determined.

Japanese amateur radio operators are building CCD cameras known as SCOPE (Spacecraft Camera experiment for Observation of Planets and the Earth) for the AMSAT Phase 3D project [10]. These cameras can be used as star sensors for attitude determination experiments. If the cameras have not yet been integrated into the Phase 3D spacecraft, the SCOPE builders can perform star position and magnitude calibrations. A position calibration can be as simple as imaging a measured grid at a known distance in order to develop an accurate conversion from pixel location to α and β. Magnitude calibrations would involve imaging easily-recognized star patterns in order to determine how star brightness is related to pixel values.

Conclusions

Star cameras can be used with proven procedures for attitude determination of amateur radio satellites. Images from satellites currently in orbit can be used for development of attitude determination techniques. If cameras on future amateur spacecraft are calibrated before launch, stellar attitude determination computations can be made more accurate.

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Appendix. Triad Method of Attitude Determination

The algebraic method for determining the attitude matrix based on two observations is detailed in Wertz [3]. In this method, the observations are used to construct two unit vectors in the spacecraft body frame. Those two observations are matched with two unit vectors in the reference frame. A triad of unit vectors is constructed from each pair of unit vectors; the two triads are used to form a direction cosine or attitude matrix.

Two non-parallel unit vectors $\mathbf{u}$ and $\mathbf{v}$ are used to create three basis vectors $\mathbf{q}$, $\mathbf{r}$, and $\mathbf{s}$:

$$\mathbf{q} = \mathbf{u}$$
$$\mathbf{r} = \mathbf{u} \times \mathbf{v} \,/\, |\mathbf{u} \times \mathbf{v}|$$
$$\mathbf{s} = \mathbf{q} \times \mathbf{r}$$

Two observations from a star camera are used to contruct $\mathbf{u}_b$ and $\mathbf{v}_b$, the two unit vectors in the body frame. The larger the angle between the stars, the better the accuracy of the attitude determination solution. The basis vectors in the body frame are used to form the body matrix $\mathbf{M}_b$:

$$\mathbf{M}_b = [\ \mathbf{q}_b : \mathbf{r}_b : \mathbf{s}_b\ ]$$

The two star observations must be matched with entries in a star catalog. The right ascensions and declinations of the stars are used to compute the unit vectors $\mathbf{u}_R$ and $\mathbf{v}_R$ in the reference (inertial) frame. The basis vectors in the reference frame are used to form the reference matrix $\mathbf{M}_R$:

$$\mathbf{M}_R = [\ \mathbf{q}_R : \mathbf{r}_R : \mathbf{s}_R\ ]$$

The attitude matrix $\mathbf{A}$ is

$$\mathbf{A} = \mathbf{M}_b * \mathbf{M}_R^T$$

where $\mathbf{A}$ is a direction cosine matrix that can be used to rotate vectors from the inertial frame into the body frame. The transpose of $\mathbf{A}$ will rotate vectors from the body frame back into the inertial frame.

One of the limitations of this method is that the first observation $\mathbf{u}$ is matched exactly while the second observation $\mathbf{v}$ is displaced by all the noise present in the data. Star observations from the same image are of similar accuracy, so more complex optimal techniques are often used to filter sensor noise. An intermediate step would be to use basis vectors $\mathbf{u}+\mathbf{v}$ and $\mathbf{u}-\mathbf{v}$ so that the sensor noise is "smeared" over both observations.

ORBITAL ANALYSIS BY SLEIGHT OF HAND

by Dr. H. Paul Shuch, N6TX [1]
AMSAT LM-167

ABSTRACT

Modern digital computers, along with low cost, high power software, have been indispensable tools in the quest to communicate by orbiting satellite. Tracking software has become so ubiquitous that a whole generation of enthusiasts is unaware that there once was another way to track the early OSCARs. While not opposed to progress, the author is of the opinion that the magical computer tends to separate its user from the basics of the underlying application. Through a review of manual, intuitive satellite tracking techniques, we can gain a more thorough understanding of the rather simple forces of nature underlying those mystical Keplerian Elements.

INTRODUCTION

There is a curious object on display in my classroom, a pancake-flat Plexiglas disk about a half meter in diameter. On one side appears a North polar projection map of the earth; on the other side, a South polar projection. Sandwiching this pre-Columbian globe are two transparent overlays, pinned to the poles with a robust grommet so as to rotate freely. On the rotating panels, great arcing lines with cryptic notations are inscribed in grease-pencil. The object looks very much its part, as an icon to the high priest of satellite navigation.

You probably know of this device as an OscarLocator, a graphical aid to satellite tracking. This particular granddaddy of all OscarLocators was in fact the original OSCAR 1 orbital plotting board, preserved throughout these countless generations of Amateur Radio satellites. We called it a Satelabe then, a word derived from Astrolabe, the navigational instrument which guided explorers across uncharted oceans from ancient times, until the development of the sextant in the 18th Century. And though my students would relegate it, along with my Osborne 1 computer and log-log-decitrig slide rule, to the musty, dusty shelves of a technology museum, it is kept for the most utilitarian of reasons: because it still works.

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THE EARLY DAYS

The microcomputer is today as indispensable a part of the world of satellite communications as is the mini-HT to Amateur Radio. Starting with Dr. Tom Clark's legendary BASIC Orbits program, continuing to the present software array with its dazzling high resolution graphics, we all have tools at our disposal, the likes of which NASA could only dream about during the days of Apollo. Yet in those eras of antiquity, BC (Before the Computer), a handful of dedicated visionaries managed to conceive, construct, and connive into orbit the world's first non-Government sponsored artificial earth satellite. They did so with tools which today would be considered laughably crude, but they did it. They left us AMSAT as their legacy. They left us their Satelabe, as a reminder.

I was not really one of the original OSCAR cadre, although I sat at their feet in awe. As a high school student sitting quietly in the back of the room, watching my heroes concoct their minor miracle, I said to myself, "some day, when I grow up, this is what I want to do." And someday, when I grow up, I will. [2]

Meantime, I've been privileged to teach satellite communications to a whole generation of technologists. Only their way, it's hard to tell where the computer ends, and the technician begins. Armed with their silicon ephemera, they manipulate Keplerian elements to the twelfth significant figure, produce orbital predictions in double precision, and haven't the foggiest idea what they all mean.

AN OLD TOOL

That's where the Satelabe comes in. With it, and applying mathematical concepts no more advanced than those available to the ancients, one can visualize the balance of forces which holds a satellite in its orbit. Utilizing purely manual techniques, one can perform orbital analysis to far less accuracy, but with far greater clarity, than can be accomplished by digital computer.

That's also what this article is all about. In it, we will review a few of the basics of the satellite orbit, armed with nothing but a pencil and a pocket calculator (a few years ago, I would have said slide rule.) And although I doubt I'll ever wean you from the MegaTrak 1000 program running on your 100 MHz 80686 with the gigabyte hard drive, I hope to remind those of you who might have forgotten, what's really going on behind the zillion-pixel screen, back in the land where the ones and zeros cavort in wild abandon.

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2 OK, I exaggerate my modesty slightly. I have had a minor role in all of this, rising through the ranks of Project OSCAR volunteers to eventually become Technical Director, and then Chairman of the Board, a position which I held until 1990.

CIRCLES AND ELLIPSES: AN ECCENTRIC VIEW

A good place to start our description of the orbits of communications satellites is with a review of the most historically significant controversy in astronomy, the nature of our solar system. Probably the first to propose a heliocentric theory of the universe was the Greek astronomer Aristarchus of Samos (circa 310 - 230 BCE). His view received little attention from the ancients, who favored a geocentric scheme, as later formalized by the Greco-Egyptian mathematician Claudius Ptolemaeus in the 2nd century CE. In Ptolemy's system, simple circular motion was used to describe the motion of all visible celestial bodies around the earth. The apparent retrograde motion of the planets was explained by a rather complicated system of epicycles on deferents. [3] Still, predictions of celestial events based upon the Ptolemaic system were crude at best.

The great Polish astronomer Nicholas Copernicus may well have been trying to smooth out some of the inconsistencies in the Ptolemaic system's prediction of eclipses. He was probably the first astronomer since Aristarchus to propose anew a heliocentric solar system (*De Revlutionibus Orbius Coelestium*, 1543). Although he placed the sun in its rightful place, his system still retained a variant on epicycles to explain retrograde motion. Circular orbits, it seemed, were tricky stuff.

Tycho Brahe was a renowned fence-sitter. Unable to decide for himself the relative merits of the Ptolemaic and Copernican systems, he created one of his own, incorporating elements of each. This Danish astronomer saw an immobile earth around which the sun revolved, with the other five known planets then revolving around the sun. To support his model he recorded a lifetime of observations of the planets, the moon, and Supernova 1572. His excellent observations, published posthumously by Kepler (in *Tabulae Rudolphinae*, 1627) led to the breakthrough which eliminated the inconsistencies in all prior solar system models. Indirectly, it also gave us our most powerful tools for satellite orbital analysis, the Keplerian elements.

Professor of mathematics at Graz, Johannes Kepler proposed in 1609 (in *Astronomia Nova*) that planetary motion be described not by circles, but by ellipses. He showed that any planet (and by extrapolation, satellite) must orbit in an ellipse with its primary at one focus. His laws of motion further described the change of orbital velocity required throughout a stable elliptical orbit, and explained (*Harmonice Mundi*, 1619) the interrelationship between the size of the ellipse and the orbital period. Kepler's elliptical orbits made possible a full understanding of not only the heliocentric solar system, but three and a half centuries later, the orbit of your favorite OSCAR.

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3 To visualize this rather convoluted scheme, think of the popular carnival ride called the Tilt-a-Whirl. Each rider (planet) sits on a cart. The cart sits on a platform which describes a circular orbit (deferent), while whipping around in its own circular sub-orbit (epicycle).

It is important to note here that a circle is simply a special case of an ellipse, one whose eccentricity equals zero.[4] Since our earliest artificial earth satellites (Sputnik I, OSCAR I, etc.) all had low eccentricities, we tended to analyze their orbits as circular. That's where the early OscarLocator came in. It turns out that the motion (relative to an observer on the ground) of a satellite in circular orbit can be easily described as an arc on a polar projection map. The Satelabe is such an arc on a map. With it, we can not only extrapolate any orbit into the future for prediction of Acquisition of Signal (AOS) and Loss of Signal (LOS) at a ground location, but we can also project required antenna bearings (azimuth and elevation) for a given pass, and predict mutual satellite visibility for two ground stations. Useful, no?

More complicated orbits (such as the highly eccentric Phase III and Molniya satellites) defy such simple graphical analysis, because their ground tracks tend to corkscrew, and do not necessarily repeat over time. It is for such orbits that tracking software really shines. However, we still have a good number of useful satellites in nearly circular orbits (PACSATs, microsats, MIR, Space Shuttles, various weather satellites, and of course the most useful Clarke, or geosynchronous, orbit). All but the latter (which stands motionless in the sky, from our terrestrial vantage point) can benefit from Satelabe analysis.

THE IDEAL ORBIT

We will begin our analysis of satellite orbits by making quite a few simplifying assumptions. For starters, let's consider an artificial satellite in perfectly circular orbit (that is, eccentricity of zero) around a perfectly spherical earth of uniform density, with no atmosphere. Of course, our planet is both lumpy and oblate (wider at the equator than at the poles, by about 0.1% or so). But ignoring these details simplifies orbital analysis; we will correct for reality later. Similarly, let's turn an n-body problem (one which includes the gravitational effects of the moon, sun, planets and stars) into a much simpler 2-body problem, by pretending that nothing exists but our satellite orbiting such a perfect planet.

For this simple and ideal case, only two influences determine the motion of the satellite around its primary: the force of gravity (pulling the satellite toward earth), and the pseudo-force of inertia (pulling the satellite away from earth). Further, for a stable orbit (one which does not change over time), these two forces must be balanced, in exact equilibrium. Since we can define both gravity and inertia mathematically, and set the two equal to each other, we can produce what I call the Basic Orbital Equation. I'll spare you the derivation (it appears in the literature) and cut to the result:

$$\frac{mV^2}{r} = \frac{GMm}{r^2} \qquad \textbf{[Equation 1]}$$

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4 Eccentricity is a measure of the "lopsidedness" of any ellipse, on a range of 0 to 1. Values approaching 0 represent a round, and those approaching 1 represent a flat, shape.

In **Equation 1**, little **m** stands for the satellite's mass, big **M** for the mass of the earth, **V** for the satellite's velocity, **r** for the radius of its orbit, and **G** for Newton's universal gravitational constant. The left hand expression relates to inertia, and the right hand side to gravity. As I said, a stable orbit requires that the two be equal. What's interesting about this equation is that it can be simplified. The **r** in the left hand denominator can cancel one of the **r**'s in the right. And the **m**'s in the two numerators can cancel. This leaves us with:

$$V^2 = \frac{GM}{r} \qquad \textbf{[Equation 2]}$$

which is not only simpler, but allows us to draw some interesting conclusions. For one thing, you'll see that **Equation 2** makes no reference at all to the mass of the satellite. The orbital behavior of any satellite appears *independent* of its mass! [5] Periodically, my students try to sell me on the notion that the mass of the satellite is absent from **Equation 2** because it is negligible relative to that of the earth, thus can be ignored. Negligible that it may be, this is not the reason. You can see from the above that, when equating inertia to gravity, the satellite's mass *cancels.*

The next interesting thing we can learn from this equation is that orbital radius varies inversely with the *square* of velocity. So you see that as you move a satellite closer to earth, it moves faster. And (since the relationship is a square), if you place it really close to the earth, it moves *really* fast. This is consistent with our observations. The Space Shuttle, only a couple of hundred kilometers up, zips right along, orbiting our planet in about an hour and a half. Our natural satellite, the moon, is more like 400,000 km up. It meanders across the sky, taking a whole moonth -- er, month -- to orbit. And at an intermediate distance of 36,000 km, satellites in the so-called Clarke [6] or Geosynchronous orbit move at moderate speeds, orbiting the earth in exactly 24 hours.

Notice now what appears in the numerator at the right of **Equation 2**. Contrary to popular belief, the **GM** Product is not a Chevy. Rather, it is a constant for all satellites orbiting the earth. If we know this value (and we do: 4×10^{14} m^2/s^3) we can easily calculate the velocity for a satellite orbiting at any radius, or the orbital radius which would correspond to any velocity. Try this one, for example: what is the *fastest* possible velocity for a satellite orbiting our ideal earth?

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5 The *launch* of a satellite into its given orbit, on the other hand, is highly mass dependent. The more massive the satellite, the more thrust is necessary to insert it into its orbit. You have to kick the football hard, so that it will not only sail *high* enough to clear the goal post, but will also be moving *fast* enough not to fall short of the goal line. That is why, for example, the launch for a heavy Phase III D is so much more costly than that for a Microsat. And did you ever wonder how we kick a Phase III football into its intended orbit? Why, with an Apogee Kick Motor, of course!

6 Named for Arthur Charles Clarke, communications engineer and science fiction author who first proposed this orbit in a 1945 Wireless World article.

Well, we know from **Equation 2** that the lower the orbit, the faster the velocity. So what is the lowest possible orbital radius? If we ignore atmospheric drag, trees, mountains and tall buildings, and rule out subterranean orbits (the tunnel isn't finished yet), that would be the radius of the earth, about 6370 km. Plugging this **r**, and the **GM** Product, into **Equation 2**, we come up with a speed of about 7900 meters per second, or 17,700 mph. So now we know the top speed for your satellite, or my motorcycle.

But what about Evel Knievel's motorcycle? Rumor has it his rocket powered monster can exceed the speed we just computed above! But what will happen to him if he does? Maximum orbital velocity is also called escape velocity. Anything which exceeds this speed will break free of earth's gravity (or more properly, will find inertia exceeding the force of gravity). So in excess of 17,700 mph, Mr. Kneivel will find himself flying free of earth's influence, departing into outer space. (Some say he's already there.) In fact, any interplanetary spacecraft must be accelerated to beyond escape velocity.

Our next task is to determine orbital period, the time required for our satellite to circumnavigate the earth exactly once. If we know orbital radius, we also know circumference, the distance the satellite travels in one orbit. Since a circle contains 2π radians, the distance traveled in one orbit equals $\mathbf{2\pi r}$. At the velocity calculated with **Equation 2**, orbital period is: $\mathbf{t = d / v}$, so:

$$\mathbf{t = 2\pi (r^3 / GM)^{1/2}} \qquad \textbf{[Equation 3]}$$

We can now do what Clarke did almost 50 years ago, compute the required orbital altitude to achieve geosynchronicity. This requires us to rearrange **Equation 3** to solve for **r**, a bit awkward but not an algebraic impossibility. Let's see now, if I did this right:

$$\mathbf{r = (GM\, t^2 / 4\pi^2)^{1/3}} \qquad \textbf{[Equation 4]}$$

Plugging in the orbital period required to synchronize with the earth's rotation (24 hours, or 86,400 seconds), and our old friend the Chevy -- er, **GM** Product, the above gives us an orbital radius of about 42,290 km. Subtracting the earth's 6370 km radius leaves us with a satellite 35,920 km above our planet. Within the constraint of our simplifying assumptions and roundoff errors, that's exactly where Clarke said it should be.

ORBITAL INCREMENT DEFINED

Let's get back for a minute to this business of a spinning earth. The earth's rotation means that if a satellite orbits our planet exactly once, it will *not* necessarily come back to rest above the same point on the earth from which it started. Consider, for example, a polar orbit with a two hour period. Say our satellite crosses the equator northbound (at a right angle), zips over the north pole, crosses the equator southbound (again at a right angle), slips under the south pole, and then returns northbound to the equator again. While all this has been happening, the earth has been spinning eastward, about 1000 mph worth at the equator. Now if we note the point on the earth over which the first northbound equator crossing occurred (we call this point the orbit's *Ascending Node*), and then note where the next ascending node happens, the second ascending node point is going to be about 2000 miles west of the first.

Incidentally, the vector sum of those two circular motions (the satellite's orbit and the earth's rotation) describes a sinusoid. Which is the source of those sine-wavy ground track lines on the flat map at Mission Control, which you've seen on the TV news. Now the distance along the equator between two successive ascending nodes is called *Orbital Increment*, or Westward Progression, and is measured not in miles, but rather in degrees of longitude on that same flat map in Houston. Since our planet spins 360 degrees every 24 hours (more or less), during the course of a two hour orbit the earth has spun about two twenty-fourths of 360 degrees, or about 30 degrees. So the two successive ascending nodes are 30 degrees apart; the orbital increment is 30 degrees.

But wait, there's an easier way. If we continue to consider our ideal, two-body problem, ignore the motion of the earth and its retinue of satellites about the sun, and accept our simplified view of a perfectly spherical earth of uniform density, then orbital increment is simple to estimate. Increment (in degrees) will equal exactly the orbital period (in minutes) divided by four! This can be readily proven by dimensional analysis, but trust me.

With the Satelabe, we use orbital increment to plot successive orbits. Say we know the equatorial crossing longitude in the ascending node for a given orbit. We lay the edge of our OscarLocator cursor over that longitude on the plotter, and the curved cursor shows us the path the spacecraft will take over the earth for the succeeding half-orbit. To forecast the next orbit, we estimate increment by dividing period by four, add increment to the previous crossing longitude, move the cursor and start again. An example: During a recent Space Shuttle mission, the orbital period was exactly one hour, thirty point four minutes. That's 90.4 minutes, which, divided by four, gives us an orbital increment of 22.6 degrees. On one orbit of that mission, the Shuttle crossed the equator northbound at a longitude of 72.6 degrees West, at exactly 2145:30 Zulu. 90.4 minutes later, at exactly 2315:54 Zulu, the Shuttle will be crossing the equator northbound again, at a latitude of (72.6 degrees West + 22.6 degrees of increment), which equals about 95.2 degrees West.

By the way, how far up was that Space Shuttle? An orbital period of 90.4 minutes equates to 5424 seconds. From **Equation 4**, the orbital radius equals 6680 km. Subtracting the earth's 6370 km radius, we see that the Shuttle is only 310 km up. No wonder the overhead SAREX signals are so strong!

We still occasionally find Equatorial Crossing times for various ham satellites published in the AMSAT literature. If you know what Ascending Node value will bring the satellite overhead of your location, you can extrapolate from any given crossing time using the above method, to estimate your next AOS.

AND NOW, REALITY INTRUDES

The above computations work well for our ideal, circular orbit. But what happens when we consider the more general case of Kepler's famous ellipse? Even in elliptical orbit, gravity and inertia must always be in equilibrium. Since the distance between the satellite and its primary varies along the elliptical path, the force of gravity is ever changing. This requires a like change in inertia throughout the orbit, which is only possible if the satellite *speeds up and slows down*.

In fact, the orbital velocity of a satellite in elliptical orbit does indeed vary, from maximum at *Perigee* (the point of the orbit which brings the satellite closest to the earth) to minimum at *Apogee* (the point of farthest separation between satellite and earth). We can readily compute *Apogee radius* as the sum of apogee height plus the earth's radius. We can insert this value into **Equation 2**, to determine the satellite's velocity at apogee. We can similarly use *Perigee radius* to compute the satellite's velocity at perigee. The mean orbital velocity will be somewhere between these two values, although we would need to apply some Calculus to determine an exact value.

Similarly, since the distance between earth and elliptical satellite is ever changing, we can't directly apply **Equation 3** to determine orbital period. And although once again Calculus gives us an exact solution, here's a simple first-order approximation. Compute period per **Equation 3** for a circular orbit with radius equal to your satellite's apogee. Do the same for perigee. Your satellite's actual orbital period is roughly midway between these two values. For example, a satellite in *Synchronous Transfer Orbit* has its apogee at Clarke altitudes (the resulting orbital period , for a circular orbit, would be 24 hours), and its perigee at Space Shuttle altitudes (corresponding period an hour and a half). Midway between these two values is just under 13 hours, which comes close to Transfer Orbit period.

Remember our myth of a uniform, spherical earth? I guess you know by now that it just isn't true. After all, our planet is a spinning body. And four billion years of spin have made earth oblate, wider at the equator than across the poles. This happens to people in middle age. The more we spin, the wider we get at the equator. So we're not obese, just oblate.

The same is true of our neighboring planets, the sun, and stars in general: the inertia of a spinning body slings some of its matter outward, and makes it bulge. The effect of this bulge on a satellite is that, even if we start with a perfectly circular orbit, the force of gravity will vary as the satellite circles the earth. Since inertia and gravity must balance, this means the satellite will speed up and slow down, which makes its orbit wobble. We call this orbital wobble *oblateness precession*, and we can quantify it, although you don't really want to see the equation.

Well, OK, if you insist:

$$\theta = 9.964 * [(R_e + h) / R_e]^{(-7/2)} * [1 - e^2]^{-2} \cos i \qquad \textbf{[Equation 5]}$$

You see what I mean? The important thing at this point is not to compute oblateness precession, but to recognize its effect. Which is to make the satellite slip a little to the East with every orbit. So there goes our nice, simple estimate of orbital increment, right out the orbital window. This explains, in part, the cumulative error in extrapolating equator crossings from a satellite's orbital period. In the short term, the estimates are acceptable for communications. But over days or weeks, a new ascending node observation becomes necessary in order to obtain acceptable OscarLocator results.

The next simplification to destroy is this notion of a stationary earth. Remember that our planet is moving around the sun, at a rate of: **(360°/year) / (365.242 Days/year) = 0.985673°/Day**. So if we did a simplified orbital analysis based upon the assumption of a stationary earth, the satellite would accumulate a Westward error of almost a degree per day, when measured with respect to the earth's surface.

Well, for purposes of communications, we *have to* describe the satellite's orbit with respect to the earth's surface -- that's where we are! And at almost a degree per day, it doesn't take many days for our accumulated OscarLocator error to become substantial. Which is why, in practice, we try to obtain a new equatorial crossing point every couple of days. These the Satelabe user gets from computer-generated orbital prediction tables, which take into account the *Sidereal Precession.*

Did you happen to notice that the errors from sidereal and oblateness precession accumulate in opposite directions, one toward the East, the other Westward? This means there exists a possibility that we can design an orbit where the two effects will cancel, and we can achieve a reasonable approximation of our ideal orbit. Such an orbit does indeed exist, and it's called *heliosynchronous*, or sun-synchronous.

Satellites in sun-synchronous orbit will trace a ground track which repeats from day to day. This is most useful for earth resource assessment, and is used by NASA for many of its environmental and weather satellites. But for communications satellites, the sun-synchronous orbit has a number of important advantages beyond simplicity of orbital calculation. One is that the spacecraft can be placed in perpetual sunlight, a useful feature for systems which derive their electrical power from the sun. Another is that a satellite in a properly designed sun-synchronous orbit can, over time, provide communications access to all points on the surface of the earth. This is handy, for example, in packet store-and-forward applications. AMSAT's early Phase II satellites were all in heliosynchronous orbit, as are some of the newer MicroSats.

The final orbital simplification, the two-body assumption, is the most difficult to dispel. Our solar system has been described as being composed of the sun, Jupiter, and assorted debris. All of it, even the debris, tugs on our satellite. I know of no simple algorithm for dispensing with the gravitational effects upon an earth satellite's orbit of the sun, moon, and planets. The computations are so complex as to defy manual solution. Here, then, is an area where computerized orbital analysis is not only justified, but really comes in to its own.

DESCRIBING THE ORBIT: SIZE AND SHAPE

But we can't use a computer to analyze an orbit unless we have a means for describing that orbit mathematically. The standard description of orbits used in the current generation of AMSAT tracking programs is the *modified Keplerian element set*, a collection of numbers which allows us to extrapolate the satellite's motion over time. The balance of this article is devoted to describing the Keplerian elements in conceptual, rather than computational, terms.

We've already seen how we can define the "roundness" of an orbit by its *eccentricity*, abbreviated **e**, on a scale of zero to one. Eccentricity, the first of our Keplerian elements, actually describes the shape of an ellipse quite completely. For current ham satellites, orbital eccentricities range from a low of about 0.00076 (UOSAT OSCAR 22) to a high of 0.72 (AMSAT OSCAR 13). That's a range of three orders of magnitude, and encompasses orbits from almost perfectly circular to quite highly elongated.

Of course, the number of different orbits which could share the same eccentricity is infinite. Once having described the *shape* of our orbit, we next need to quantify its *size*. This can be accomplished in several different ways. The size of a given ellipse can be described by measuring the distance across it in the longest direction (Major Axis) or in the shortest direction (Minor Axis). These two axes intersect at right angles, midway between the two foci of the ellipse. We sometimes define orbital size in terms of half these values (Semi-Major Axis or Semi-Minor Axis). Similarly, Apogee and Perigee (the sum of which equals Major Axis) will define the size of the ellipse, or we could use Orbital Distance, the "circumference" of the ellipse.

Another way to define the orbit's size is in terms of not dimensions, but rather time. Here we would invoke the elliptical equivalent of **Equation 4**. Since the larger the ellipse, the longer the orbital period, if we know period and eccentricity, we can determine all the critical dimensions of the ellipse. And this is *almost* how we define orbital size when using satellite tracking software. But not quite.

Consider that a sine wave can be described either by its *frequency* (in cycles per second) or, alternately, by its *period* (in seconds per cycle). The latter is what we measure on an oscilloscope, and it is readily converted to the former, since the two are reciprocals. Similarly, the reciprocal of Orbital Period is Orbital Frequency, or Mean Motion. As a Keplerian Element, Mean Motion is abbreviated **N**, and is typically measured in Orbits per Day. Our current crop of satellites have Mean Motions ranging from 2.059 orbits per day (AMSAT OSCAR 10) up to 14.69 orbits per day (UOSAT OSCAR 11). The higher the Mean Motion, the shorter the orbital period, and hence the smaller the orbit.

Eccentricity **e** and Mean Motion **N** adequately define the size and shape of an orbit. It now remains for us to define the orientation of the orbit in space, and the location of the satellite within the orbit for any given point in time.

DESCRIBING THE ORBIT: ROLL, PITCH, AND YAW

Just as aircraft require three angles (roll, pitch and yaw) to describe their orientation with respect to the earth, so can we locate our elliptical orbit in three-dimensional space by developing three appropriate Keplerian Elements. The "roll" parameter refers to the angle between the satellite's orbit and the earth's equator, measured at the Ascending Node. This angle is called Inclination, is measured in degrees, and is abbreviated i. An inclination of zero degrees means the satellite's orbit always remains over the equator, with the satellite moving Eastward. Clarke orbits are an example of 0^{o} inclination. Another possible equatorial orbit, with the satellite moving Westward, would have a 180^{o} inclination. A polar orbit has an inclination of exactly 90^{o}.

Any inclination between 0 and 90 degrees defines a *prograde orbit*, which means that the satellite's horizontal motion is in the same direction as the earth's rotation. Any inclination between 90 and 180 degrees makes for a *retrograde orbit*, with the satellite's lateral motion opposite to the direction of the earth's rotation. Prograde orbits are easier to achieve, because the Eastward rotation of the earth gives us some free thrust at launch time. In fact, the closer to the equator we move our launch site, the more of this free thrust is available. Which is why the European Space Agency maintains its launch facility at Kouru, Guiana, practically on the equator. [7]

A retrograde orbit, with an inclination slightly above 90^{o}, is required to achieve sun-synchronicity. This is because **Cos i** in **Equation 5** needs to be negative, to give oblateness precession its proper direction to overcome sidereal precession. This means that launch to heliosynchronous orbit is most readily achieved from extreme Northern or Southern launch sites, where there is less of the earth's Eastward rotational velocity to overcome.

Currently our most nearly polar prograde satellites, AMSAT OSCAR 21 and Radio Sputnik 12/13, have inclinations on the order of 83 degrees. Our most nearly polar retrograde satellites, OSCARs 14, 16, 17, 18, 19, 20, 22, 25, 26, and 27, all have inclinations on the order of 98^{o}. (See, I told you heliosynchronous orbits are popular.) And our most equatorial ham satellite, OSCAR 10, currently has about a 27^{o} inclination.

For our "pitch" parameter, we locate the orbit's perigee point, in degrees with respect to earth's equator. Consider that perigee of an orbit, like the nose of an aircraft, can be oriented up or down. An *Argument of Perigee* (abbreviated **w**) of 0 to 180 degrees indicates perigee in the Southern hemisphere, with **w** = 90^{o} meaning perigee occurred over the South Pole. Values of **w** between 180 and 360 degrees mean that perigee occurred in the Northern hemisphere, with **w** = 270^{o} placing perigee over the North Pole.

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7 As that old Greek philosopher Will Rogers said, there ain't no free launch . . . but a little extra thrust reduces the cost.

Our reference for Argument of Perigee was the earth's equator. But in order to define "yaw", we need an external celestial longitude reference. The First Point of Aries, a fixed point in space by which we define the beginning of Spring, is such a reference. If we draw a line from this reference point to the center of the earth, and another line from the center of the earth to the orbit's Ascending Node (Northbound equator crossing), then the angle between these lines is our third orbital attitude parameter. This Keplerian element is called *Right Ascension of the Ascending Node* (RAAN), and is generally abbreviated **Ω**. Of course, since our planet is both spinning and orbiting the sun, **Ω** is not stable, but varies over time.

The Keplerian elements **Ω**, **w** and ***i*** give us three degrees of freedom, by which we can completely describe the orientation of our elliptical orbit in three-dimensional space. Which leaves us with but one problem yet to solve: Just where within that orbit is our satellite, at any given instant?

DESCRIBING THE ORBIT: LOCATION, LOCATION, AND LOCATION

Before we can say where a satellite is *now*, we have to know where it was *then*. But when is *then*? We need to make an observation, and clearly document exactly when that observation was made. Epoch Time, **T**, is the exact time at which a positional reading was taken. It is normally entered into tracking software as year, day of year, and fraction of a day since 0000:00 hours. Looking up **T** for an OSCAR in a recent Orbital Elements printout, I see a value of: 94159.69677441. This is interpreted as Year = 1994, Day = 159 (that's June 8th), and Time = (0.69677441 * 24 hours), which comes out to about 16 hours, 43 minutes, 21.3 seconds. Don't worry, the tracking software will do the conversion for you.

So much for the *when*. Now how about the *where*? At Epoch **T** we locate the satellite in its orbit. We use perigee as our reference point. If we divide the orbit into 360 increments which are equal by *time* (not equally spaced in position), we can measure how long since perigee, on a scale of 0 through 359. It's important to note that, even though we measure this parameter on a scale of 0 to 359 (and even call the unit "degrees"), this is *not* an angular measure of the satellite's position. Rather, Mean Anomaly (abbreviated **M**) tells us what time fraction of an orbit had occurred since the last perigee, as of Epoch **T**. Since the other Keplerian elements give us (indirectly) orbital period, we can then compute exactly where the satellite was in space at **T**, and where it will be at any future time.

Finally, we have assumed our satellites to be traveling in a vacuum, but as you know, we live at the bottom of a gaseous ocean. This stuff (mostly nitrogen, a little oxygen, and various trace elements) which we call air stays pretty much near the surface, but some of it does extend into space. To compensate for atmospheric drag, we often plug in to our software a figure called Decay Rate. This tells us by how many revolutions per day our Mean Motion will actually change, each day. It's usually pretty close to zero.

CONCLUSIONS

For ease of operation, there's nothing to beat a good GUI-driven, high resolution, math co-processor supported satellite tracking program. After all, communicating with an orbiting satellite can be equated to downing the soaring eagle with a hurled ping pong ball, while blindfolded. The computer can at the very least help to strip the blindfold away. And yes, I admit that my lab on campus boasts a fairly capable PC, on which my students crunch ephemera using a number of different AMSAT tracking programs.

But on the wall above that computer is that original OSCAR I Satelabe of which we spoke earlier. It occupies a place of honor, as it were, an anachronism of inestimable value. For it not only helps the students (and their Professor as well) to visualize the intricacies of the elliptical orbit. As we reach for the stars, it also serves as a reminder. Of where we started, how far we have come . . . and just how much further the journey may yet carry us.

ABOUT THE AUTHOR

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Paul was the 1993 recipient of the Central States VHF Society's John Chambers Memorial Award, for his contributions to amateur microwave communications. He has chaired the ARRL VHF/UHF Advisory Committee, served as Director, Technical Director and Chairman of the Board of Project OSCAR Inc., and has been a featured speaker at numerous regional VHF/UHF Conferences and ARRL Conventions. His teaching and research have won numerous national awards. He is listed in Who's Who in Aviation and Aerospace, Who's Who in California, Who's Who of American Inventors, Who's Who in Science and Engineering, American Men and Women of Science, and International Directory of Distinguished Leadership.

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DISH FEEDS FOR MODE S RECEPTION

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INTRODUCTION

For several years, I used a single loop yagi for AO-13 mode S reception. This was adequate, but sometimes just barely. In the interest of finding more gain (and the eternal quest for "armchair" reception), I started experimenting with small dish antennas. This paper offers the result of that investigative legwork and quite a bit of actual testing of parabolic antennas and feeds. An extensive bibliography is provided for those who desire additional information. This paper is purely practical and not intended to tell everything there is to know about this type of antenna. It's goal is to provide background for understanding and to offer hardware advice specifically for the reception of mode S.

DISH BASICS

A parabolic reflector, or "dish", is a reflector that focuses parallel incoming rays on a single point, called the focal point. The relationship between the location of the focal point and the geometry of the dish surface is defined (and dishes are characterized by) by the ratio of the focal length to the diameter, usually called the f/d. F/d's from .25 (where the focus of the dish is very close to the dish for a given dish diameter; this is called a "focal plane" dish because the focus is equal to the depth of the dish) to 1 (where the focus is a distance from the dish equal to the outside diameter of the dish) are practical. Is there one best? Well, like most things in life, each has its strong and weak points. We make tradeoffs to fit our requirements (or we make do with what we can get our hands on!).

FEED BASICS

Now we will leave reflectors for a minute and move to the other part of a parabolic antenna, the feed. Since the function of the dish itself is to focus all the energy coming into it on a specific point, the purpose of the feed is to efficiently gather all that energy. In yagi antennas, the longer the boom, the higher the gain. This gain is obtained at the expense of beamwidth. In other words, the longer the antenna, the more closely you have to point it at the intended target. This beamwidth characteristic, rather than the gain number, is what we are interested in for feeds for parabolic antennas.

Beamwidth is characterized in total degrees either side of center, where the gain of the antenna drops off some specified amount. In normal yagi characterization, beamwidth is defined to half-power points, where the gain drops off 3 db from the maximum. However, for dish antennas we need beamwidths at 10 db points. Standard practice for maximum efficiency is to get a feed whose beamwidth is such that the strength of the main lobe is 10 db down at the edges of the dish. This pattern of the feed on the dish is referred to as "illumination". There is also a phenomenon called "space loss" which is determined by the distance from the feed to the dish at various angles and increases with decreasing f/d of the dish. See VE4MA's articles for additional information.(1)

ANTENNA PATTERNS AND SIDELOBES

An ideal antenna would have a single gain lobe pointing directly off the end. All the energy would be concentrated in a single, defined beam. In the real world, things are not quite that nice. Besides the central main lobe, antennas have all kinds of other minor lobes shooting off in all kinds of strange directions, including backwards. A common term, the front to back ratio, is the difference in gain an antenna has straight out the front compared to the gain it has straight out the back. Yagi antennas also have sidelobes, which are usually strongest near the main lobe. On either side of the main lobe, there will be a sharp drop off in gain, called the first null. Then the gain will increase up to some maximum (hopefully less than the strength of the main lobe), then drop off again to a null, then so on to other lobes. The gain of a yagi can be estimated from the angular location of the first nulls and the strength of the first sidelobes (2). Now, you may ask, why all this business about sidelobes? If the side lobes are strong, they will pick up either other signals or just plain noise which will interfere with the desired signal. When we are dealing with UHF, this noise pickup is very important. Remember that the sky has a noise temperature of only 3-15 degrees K, and a good preamp isn't much more; maybe 80-100 degrees K total. But the earth is 300 degrees K. If your sky-pointing antenna is getting a good bit of the ol' Earth in it's strong sidelobes, the noise in the whole system goes up in a hurry. So, for space receiving antennas, we want to minimize Earth noise pickup. Obviously, for a dish antenna feed, we want one that only gets the signals reflected from the dish itself, not the nice warm ground around the dish. In practice, it is common to "under-illuminate" a dish for receiving, where the gain is allowed to drop off more than 10 db at the dish edges, because this minimizes noise pickup and improves the performance of the dish.

DISH SURFACE ACCURACY

Another point, near and dear to the hearts of homebrewers like me, is surface accuracy. Just how close to parabolic does the surface of a dish have to be to work? Fortunately, there is not a black and white answer here. Dish inaccuracies are not the difference between "it does work" and "it doesn't". The less accurate the dish surface, the more reflected energy misses the focus and the lower the gain. Generally, if the dish surface accuracy is within .1 wavelength at the frequency of interest, the effect on gain will be minimal (3). At 2400 MHz, that amounts to about 1/2 inch. Also, this rule applies to the reflective nature of the dish. While a solid dish seems like the best way to go, a solid dish has a lot of surface area to catch wind, snow, etc. and put a lot of strain on its mountings and rotors. A better approach is to use a dish with a wire mesh reflector, that will have much less wind loading, is lighter and generally easier to handle. If the size of the mesh is less than .1 wavelength, it will appear solid electrically. A larger mesh will result in reduced efficiently and more noise from the warm Earth behind the dish.

FEED CHARACTERISTICS

A question I have been asked on the air is "if I make my dish feed have more gain will it help my reception?". The answer here is a definite maybe. Remember when we talked about the fact at dishes come in various f/d's? And we want to absorb all the energy the reflector puts at the focus? And that antennas have beamwidths and patterns? The whole idea of a dish feed is to "efficiently illuminate the dish". That is, the beamwidth pattern of the feed must be matched to where it is mounted (at the focus) relative to the dish. As an example, let us take a pair of dishes, each the same diameter, say 30 inches. One is a "deep" dish with an f/d of .3. This means that the focus of the dish is .3 times the diameter of the dish, or 9 inches away from the dish. The other dish is a real flat fellow, with an f/d of .7. This dish has a focus 21 inches away from the dish. The feed's beamwidth should be such that the gain of the main lobe drops off 10 db at the outside edge of the dish. So, going back to our sample dishes, the beamwidth of the feed used to illuminate the deep, .3 f/d dish must have a -10 db beamwidth equal to the subtended angle of the edges of the dish at the focus, or 160 degrees. But the .7 f/d dish, with it's focus much further away from the dish, requires a -10db beamwidth of only 75 degrees. Clearly, one feed cannot do both!

WHAT TYPE DISH IS BEST?

So, should we use a deep or a shallow dish? After questioning a number of people who really understand this stuff, and getting several somewhat conflicting theories, there appears to be little functional difference between deep and shallow dishes, assuming correct illumination. Physically, a shallow (large f/d) dish is more cumbersome, with its feed sticking way out in front of the dish, and would require more counterweighting than would a deep dish with its focus very close to the dish. The deep dish makes a nice, compact package. But, a shallow dish deals with the section of the parabolic curve close to the center, where changes in curvature occur slowly and is therefore easier to construct. Also, the location of the feed is not as critical on a long focal length (shallow) dish. Shallow dishes become mechanically cumbersome and the feeds get quite large in order to restrict the beamwidth. A large feed may shadow a significant area of the dish itself. A deep dish, on the other hand, is more critical from a construction point of view in that it is more difficult to accurately reproduce the rapid changes of the parabolic curve further from the center of the dish. Also, it is difficult to make an efficient illuminator for a very deep dish.

Commercial dish antennas run the gamut from very deep to quite shallow, although .35 to .5 appear to be the most common. Because of the difficulty in obtaining proper illumination characteristics, .25 and .3 f/d dishes are not common in amateur circles. So the most useful range of dish dimensions tend to be in the .4 to .6 f/d range, where a number of good, efficient feeds have been published. If you are building a dish, that is a good range to think about. If you get a commercial dish, hope that is has a usable f/d! (1,4)

POLARIZATION

Mode S is circularly polarized, and while linear polarization is usable (loop yagis are linear), circular adds a few db more gain. Circularity may be obtained either directly from the design on the antenna (helix) or indirectly from feeding 2 radiating elements mounted at right angles to each other in quadrature (90 degrees out of phase) (1).

Circular polarization is used at and above 1296 MHz for moonbounce. When using circular polarization for moonbounce, it is necessary to receive on one polarity and transmit on the other (reflection off the Moon changes hand). This requires the ability to switch quickly. Fortunately, for Mode S, a single polarity is satisfactory.

The hand of circularity is critical. True circular polarization causes over 30db of attenuation between hands. For receiving AO-13 directly, the helix must be wound right-handed. But for a dish feed, it must be wound left-handed since reflection off the dish surface changes the hand of polarity.

TYPES OF FEEDS

The simplest dish feed is probably the WA3RMX tri-band feed published in QST (5). This simple printed circuit board feed should work fine with a 3' or larger dish, in the .3 to .4 f/d range. I have run swept return loss plots on this feed and while it is designed for 2304 MHz, it appears satisfactory at 2401 also. It is linearly polarized.

Another simple feed is the coffee can, more elegantly referred to as the "feed horn" (6,7). This is simply a standard 1 pound coffee can with a single probe mounted in it. Coffee can feedhorns are nice in that they are reproducible, have about 10 db of gain over an isotopic radiator and do a good job of illuminating a .5-.6 f/d dish. I have used them and they work adequately. For best efficiently, the return loss should be adjusted, but they will work adequately if built to spec. This single probe type feed is linearly polarized.

The helix is the most basic feed with intrinsic circular polarization, though they are not always truly circular. We will talk about the helix in detail.

The moonbounce guys are the ones who have developed dish feeds the most, since they demand the most from their antennas. Frequently used feeds include dipoles mounted over reflectors, EIA standard gain antennas and a wild assemblage of crossed dipoles and multi-feed horns feed in phase to produce desired polarization characteristics. See the included references for more details (1,2,3,8), as these are beyond the scope of this paper.

THE HELIX

First, helixes (helices?) come in a variety of types. The general geometry determines how the helix will radiate. When the helix diameter is small (<< 1 wavelength circumference) and the spacing between turns very close, the helix will radiate at right angles to the axis, called "normal" mode. HT's have normal mode helixes in their rubber ducky antennas. An "axial mode" helix, with circumference of about 1 wavelength and a spacing around 1/4 wavelength, radiates out the end, parallel to the axis. Much work on helixes has been empirical, so most design data exists for about a 13 degree helix pitch angle. Beamwidth and gain are related to number of turns (2).

The little helix, however, is not quite as benign a beast as it appears. I had never had particularly good results with them and wondered why. Some serious investigation and experimenting has shed some light on the subject.

First, while we have all heard how broadband they are, this may be true of gain, but it is not true of return loss, which appears to be quite narrow. And return loss is the measure of how efficiently energy is transferred (better RL means less reflection) between two devices. Also, just because a helix is round doesn't mean it is circularly polarized (return loss also greatly influences circularity).

A problem with helix feeds is feedpoint impedance. Most literature indicates that the typical helix has about a 140 ohm impedance. While it could be used with a preamp with a matching 140 ohm impedance, most common equipment has a 50 ohm impedance and the two must be matched to get efficient energy transfer between them. Although separate 1/4 wave stubs and matching sections could be used to convert the 140 ohms to 50 ohms, a popular method is to incorporate the matching transformer directly on the helix itself. This matching transformer is in the form of a widened first quarter turn of the helix itself. That fin you see on well designed helixes is not a capacitor, but actually an impedance transformer. It accomplishes its transformation by its proximity to the ground plane reflector. This is made very close to the reflector (low impedance) at the connector, tapering out away from the reflector for the first quarter turn (and quarter wavelength). Works fine, but herein lies the problem afflicting most homebrew helixes: if a proven design isn't duplicated exactly, it might work, but not very well! "Close" can yield some surprisingly different characteristics. By experiment, I have found that while you set return loss with the geometry of the matching section relative to the reflector, you set the frequency of the return loss null by trimming the end of the helix. The two are somewhat interactive. Frequency of best null is repetitive; if you continue to prune the end of a helix a little bit at a time, the frequency of the return loss null will continue to move up and deteriorate, then disappear and start over again at a lower frequency. Similar peaks occur at half turn intervals, with best peaks occurring when the overall number of turns are odd quarters; e.g. 4 1/4 turns, 4 3/4 turns. This proved true on a variety of short (<9 turn) helixes.

The ideal way to set up a helix feed is to build it to some computed geometry, then tweak it by bending and trimming while observing swept return loss. An alternative is to tweak the antenna for best return loss at a single frequency. But the way most of us will have to do it is to duplicate a published design.

By trial, a 5 turn helix has a half-power (-3 db) beamwidth of around 50 degrees and -10 db points of a little over twice that. This would indicate that a 5 turn helix would be suitable for proper illumination of a dish with a subtended angle of maybe 110 degrees, which is pretty close to an f/d of .5, a nice common value. Flatter dish, more turns. Shallower dish, less turns.

The following 4 3/4 turn design is one that has proven satisfactory for use with a .5 f/d dish (or really anything close) and provides quite good on-the-air performance. As I said, to expect this feed to work properly, you must duplicate it exactly. This construction of this feed is similar to that published by G3RUH, and since James did such a complete job of detailing his construction techniques, I won't repeat them here. Follow his instructions as noted, with the following exceptions:

1) use #8 (.125") bare copper wire.

2) Mark the wire every 5.75"; this is the length of one complete turn and insures that the helix turns will be equal after winding and stretching.

3) The total 4 3/4 turn helix will require 27 5/16" of wire, plus 3/32 nib to be filed to fit into the solder pocket of the N connector.

4) Turns spacing must be 1 1/4". Make a spacing mandrel by marking a 1 1/2" dia. rod every 1 1/4 inches (this will help get the spacing between turns right).

5) In order to position the impedance matching section properly, tape a .040" drill bit to the reflector as close as possible to the solder pocket of the N. Then tape a 5/32" (.156") drill 1/4 turn away at right angles to the first drill. These are your spacing gages. Set the matching section on the 2 drill bits and into the solder pocket on the N and solder away. If it falls apart or doesn't wind up nice and even, start over.

6) This design is set up to take weatherproofing into account and won't work right without it. Clean all flux off the start of the helix. Put a glob of RTV (I used Dow Corning 100% Silicone Sealant - Clear) on the start end of the helix and around the end of the connector to keep water out. The put another (3/8" dia) glob at the end of the matching section, between the end of the fin and the reflector. This adds mechanical rigidity to the helix, which it really needs. Note that the RTV has a dielectric constant quite different from air; if you set the return loss of the helix in air, then add RTV, it will change drastically. So these dimensions were finalized when the RTV was in place.

7) I used a 3/4" wood dowel rod (varnished) through the center of the helix as a support. It has little effect on return loss. See OTHER THOUGHTS for other notes on supports.

8) Follow the instructions on using the Sun as a noise source in order to set the location of the helix in the dish. The helix must be mounted with its "phase center" at the focal point. Where is the phase

center? On this helix, it appears to be about 1 1/2 inches in front of the reflector. So my 16 1/2" focal length dish got the feed's reflector positioned about 18 inches from the dish. While there may be a scientific method of finding the phase center, the Sun works quite well. It makes a really significant difference in dish performance.

OTHER THOUGHTS

This is the random but useful thought department.

- A useful addition to your dish is a small reflective cone directly at the center of the dish. The idea here is to reflect any energy radiated by the feed away from the feed and not directly back into it. The center of the dish is shadowed by the feed anyway and doesn't add to the signal capture. This also seems to reduce the variation in measured return loss as the position of the feed is adjusted.

- The popular small TV link dishes marketed by W1XT and Conifer are also parabolic antennas, but they have a linearly polarized feed dipole with reflector. No adjustment is necessary (or possible).

- Patch antennas (10) make satisfactory feeds for very deep dishes. Certain designs are inherently circularly polarized. Problem is that they are very touchy and do not appear to be home-buildable without network analysis gear.

- W3IWI had a very interesting concept in a helix antenna at the Central States VHF Society meeting that he called the "heli-bowl". It consisted of a 2 turn helix on a perf-board form, with a coaxial matching section, mounted in a flat-bottomed stainless bowl. It performed quite well on the antenna range.

- Don't wind a helix on a lossy form. PVC pipe is lousy and fiberglass isn't much better. Air-supported appears best for very small helixes. However, it does appear that adding a small diameter metal tube through the center of the self-supported helix for mounting has little effect on the return loss. But this is only true if the metal tube is exactly centered in the helix; the effects of lack of concentricity are graphic on a swept return loss setup and rapidly ruin the return loss as well as fouling up the pattern.

- Low-temperature silver hobby solder stands up best to outdoor service. Clean the flux off after soldering.

- Return loss testing was done with an HP 8690A sweep generator and SMA directional couplers feeding an HP 1416A indicator, and spot checked with a slotted line.

AND SO...

This is certainly not the last word on the subject, but hopefully provides some insight on small parabolic reflector antennas and feeds. Please consult the references listed for additional information.

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Monolithic Microwave Integrated Circuits at S-Band

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0.0 Abstract

Due to the increasing interest in the wireless market, an expanding number of commercial products have been introduced with improved functional integration. Dubbed monolithic microwave integrated circuits, or MMICs, these devices have reduced the number of parts required to implement many wireless applications, including GPS, DECT and PCS. This paper will focus on the TriQuint Semiconductor family, with a discussion of relavant devices from competitors. A discussion of power, size and ease of use, with an S-Band DSP application, will be presented.

1.0 Introduction

Semiconductor devices have been used in microwave systems for many years, but it is only in the past 25 years that direct generation and amplification has become practical. With the introduction of gallium arsenide (GaAs) material and its field effect transistor device (FET) in the early 1970s, the path was clear that with increasing integration of silicon (Si), that GaAs would be close behind. By the mid-1980s, the GaAs monolithic integrated circuit (MMIC) was offered as a replacement to discrete components, thereby reducing component count, PCB requirements, power consumption, and ultimately, cost.

2.0 Silicon vs. Gallium Arsenide

It has been know for many years that GaAs offers potential advantages over Si as a high frequency semiconductor material. The electron velocity in GaAs can be up to twice that of silicon yielding faster transit time for a given dimension. Also, the electron mobility is typically six times that of Si, significantly reducing parasitics. In addition, GaAs can be obtained as a substrate material with resistivity as high as 10^7 ohm/cm, compared with many orders of magnitude lower for Si [1].

As a result, gallium arsenide offers a higher frequency and lower noise behavior than its silicon counterpart. These potentials were first demonstrated in the mid-1960s and by the early 1970s the first commercial devices were available. Since that time, the FET has become the ubiquitous building block of the microwave industry.

2.1 GaAs Material

To obtain optimum performance it is essential that the devices be fabricated on the highest quality uniform material. A constant carrier concentration of approximately 10^{17} cm^{-3} with a very sharp back interface is especially important for low noise operation.

Various techniques are available for fabricating the device layers. The oldest technique for low noise devices is the epitaxy method, whereby chemical processes are used to dissociate various Ga and As compounds to deposit GaAs on the substrate. The arsenic trichloride vapor epitaxy process is the oldest, but other precesses such as organometallic techniques are becoming more common.

For the highest frequency devices where the doping and thickness require very careful control, molecular beam epitaxy (MBE) is often used. In this technique, multiple molecular beams of differing flux density and chemistry[1] are injected into a ultra high vacuum (UHV) onto a heated single crystal substrate, building material at the atomic level.

3.0 GaAs MMICs

Small signal discrete devices are used in hybrid circuit arrangements where the matching circuits are provided by thick or thin film techniques on ceramic or other substrate material. While these techniques allow flexibility in obtaining the optimum performance, they are large, and more prone to failure due to multiple bonding operations compared with a fully integrated process. The properties of GaAs semi-insulating substrates are quite acceptable as microwave dielectrics at the frequencies of interest and this allows the complete microwave circuit, containing all active and passive elements to be realized on the chip. These devices, based upon the FET as the active device, were first demonstrated by Plessey in 1976, are now commercially available from many sources and are starting to make a significant market impact.

3.1 GaAs MMIC Types

Over the frequency range of VHF to 20GHz, may circuit functions have been successfully realized as MMICs. A representative sample of the functional components follows,

- Amplifiers - small signal and power
- Oscillators - fixed frequency and tunable
- Mixers - single ended, balanced, image reject
- Phase Shifters - time delay and constant phase
- Switches - SPDT, etc
- Multipliers - xN
- Power combiners/splitters
- Logic

3.2 GaAs in Wireless Applications

Most cordless links are either in or being developed for the 0.3-3Ghz bands. Investment in technology for the 0.8-1GHz and 1.8-1.9GHz bands is directed mainly at portable phones. The 0.8-1GHz spectrum is currently used by the United States, Japanese and European communication industry. Second generation digital networks (CT-2/3), currently being developed, which will be described below, will reside in the same bands, including GSM

[1]The more widely used dielectrics are Si_3N_4, SiO_2 and polymide.

and IS-54 (NADC).

3.2.1 PCN

Also known as *DCS-1800,* PCN (Personal Communications Network) is a digital cordless phone system that occupies the 1.7-1.9GHz band in Europe, placed in service during 1992-93.

3.3.2 DECT

NADC	PCN	GSM
824-849 869-894	1.7-1.9	935-960 890-915
TDMA	TDMA	TDMA
Pi/4 DQPSK	GMSK	GMSK
8kbps	13kbps	13kbps
30kHz	200kHz	200kHz
832	3000-6000	124

CT2	DECT	ISM
864-868	1.88-1.9	902-928 2.4-2.83 5.725-5.85
TDMA	TDMA	
Pi/4 DQPSK	Pi/4 DQPSK	
32kbps	32kbps	
100kHz	1.726MHz	
40	132	

3.3.3 GSM

The Groupe Speciale Mobile (Global System for Mobile Communications) specifies the European standard for speech coding used in digital mobile communications. This system implements the RPT-LTP Linear Predictive Coding algorithm.

GSM currently has greater than 14% of the European market, with 80% of the users in Germany.

3.3.4 PHS

The Japanese Personal Handyphone System digital cordless service operates in the 1.9GHz band. Operation is expected by 1995.

PHS is a two-way TDMA comunications system operating in the 1.895-1.918GHz band and accomodates 77 channels.

A disadvantage of PHS is that is will not funcion from moving vehicles.

3.3.5 ISM / WLAN

Wireless Local Area Networks have been allocated frequency spectrum at 2.4-2.483GHz. This is within the ISM (Industrial-Scientific-Medical) non-licensed band. The spread spectrum output is limited to 1W.

4.0 MMIC Products

As the network specifications become increasingly more complex, there is also pressure to decrease the size, cost and power requirements of user equipment.

Chip makers are moving rapidly to respond to the market. M/A-COM's European business is 23% wireless related with an expected growth to 50% and a shift to subscriber equipment. Like M/A-COM, Harris Semiconductor is also trying to define is product niche, with an emphasis on base station components.

The following is a representative sample of RF chip manufactures and their products. Not all are GaAs, as silicon presents satisfactory results and will also be represented.

Motorola

Two famalies of chipsets are available for PCS, PHP and ISM wireless applications [2,3]. The MRFIC1800 family is usable in the 1.8-2.5GHz range and the MRFIC2400 series is intended for the ISM band at 2.4GHz.

The MRFIC1801 is a 2W antenna switch for the 1.5-2.5GHz band. For downconversion, the MRFIC1804 incorporates a LNA/ mixer pair with a 2.3dB NF and 18.5 dB gain. With a 1.8-1.925GHz RF input, the mixer can translate the IF to 70-325MHz. The MRFIC1802 can provided a 500mW signal to match the range of the 1804. 3.3v operation is specified for these SOIC packaged parts.

For the ISM band, the MRFIC2401 provides a downconverter block with an LNA and mixer. A break-out for a filter between the internal components is provided. The MRFIC2404/3 provide 50 ohm matching with 7dBm and 19dBm power output respectively. The MRFIC1801 can be used for a T/R switch.

RF Micro-Devices

Unlike most of its competitors, RFMD does not manufacture its own chips, but provides a foundary with the specifications.

The product line includes quadrature modulator/demodulators, LNA/mixers, attenuators, IF amplifiers with digital gain control, and power amplifiers. RFMD products cover the 0.1MHz-2.5GHz. Many parts have power down capability, and can be easily interfaced to ceramic filters.

Plessey

An excellent line of synthesizers and radio communication circuits is produced by this U.K. based company. Also, Plessey is the only manufacture of an open-architecture GPS chipset, the GP1010/1020.

Siemens

The maker of the NE602, Siemens provides an interesting line of radio circuits, including the NE604-627 IF amplifier/discriminators. With an input sensitivity typically better than -100dBm, a small number of external components, that include RLC, crystal and filters are required.

M/A-COM

Formerly Microwave Associates, M/A-COM provides GaAs DBMs, switches and amplifiers. The MA40-7100, with RF input from 0.3-3GHz will be tested for this project.

TriQuint Semiconductor

Several new low noise amplifiers and downconverter parts are available, with new products in development for ISM.

The TQ9203 RFIC downconverter is designed for cellular phone service in the 0.8-1GHz band.

The TQ9206, in development for the ISM band, contains a VCO, trnasmit/receive amplifers and control selection. The TQ9272, a general purpose downconverter rounds out the converter set. The RF input range of 0.5-2.5GHz translates to an IF of 30-500MHz. The on-chip VCO is tunable within 15% of F_c from 0.6-1.8GHz. The 13-16dB NF is rather high and with a phase noise of -65dB at 10kHz off the carrier, some care is necesasry in the use of this part.

LNAs are available separately in the TQ9121/2. Both parts are intended for use with the downconverter family, its low current drain and SOP-8 package making it ideal for battery operated equipment. Internal biasing and 50 ohm matching is included. For optimum matching on the input, an external LC network is required, either with chip components or stripline.

AT&T

For GSM, the most highly integrated chip is the W2020 transceiver, which includes a frequency hopping UHF syntheziser, two fixed synthesizers, an RF mixer, digital gain-controlled IF amplifier and quadrature demodulator. The transmit path includes an offset oscillator, mixer and 90° quadrature modulator.

The W2005 is a IS54 (North American dual-mode), GSM and WLAN compatible receiver MMIC. The RF input range is 0.8-1GHz The dual second IF amplifiers and demodulators are capable of

- analog FM limiting and FM detecttion
- DQPSK AGC amplifers with I/Q quadrature demodulators.

The 2005 is a very interesting part, low power (including sleep mode), and simple matching networks. The second IF output is matched to ceramic bandpass filters, typically centered at 455KHz with a 15KHz bandpass. Therefore, if a wider passband is required, an active filter, using a NE5532 would be acceptable.

Hewlett-Packard / Avantek

HP has been manufacturing microwave components for many years, and their SBDs have been used in many high-quality commercial and amateur mixers. With the recent purchase of Avantek, HP is now poised as a dominant force in high quality MMIC devices for cellular phone and other compact receiver designs.

Several families of parts are available, including 50 ohm matched amplifers and mixers. The INA is the preferred series for pre-matched low-noise parts with the MSA family providing typically a higher gain with increased noise figure.

The IAM mixer series, utilizing the Gilbert cell technology is available in a SOP package. Two types are available, the IAM81 and the IAM82, the later with improved performance.

Although not generally available, HP also manufacures a Receiver On a Chip (ROC) for GPS.

Analog Devices

Although not known for RF

components, AD has recently offered the AD831 mixer, with an RF input of 500MHz.

Also available is a line of Digital Signal Processors (DSP) for general signal processing, with a subset targeted at cellular phone applications, including GSM.

National Semiconductor

Targeted at DECT, the LMX BiCMOS series is intended to compete in the 3v market, with few passive external components required.

The family consists of the LMX2216 downconverter, LMX2240 five-stage IF, the LMX2320 PLL for transmit and receive, and the LMX2410 baseband processor.

The LMX2216 is a low current part (15mA), with power down to 10uA. All but one port is matched to 50 ohms.

For the IF, the LMX2240 has an RF sensitivity of -72dBm. The input is matched to interface with 110.592MHz SAW filters. A receive signal strength indicator (RSSI) is used to adjust the power level, dependent on the input signal.

A PLL is implemented in the LMX2320, with a 2GHz input and only 12mA current requirement. A 500uA power down mode is available. Like many of the new systhesizer chips, the LMX2320 has an adaptive loop filter, allowing fast lock-in times. Programmming is via a 3-wire interface.

For baseband processing, the LMX2410 provides the connection between the RF and digital logic system of the DECT radio.

Mini Circuits

MC is one of the stallworths in miniature components for compact receiver development. For RF amplifiers, the MAV, MAR series of silicon components provides stable 50 ohm in/output matched gain blocks. It is also possible to realize oscillation by applying a feedback loop.

Along with simple to use amplifiers, a new line of GaAs switches, both reflective and absorbtive, is available in 20pin quad flat package (QFP).

Philips

The majority of the components need some method of stabilizing the LOs. The SA7025/8025 series provide a dual-systhesier capabilty, with the primary unit having a fractional N capability, with a secondary PLL syncronized to the primary unit. The primary PLL has a fast, adaptive lock-in for initial setting of the channel.

These parts are packaged in two pinouts, D (50mil) and DK (26mil) pin separation. The DK part requires special care in soldering, due to the closeness of the leads.

4.1 Conventional Receiver Design

Most receiving systems for UHF and microwave bands are based on the double-conversion superhetrodyne principle. The second mixer (first IF) is generally in the VHF band. Figure 1 is a block diagram of a typical receiver, including the control back-end. The first filter (BPF) if generaly broad-band, eliminating much of the extraneous out of band energy, helping to prevent overload. A second filter defines the overall passband shape, and is typically part of the IF signal path. Either ceramic or surface acoustic wave (SAW) filters are used. SAW filters, although more expensive, are superior in out of band rejection, however, they typically have greater insersion loss.

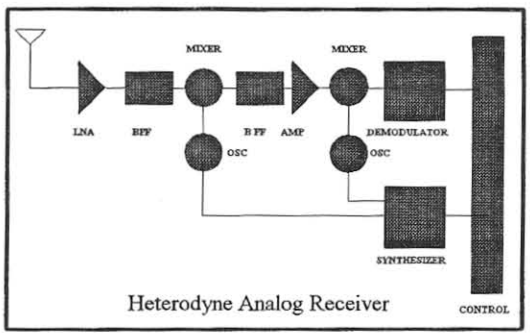

Figure 1.

Demodulation for AM, FM and digital baseband processing has been implemented with simple discrete and IF processing circuits, including the Plessey SL6601 and I/Q demodulator components from Mini Circuits.

4.2 MMIC Designs

To reduce component count, power drain, and cost, many new designs are using MMICs.The building blocks available to the designer outlined in section 3.1 are available from many suppliers. These parts are extremely easy to use and any radio engineer, amateur or professional, can design and build a successfull receiver (or transceiver) for less than $200. A digital system typically requires a greater expense in the baseband processing subsystem, such as a DSP to demodulate GSM.

4.3 DSP-based Multi-Mode Design

Since mid-1993, the author has been experimenting with the availalble RFICs for use in the 0.1-2.5GHz range. As the primary interest is GPS, Inmarsat and amateur satellite data recovery, the requiremens imposed for the design were low noise, tunable, minimum parts count, and low power. As a processor is required for GPS, the selectd device could be used for other demoluation modes, simply by initiating a new program.

The front-end (LNA) of the receiver is mounted at the antenna with an Avantek two-stage preamp providing a 0.6 dB NF with 40 dBm of gain. At the receiver is a TQ9122 preamp, primarily to provide a 50 ohm match to the antenna cable, and compensate for any loss. The 9122 output is matched to a mixer were conversion loss is minimized.

The mixer in most of the MMICs employees a Gilbert cell structure, which is not low noise. If the purpose it to use the design without the external LNA, using just the TQ9122, then care must be exercised in selecting this component for best response. In this design, several front-end mixers are prototyped, including a single-balanced FET using a Seimens CF750, a Mini Circuits RMS-25MH DBM, a Hettite Microwave HMC140S8 GaAs DBM, and a new M/A-COM DBM, the MD40-7100.

For the local oscillator (LO) that feeds the first mixer, several alternatives are available. TriQuint offers a convenient VCO in the TQ9272, that is tunable from 0.5-1.8GHz with a -7 dBm output. For a FET mixer, this is sufficient LO power, but for a DBM, requirements are typically +7 to +23dBm. This level of LO will require some degree of amplification, regardless of the type of oscillator circuit. The TQ9272 VCO can be used to downconvert the L/S-band RF, but at 1.4GHz the phase noise may be unexcept-able[2]. However, if an IF is selected in a cellular phone band, there are many inexpensive 50 ohm filters than can be used after the mixer, and the phase noise will be reduced by 20dBm at 860MHz.

It is also possible to use the standard multiply circuits, or jam a low VHF frequency into a UHF cellular filter and use the resulting harmonic. However, the TQ9272 is in a compact 20pin QFP that makes its use an interesting possibility, at least worth evaluating [2,3].

With the mixer IF output at 859MHz, a Trans-Tech cel-phone BPF, followed by a simple MSA-0611 gain block complets the first IF. The second IF is a second TQ9272. Between the mixer and the 9272 is a cel-phone SAW filter. For different bandwidths, the following filters are used

Type	GPS	DECT	CT2	IS54
F_c	35.42	110.6	150	83.16
BW_3	1.8	0.576	0.030	0.015
IL_{dB}	17	8.5	3	3

Most manufacures will provide either 50 ohm or S-parameters for custom matching circuits. A simple LC match requires only 3-4 components.

As RF gain is expensive, the final conversion to baseband can use a NE602A or RF Devices RF2701, followd by low-noise op amps to bring the signal to a level manageable by high-speed comparators or an A/D. The later component is intended for quadrature demodulation, i.e., digital systems. Typically, the RF2701 is used in a self-tuned circuit, where the quatrature phase (Q) is used as a correction voltage, and the in-phase (I) is used for data recovery.

Depending on the data recovery requirements, the level of baseband processing can load the processor only 25% for GSM to almost full up for GPS. For example, in [4], Phil Mattos used a T225 as a correlator and a T800 for computing the navigation solution and proving the map display updates. Canadian Marconi, a manufacturer of GPS receivers for the B777, uses a i486SX. GSM has been implemented with ADSP2156 and the TI 320C5x.

For this design, the TI DSP starter kit for the C50 is used. This kit includes a small circuit board with an RS232 interface, an A/D converter and software for assembling and debugging programs.

[2]A disadvantage in the exclusive use of highly integrated MMICs, the the lack of isolation between subsections, yielding less than ideal performance.

Although not complete as of this writting, the receiver outlined in this paper has been redesigned twice since the initial idea in mid-1993. The final design has been selected, with all active parts procured. Artwork for the circuit boards will use 31mil G10 substrates. The results will published at a later date.

5.0 Summary

Each component in this deisgn was tested separately. A note of caution, be wary of data sheets. If you intend to use a part in a design, don't place an unproven component on a finaly layout, unless it is tested independent of the remaining circuit.

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A Major Field Day Satellite Operation

A major FD satellite operation does not happen without a lot of planning, preparation, drive and a large dose of luck.

By Ned Stearns, AA7A

The Scottsdale Amateur Radio Club (SARC) and the Central Arizona DX Association (CADXA) have teamed for several years in putting together a major 4A Field Day operation, signing K7TR. In the past two years, the satellite station and the operating plan of that station has undergone a major change in philosophy. A partnership was made in 1993 between Bob Myers, W1XT, (FD Chairman for SARC) and Ned Stearns, AA7A, President of the CADXA to put on a major satellite effort at Field Day. The purpose for putting together the satellite operations was not only to provide QSO and bonus points for the aggregate club score, but to demonstrate satellite operation to many prospective operators. The satellite operations at the SARC/CADXA Field Day have become a central attraction and source of pride for these two major Arizona Ham organizations.

Ned, AA7A, shown here operating the 1994 K7TR Field Day satellite station. (Photo by Bob Myers, W1XT)

The prime mover in the satellite operations at K7TR has been Ned Stearns, AA7A. His background in satellite operating, Field Day operating and contesting provides a combination that is ideally matched for this effort. Planning for the 1994 FD event started on the drive home from the 1993 affair. Shortfalls in expectations were analyzed. Equipment failures were assessed. Operating strategies were critiqued. Fresh from the experiences of the 1993 Field Day operation, the planning and preparation for the 1994 effort was launched.

Field Day 1993 was a considerable success. Over 150 QSO's were made using 5 satellites; AO-10, AO-13, RS-10, FO-20 and AO-21. AO-10 made a perigee pass and provided a wild ride for an hour in 1993. Our efforts on AO-13 were hampered somewhat by the loss of the down link preamp an hour before the start of FD. The operators had moonbounce-quality signals on the two meter receiver but still managed over 100 QSO's on that bird. RS-10 sounded like twenty meters during sweepstakes with wall-to-wall signals across the transponder. Intermodulation problems hampered receiving on FO-20 due to the presence of high levels of RF from a hilltop commercial FM transmitter nearby. Operating on AO-21 during FD was a novel experience. Meek operators made no contacts on that bird. A factor that hampered the satellite effort at the K7TR station was as a result of the decision to combine VHF operating with the satellite. It seemed attractive since the satellite station had most of the ingredients needed for a hilltop VHF operation. The drawback was the resultant complexity of the station and the loss of access to the transponders during peak times while making only a handful of VHF contacts.

The real shortfall in the 1993 effort was the fact that there was only one operator — AA7A. A few brave souls stepped up and made one or two contacts but the station was complex and user hostile. It consisted of a pair of VHF/UHF mobile multimode radios, a bundle of amplifiers, a tower of power supply chassis and a bank of unmarked switches for antenna polarity control, signal routing relay control, radio control and things soon forgotten after the start of FD. In fact, the failure of the 2 meter receive preamp was caused by the station designer's failure to heed the warning on the post-it note on the switch bank and managed to use it as a dummy load. Casual observers of the satellite operation at the 1993 event probably came away impressed but thinking that satellite stations and operators are complex oddities.

The Objective for 1994 FD

The principle objective for 1994 was to broaden the appeal for satellite activity for potential new operators. Since the FD operation for SARC/CADXA involves well over one hundred participants and the two clubs' combined rosters approach 400, the number of people who would benefit from the demonstration of satellite operation is significant and warrants a first-class effort. The means of meeting this objective were to do the following:

1) Involve more operators,

2) Attract and entertain more potential satellite operators,

3) Demonstrate as many satellites as is possible,

4) Work every satellite operating mode including Mode S on AO-13,

5) Show the impact of satellite operation and help the club FD score, and

6) While we're at it, WIN THE AMSAT CONTEST!

These were not only the objectives of the satellite station operators, but were also held dear by the FD planning team and entire FD crew. The "buy-in" of the whole team is an essential element in the planning process. VHF spectrum utilization at a FD site is a premium and it would be a disaster if satellite operations were to be attempted while HT's were in heavy use. Scheduled quiet times and general coordination of the VHF spectrum are important steps to success.

THE PLAN for 1994

The resulting PLAN that was developed to meet the objectives for 1994 was similar to the initial attempt in the 1993 effort. Of course, the operation was to maximize the satellite transponder time. Over 15 hours of satellite operation was available during FD '94 and it was a given that the station would be on and operating on the most effective satellite and mode at all times. This is the same practice that is used at all FD operating positions at K7TR as well as all other serious FD stations. In assessing computer predictions of satellite passes during FD, it was apparent that AO-10 and AO-13 were in excellent positions for the contest. Good visibility to Europe was available on AO-13 and it was hoped that higher than average levels of activity would be found from there. FO-20 was still engaged in the analog mode and was available for many long passes. RS-10 and RS-12 were both in good state of health and it was expected that these would carry a large load in the contest. AO-21 and AO-27 were expected to be popular given the availability of FM mode radios, but given the experiences from 1993 it was expected to be a little difficult to make a large number of QSO's on those birds.

It seems to be a little known fact that CW contacts and Phone contacts count separately in FD.

It seems to be a little known fact that CW contacts and Phone contacts count separately in FD. It was surprising in 1993 to see so few people on this mode in 1993. Working CW on AO-10 and AO-13 was expected to be a good way to involve some low band operators on the satellite. CW signals are easier to tune in on the transponder and this was thought to be a easy way to involve some new operators.

A new concept for the 1994 satellite FD station was satellite tracking. Satellite antenna steering at a new station with unfamiliar equipment is difficult for even an experienced operator. Use of a satellite tracking device would free up the hands and the minds of the operators for the more important task of working the radios. With 28 separate satellite passes in the contest period, it was deemed to be an essential element of the system.

An essential ingredient of any contest operation is good operators. Finding a gaggle of good satellite operators with contest experience is difficult in Arizona. The approach taken at K7TR was to assemble an easy to understand satellite station and use good HF contest operators to work the station during the Molniya orbit birds where the effects of Doppler shift, polarization and antenna tracking were minimal. Several extremely competent contest operators (W7ZMD and K7NO) were made a part of the core operating team. They both were avid RS-12 operators but neither had worked any other satellite before. It is heartening to note that these two operators are both on their way to assembling significant satellite stations having had a taste of a serious operating at FD.

Finally, the last and possibly most important aspect of the PLAN for 1994 was to maximize the observability of the operation to the attending public. This was accomplished in three ways. First, the observers of the satellite station were given a feel of the operation by providing down link audio from the satellite receiver on speakers set up outside the operating tent. This was done as a result of comments received from observers in 1993 who said that they were not able to understand what was going on during satellite operations. Secondly, walk-in operation was encouraged during the longer passes of AO-10 and AO-13. Five hams at the FD site had their first experience at satellite operation as a result of this effort. And third, the satellite operation was captured on video and replayed for both clubs at the next meeting where FD results were discussed. The operation of the satellite station was the principle subject of discussion at both the next SARC and CADXA meetings.

Satellite Station Hardware Selection

The preparation for the 1994 FD satellite operation at K7TR happened to coincide with the preparation for a second operation — a DXpedition to a satellite-rare country in Africa. Several key elements of the station were being purchased by AA7A and the selection criteria for this equipment was established to maximize their utility on both operations. The criteria used for the selection involved the following equipment attributes:

1) Minimum number of components,
2) Minimum complexity for ease of setup, and
3) Minimize cabling harness.

It was envisioned that the station assembled for FD would have to be boxed up and carried on a plane to Africa two months later. The trip to Africa was later postponed, but the station is now ready-to-go for any operation involving satellites at a moments notice. The only difference between a satellite DXpedition and FD would be a minor trimming of capability for, say, Mode K and Mode S operations. The incremental benefit of those two modes has minimal payback given the costs of shipping excess baggage.

The design of the operating station for FD also affected equipment selection. The station was designed to support two operator access in order to facilitate novice operator training.

The design of the operating station for FD also affected equipment selection. The station was designed to support two operator access in order to facilitate novice operator training. The equipment selected should also be simple to operate and idiot-proofed to prevent damage to equipment that was unrepairable in either Africa or deep in the ponderosa forests of northern Arizona.

The satellite equipment must, of course, provide coverage on all of the satellite bands and modes. The initial requirements for the station were to provide the following:

1) 21 MHz — rotary gain antenna, 100W, CW/SSB

2) 28 MHz — Omni antenna with narrow band preamp

3) 145 MHz — RHCP antenna, 100 W with preamp, FM/CW/SSB

4) 435 MHz — switchable polarity CP ant, 100W, FM/CW/SSB

5) 2.4 GHz — something easy

It was also important to not be required to totally disassemble a home satellite station in order to go on FD or DXpedition. This requirement actually affected the selection of the satellite equipment as well as a re-design of the home satellite station at AA7A. The equipment selected for the 1994 FD satellite operation was the following:

1) Mode K uplink: FT902DM

2) Mode A uplink: FT-726R, RFC 2-117

3) Mode A/K down link: Ameco PT-3 preamp, FT-726R

4) Mode B uplink: FT-726R, D1010

5) Mode S down link: DownEast Microwave P/A & Xvrtr, MMT144/28S, FT902DM

6) Mode J down link: Mirage KP-2/70CM preamp, FT-726R

7) Mode B down link: Mirage KP-2/2M preamp, FT-726R

8) HF Antennas: 21 MHz - 3 element monoband Yagi with rotor and mast

9) 28 MHz: RHCP array with self-supporting antenna stand

10) VHF/UHF Antennas:
145 MHz — M² 22CP
435 MHz — KLM 40CX
Mode S — R. Myers SB-32 2' X 3' linear feed dish
AZ/EL system — Create tower, G5400 rotor, 10 foot crossboom

11) Satellite tracking:
SASI Sat Tracker
Battery operated laptop computer
InstantTrack (IT) tracking program

The satellite down link audio was derived from the FT-726R and was piped into a small monaural amplifier which drove speakers outside of the operating tent. This did not affect the satellite operators at all and did not give rise to any audio feedback problems during satellite operations.

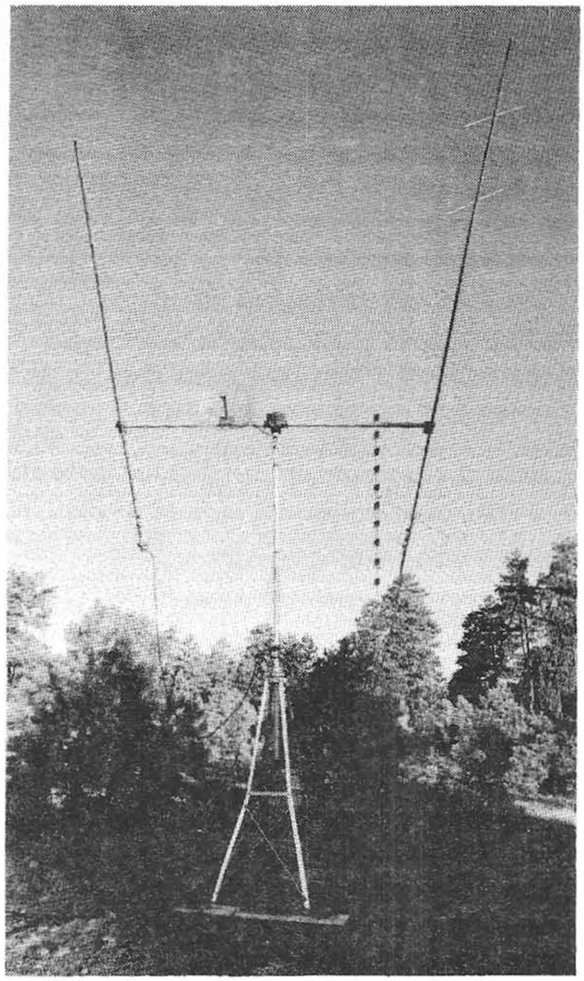
Hardware Preparation

The effort to assemble the satellite station at the FD site without a hitch was a primary goal in preparing for the equipment. The home satellite station at AA7A was modified significantly in order to support system checkout for the FD and DXpedition equipment. The AZ/EL antenna system at AA7A was converted into a satellite antenna test site. A base-hinged, tilt-over tower was developed to support rapid assembly, test and disassembly of antennas and support equipment. Numerous combinations of antennas and preamps were evaluated in the months prior to FD using this setup. A full configuration of the planned antenna farm for FD could be assembled and erected on this facility in less than one hour and could be performed single-handedly.

The FD satellite tower was fully assembled prior to departure. The azimuth rotor was mounted in the tower and the tower was transported to the site in one piece. A weather-proof box was mounted to the satellite tower and included mounting features for the Mode S down converter and provided barrier strips for wiring terminations for cables to the rotors and Mode S equipment. The satellite tracking system using the SASI Sat Tracker was integrated with the AZ/EL rotors and the laptop computer as an entire system and tested prior to departure. Aiming accuracy was proven before attempting to accomplish this technical challenge while out in the woods.

All radios that were to be used in the satellite station were thoroughly checked out prior to departure. The entire station was assembled and operated for two weeks prior to FD to work out all the bugs. All interfaces between radios and amplifiers were tested for compatibility and interoperability.

The most time consuming activity in preparing for FD was in the preparation of cables. A single, multi-conductor cable was prepared which would include rotor control, polarity control and Mode S converter power. The cable was unambiguously marked to prevent malassembly at the FD site. One-half inch hardline was used as feed line to the satellite antennas. This effort was probably not technically critical but was done to prevent damage to the feedline from rain (a somewhat rare event at FD in Arizona) and from the effects of four-wheeled drive trucks running over them (a somewhat common event at FD in Arizona). Needless to say, the uplink transmitter power delivered to the satellite antennas at our FD site were better than what was done at the home station.



The portable tower, rotor, crossboom, 2 meter and 70 cm antennas and the S-band antenna assembled by AA7A for the K7TR Field Day 1994. The vertical "item" with ten "dots" near the right side of the boom is an antenna for a 100 kW FM station about 1500 feet away from the K7TR setup. (Photo by Bob Myers, W1XT.)

Planning the Operating Schedule

Computer predictions of the satellite orbits of the seven selected satellites (AO-10, AO-13, RS-10, RS-12, FO-20, AO-21 and AO-27) indicated that a total of 28 passes were available during FD 1994. Not all satellite passes were usable with some of them occurring at extremely low elevations, some during transponder OFF periods and some occurring simultaneously with others. In fact, at one point in the FD event, 4 satellites were simultaneously available. Preplanning activities consisted of evaluating the orbits and establishing a operating schedule for the FD weekend based upon maximizing the station score in FD. In addition, a set of satellite pass predictions was prepared for the full day before FD and a station checkout plan was derived to assure that all equipment was working and modes available prior to the start of FD. Satellite orbit pass data was printed out and encapsulated in plastic sleeves in case manual tracking was required (these sheets doubled as coasters for coffee mugs). All data was at hand in the satellite operating position in case a change in the operating plan was warranted as a result of last-minute changes to the satellite transponder schedules.

Every operator at FD at K7TR spent time at the satellite station and got a first-hand view of the operation.

As a means of meeting the objective of demonstrating satellites to potential new users, predictions were also made for MIR, UO-11 and DO-17. Between passes of the low Earth analog Birds when no FD operating was in progress, DOVE passes were caught and the digitalker was played on the speakers for the crowd surrounding the tent. With this in the background, the operating crew was able to spend time demonstrating the equipment to on-lookers and spread the word about satellite operating.

Results of FD 1994

It is abundantly clear that the satellite FD effort at K7TR was a monstrous success. The comments from the fellow FD operators was quite satisfying. Every operator at FD at K7TR spent time at the satellite station and got a first-hand view of the operation. Many members of both clubs have launched efforts to build or upgrade satellite stations as a result of their exposure to satellites at Field Day.

Over 300 contacts were made using all seven selected satellites in the 1994 effort. This accomplishment may be hard to duplicate if either AO-10 or AO-13 expire soon. Having two major Molniya orbit passes during the FD event may never happen again. It will certainly be a challenge to beat this score in years to come.

It was considered a huge success to make contacts on Mode S. The band was "worked out" in a matter of minutes. Most stations on that mode were oblivious to FD and most of the time was spent reiterating the fact that we were truly operating portable in the woods in northern Arizona. You could count on a couple of fingers the number of portable stations that were equipped for FD in 1994. Given the size of the antennas needed for this mode, it might be reasonable for some FD stations to work the satellite for the bonus points on just this one mode. The challenge in that is finding the 2.4 GHz equipment that is portable and available for use in FD.

Two new satellites were worked this year — RS-12 and AO-27. A large number of stations were found on these Birds but a very small number of contacts were made on these two Birds.

In summary, satellite operation was a major attraction at the FD site and was a source of incredible satisfaction for all involved at the operation.

Conclusions and Observations

Mode A and Mode K operation was incredibly hectic this year. The Mode K station at K7TR had full duplex capability and it was very frustrating to call stations on their frequency with the same or higher signal strength and not be heard. Our impression was that the majority of stations operating Mode K were not receiving their own down link signal and were basically guessing where they were in the mess on the transponder. It would help all Mode K operations to try to work full duplex. Mode A operating was not as good this year as in 1993. The only explanation may be that the number of stations trying to operate was much higher this year and the amount of tuners and whistlers trying to find themselves was much higher. Since Mode A and Mode K operations are the mainstay of most of the satellite operations of FD stations, this may always be the case. The only suggestion to make is to work on the receiving capability of the satellite station, just as you would at your home station. The "Hang Ten" RHCP loop array used at K7TR has been in use for two years and is an outstanding antenna for use on ten meter satellite down link. Getting the word out on simple and effective satellite antennas for portable operation may help in this area.

It is clear after two years of FD satellite operating that some form of operating protocol on AO-21 and AO-27 is needed. Much of the transponder time during passes was dominated by stations who either could not receive at all or failed to listen. On one pass on AO-27, a southern California station spent the entire pass capturing the transponder by calling CQ without responding to a single station's reply. There is a principal difference between operating on these two transponders and those employing linear pass bands. On AO-13, if you cannot hear the down link signals then you do not make QSO's but everyone else will. On AO-21, if you cannot hear the down link signal then nobody makes QSO's. Either the satellite station operators at FD must be savvy enough to understand that they should not be trying to operate AO-21 or AO-27 when they are not hearing the down link signal (fat chance!) or it should be announced that these two birds are not to be used for operation during Field Day. There were times during the last pass of AO-27 during FD that the down link audio was disabled from the local P/A system due to the operating practices and language that were being displayed. Some of this was no doubt due to the frustration levels of operators and some of it was that stuff that always comes out from jerks on frequencies where there is a built-in, captive audience. For this reason, K7TR will no longer use AO-21, AO-27 or other channelized satellite transponders in FD operations in the future.

Plans for next year

The principal objective for the K7TR operation next year can be stated simply — "Try to find some shade." It is understood that every FD operation across the country has their own, unique brand of hell. In Arizona, it comes in the form of intense "dry heat". On the weekend of Field Day in 1994, temperatures at the site exceeded 100 degrees. The satellite station, however, was situated in an open gravel pit (visualize solar furnace, if you will) without any form of shade and temperatures of 110 or more were estimated in the tent during the day.

We are anxiously awaiting the launch of RS-15. The orbital predictions for this Bird indicate that it will provide spectacular coverage with pass durations exceeding 30 minutes. This will provide an outstanding Mode A satellite that will be very popular on FD.

We are all hoping that we don't see the demise of AO-13. We are all patiently watching the telemetry data and observing the delicate control of the satellite operation as it passes through the eclipse periods and as its orbit decays. It may be that FD 1995 will be the last time that this tremendous satellite will be available.

It is the expressed intent of the K7TR satellite group to exceed 400 satellite QSO's in 1995. This will be accomplished by even better preparation, expanded capabilities and more trained operators. The group will also include digital satellite operation next year to increase the score in the AMSAT contest. The group may also attempt some contacts using OSCAR Ø (EME).

See you all next year from K7TR/7! ■

Arctic HF Satellite Radio Propagation Studies

by John Branegan CEng MIEE GM4IHJ on 24 July 1994

HF radio propagation events over or near Arctic regions occur in repeatable sequences in accordance with a prescibed menu. If you are alerted to the opening overture. Then you can anticipate the timing of the various modes of propagation involved, usefully employing almost everything on the menu sequence. This situation became clear as a consequence of the availabilty of HF satellites, which covering the world as they do, permit examination of propagation, irrespective of time and, the availability of operators or beacons, at the far end of any potential communications link. A few years ago the word was that as the Solar cycle moved towards its 11 year minimum , sensible operators shut up shop on certain circuits and frequencies. The same philosophy applied to polar circuits in winter darkness. They were almost completely abandonned . This is no longer the case . This report attempts to explain why.

History

The main impetus for these studies began when Patrick Gowen G3IOR began to try to explain some of the, at times, surprising results being obtained on Mode A 29 MHz down Oscar satellites in the 1970s. Launch of the two ISKRA satellites (HF up and HF down) in the early 1980s provided more information, and thereafter a group of UK radio Amateurs began exchanging data on the sometimes strange propagation events they were encountering. Again G3IOR led the way and he continues to do so, now in the 1990's, using the almost perfect propagation probe represented by the Russian RS12 HF up HF down satellite. Meanwhile in a related but originally separate study Professor Bob Brown NM7M began collecting evidence which would reveal that far from being dead as far as HF propagation was concerned, the Arctic regions in their winter months of 24 hour darkness, had at least two modes of useful propagation as high as 29 MHz, which could be exploited on a roughly one day in 5 basis. Indeed follow up work by GM4IHJ has established that these events have a pattern and are, to a great extent predictable, thus bringing the subject to the point were it can be usefully used by all radio amateurs who wish to do so.

Method

Several different procedures have been employed to unravel, the at first, rather mixed evidence whereby the propagation mode was observed but its physical characteristics were at first unknown. G3IOR combined regular operation on HF satellite RS12 (whether it was above the UK horizon or not), with terrestrial DX working on 14, 21 and 28 MHz (Ref 3). GM4IHJ favoured by the most northerly site, monitored the 29MHz beacons on RS10 and RS12 satellites where ever they where on their orbits, and complemented this with regular checks of 28 MHz beacons and communications traffic (Ref 4). NM7M monitored RS10 and RS12 from his station in the Pacific NorthWest of the USA, and in addition he carried out regular checks of long and short path HF communication circuits (Ref 1). Short Wave listener J K Andersen in Skagen Denmark, added essential corroboration to everyone elses studies, monitoring the RS10 and RS12 satellites, from his home station.

Results Table 1 Typical Polar Propagation Event Sequences

Sequence 1 caused by a Coronal Hole
30 Nov Plasma Injection Propagation
1 Dec Terrestrial HF propagation pre storm enhancement, and a Major Plasma injection event series, with magnetic storm commencement followed by Trans Auroral propagation
2 Dec Magnetic storm and Trans Auroral Propagation
3 Dec Magnetic storm decreasing

Sequence 2 caused by Solar Filament Break Up
7 Dec Magnetic storm followed by Trans Auroral propagation
8 Dec Magnetic storm and Trans Auroral Propagation

Sequence 3 caused by a Coronal Hole
15 Dec Terrestrial HF Propagation temporarily enhanced
16 Dec Magnetic storm and Trans Auroral propagation

Note.. In none of these sequences did the Planetary Magnetic Index Kp rise above Kp4. So these were all relatively minor storms. This is probably why no Sudden Ionosperic Disturbances (SIDs) were reported. What is apparent is the presence of a general "Menu" of propagation types appearing in a rough semblance of order. The individual sequences have a varying assortment of items from the general menu of propagation types comprising, in chronological order :-
Solar event Enhancing the Solar Wind
Sudden Ionospheric Disturbance on the daylight side of the Earth
Temporary Enhancement of Terrestrial HF Ionospheric Propagation
Sub Polar F layer Plasma Injection (Ref 1, 5 and 6)
Onset of Magnetic Storm
Trans Auroral propagation
VHF Back Scatter Propagation
Some sequences include more propagation types than other sequences, with "Trans auroral " being the most frequent. Plasma injection is the next most frequent type encountered with Terrestrial propagation pre storm enhancement and VHF Radio back scatter being present only rarely. A detailed description of each of the propagation types involved is attached as Appendix 1.
Table 2 shows a record of 29 MHz propagation events over the Arctic between 22nd Oct 92 and 25 Dec 93. A total of 430 days with 251 events. In the period up to 1st April 93 only Polar Plasma injection events are reported . It was not appreciated at this time that there was a second family of Trans Auroral propagation events. From April 1st 93 both Polar Plasma Injection events and Trans Auroral events are reported. There were 62 Polar Plasma events and 110 Trans Auroral events. By May 93 it was becoming clear that a careful watch on Solar Events was producing evidence of a direct connection between what happened on the Sun, and what happened a few days later over the Earth's Polar regions. Forewarned by Solar events it gradually became possible to discern in the records a regular pattern or menu of events as described above. Attention to this pattern has revealed that almost all the propagation events can be coupled to a precursor event on the Sun, and given the regular timely distribution of solar information becoming available to Radio Amateurs via their worldwide High speed Digital communications satellites, there is now no reason why usage of these exciting polar zone propagation events should be restricted to specialists. Indeed all radio amateurs should henceforth be able to utilize these communications opportunities both via HF satellites and, HF terrestrial communication via the ionosphere.

Conclusions

For the student of HF ionospheric propagation it is now clear that the higher HF frequencies 18, 21, and 28MHz do not cease to be useful when the solar cycle is near its minimum , or when local winter brings 24 hours a day darkness to polar areas. For the experimenters, there is still a great deal that needs to be cleared up. We know from Ref 2 Professor Rosenbergs work in the Antarctic that conditions there mimic Arctic conditions in the appropriate seasons, but we have no other Southern Hemisphere information. Meanwhile, general distribution of the information in this report in the Northern Hemisphere should rapidly multiply the knowledge base there and perhaps allow us to find the reasons why some propagation menu features are absent from some events, but not from others.

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4. Branegan, RSGB Space Radio Handbook p8 to 12. RSGB Potters Bar London 91
5. Lockwood,Denig,Farmer,Davda,Cowley and Luhr, Ionospheric signatures of pulsed reconnections at the Earth's Magnetopause, Nature Vol 361, 4 Feb 93 p424
6. Rodgers and Dudeney, Merging at the Magnetopause , Nature Vol 361, 4 Feb 93 p407
7. Gosling J T, Coronal Mass Ejections, Phys Fluids B4 Vol5 No7 July 93 Am Inst Physics

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TABLE 2. NORTH POLAR PROPAGATION EVENT CALENDAR GM4IHJ 56N 3.6W
            November 92      I I       December   I
                             III     I            II    I
                    II     I III I IIIIII    I   III IIII I   II
..................................................................
    2    1     6    1    1    2    2    1    6    1    1    2    2
    7               1    6    1    6              1    6    1    6
                                                      I
      January 93                  February 93         I     March
                                                      I  I
                                             I  I  I  I  I
                                             II I  I  I II
                                             II I  I  IIII I
         I                                   IIII  I  IIII I    I
..................................................................
    5    1    1    2    2    3    4    9    1    1    2    1    6
         0    5    0    5    0              4    9    4
         I
    I    I March        April 93                   May 93
    I    I             X                                       X
    I    II         I  I XX                     I       X      X
..................................................................
    1    2    2    3    5    1    1    2    2    3    5    1    1
    6    1    6    1         0    5    0    5    0         0    5
                       X  X        X
     X  June    X      XX X        X   July 93
I    X          XX  XX IX I       XX                             X
I    X   X      XXXXXX II III    XXI                 XX          X
IX   XX  X X    XXXXXX II III    XXIX   XXX   X   X  XI         II
.....................................//...........................
    3    4    9    1    1    2    2    9    1    1    2    2    3
    0              4    9    4    9         4    9    4    9
                        X
                X  I    X
   August 93    XX I    X      September 93               October
                IX I  X X
                II I IX XX                    X
      X  X      II I IX IX  IX         X      X          X
.................................................................
    9    1    1    2    2    3    8    1    1    2    2    3    8
         4    9    4    9              3    8    3    8
         X                       X
         X                       X
         X                       X
October  X         November 93   X       X December 93
         X                       X       X
         I                   X   X       X
       I I                   X   I       IX    X
I      III X    X I          X   I       IX    X
I     IIIIXX X  IIIX         I   I      IIX    XX I     X      XX
................................. // ............................
   1    2    2    3    8    1    1    2    3    8    1    1    2
   9    4    9              3    8    8              3    8    3
```

Legend I indicates a presumed plasma injection propagation event
X indicates a presumed Trans Auroral propagation event

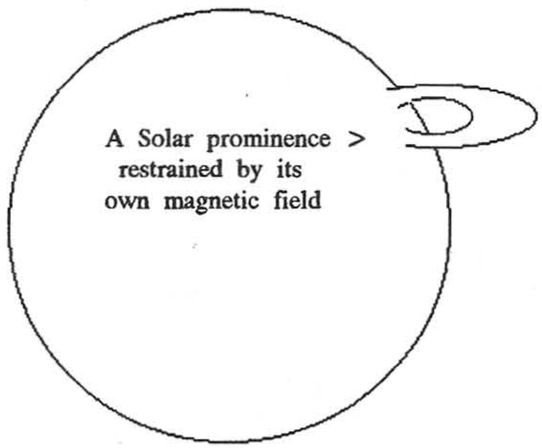
Oct25 4 plasma injection sub horizon and 5 Trans auroral events

NB Trans Auroral events were not sought/recorded before April 93

Appendix 1 - Operating Notes

Eruptions on the Sun

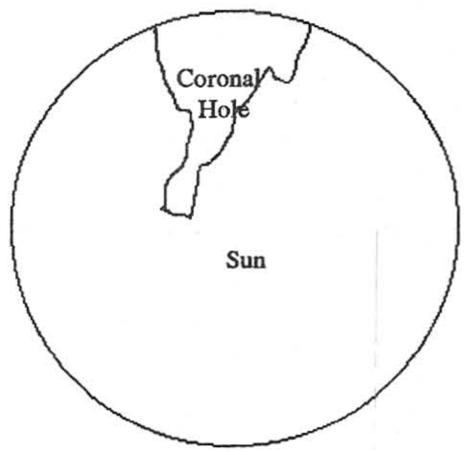
Figure 1



Driven by changes in the Solar Magnetic Field Coronal Mass Ejections send billion ton blobs of gas into space at up to 2000 km/sec. The Earth intercepts about 70 Mass ejections each year when solar activity is at its peak, but fewer than 10 per year at solar minimum.
The first indication of a mass ejection is usually the arrival at the Earth of ultra violet and X rays which have travelled at light speed. These rays cause heavy HF signal attenuation in the ionosphere for minutes or hours. The Mass Ejection plasma material then arrives at the earth about 1.5 days later triggering a massive magnetic storm.

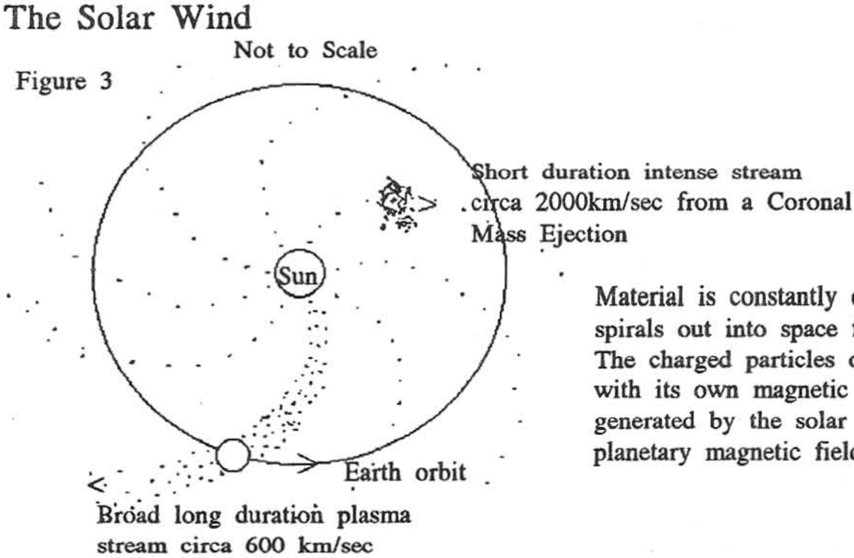
At other times. particularly as the Solar Sunspot cycle decreases towards its minimum, areas near the solar poles lose their restraining magnetic fields. This allows a slow but steady drain of escaping solar plasma to leak into space At times, big coronal holes can extend down across the Solar Equator. Coronal holes can have long lives, extending over several 27 day solar rotations . So the Earth can encounter Coronal hole plasma discharges every 27 days or so, and because of the size/width of some Coronal holes ,the earth can be in the discharge stream for several days.

Figure 2



The Solar Wind

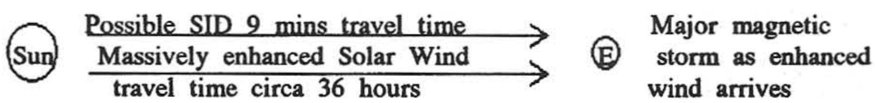
Figure 3



Material is constantly escaping from the Sun. It spirals out into space forming the "Solar Wind" The charged particles of this wind form a current with its own magnetic field. This magnetic field generated by the solar wind is called the Inter planetary magnetic field (IMF for short).

Large scale solar events such as Coronal Mass Ejections, inject very dense concentrations of material into the solar wind which moves at high speeds of 2000 km/sec. This high speed means that mass ejections travel down the solar wind much faster than the output of coronal holes which move at about 600 km/sec. So the mass ejection induced sections of the solar wind often overtake and crash into slower material which left the Sun some time before. These collisions can produce very dense wave fronts which can still be recognised far beyond Pluto the outermost of the known planets

Mass Ejection Sequence



Coronal Hole Sequence

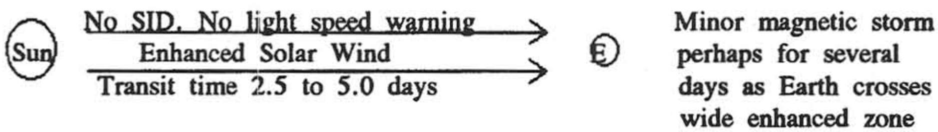


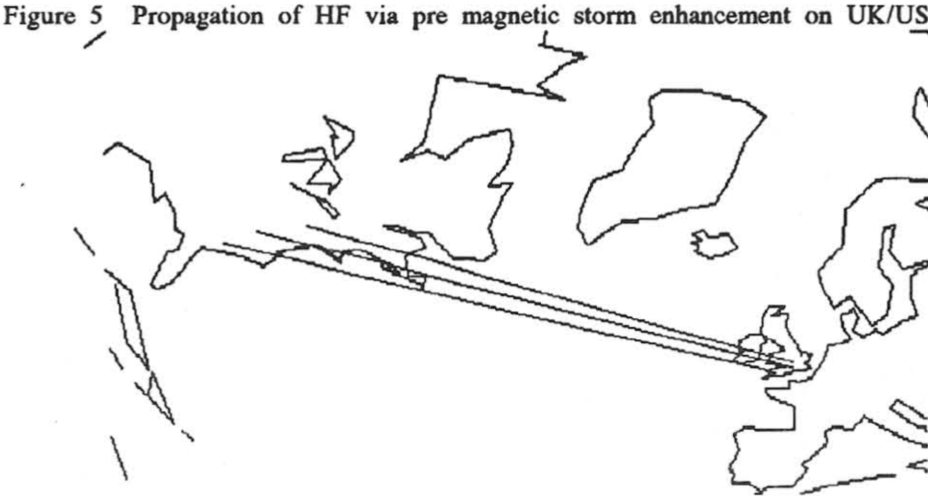
Figure 4A and 4b

In both cases the magnetic polarity of the solar wind and its interplanetary magnetic field are dependent on the instantaneous content of the solar wind front hitting the earth.

Temporary - HF Propagation Enhancement

Almost directly coincident with the arrival of the enhanced solar wind at the Earth, there is often a short period of one or two hours when the daylight ionosphere is strengthened to the point were the maximum usable frequency for HF propagation is temporarily increased. As a result of this as Figure 5 shows, communications between UK and Eastern USA which had been dead on 28 MHz for weeks. suddenly became possible on transatlantic paths where the local time at the centre of the path was around local noon or early afternoon. This particular enhancement was caused by a coronal hole enhanced solar wind and the effect dissipated as the magnetic storm triggered by this enhancement began to affect the sub polar ionosphere.

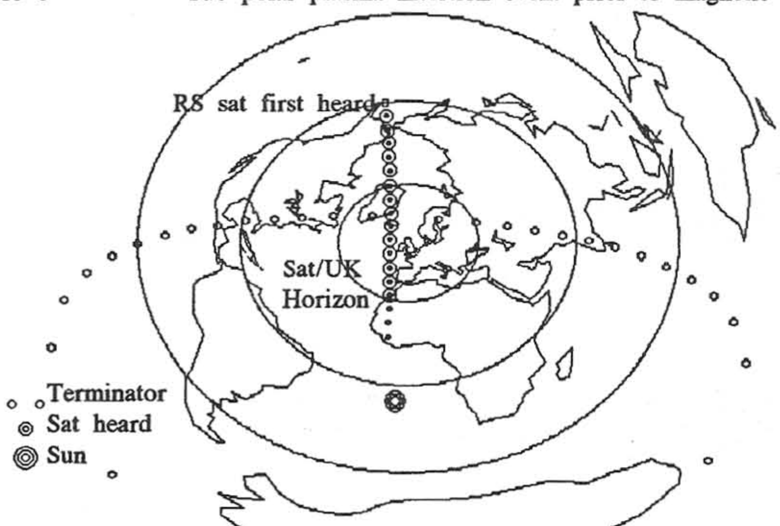
Figure 5 Propagation of HF via pre magnetic storm enhancement on UK/USA path



Plasma Insertion

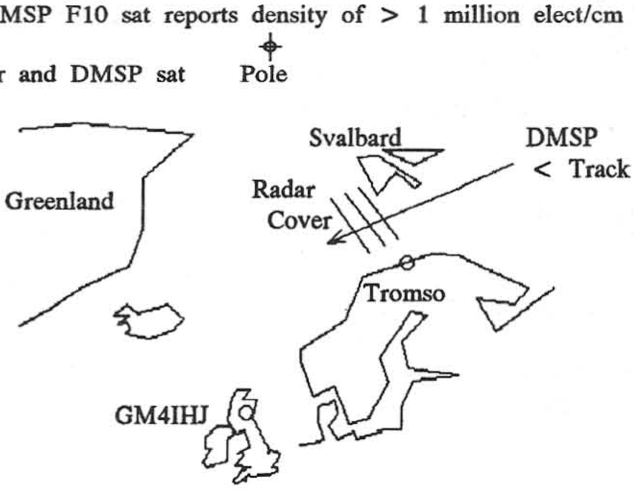
During enhancement of UK/USA terrestrial communication mentioned in the previous paragraph , there was evidence of F layer plasma insertion into the local noon time ionosphere over sub polar paths. This was noted as an extension of the range of RS12 signals from beyond its natural horizon.

Figure 6 Sub polar plasma insertion event prior to magnetic storm



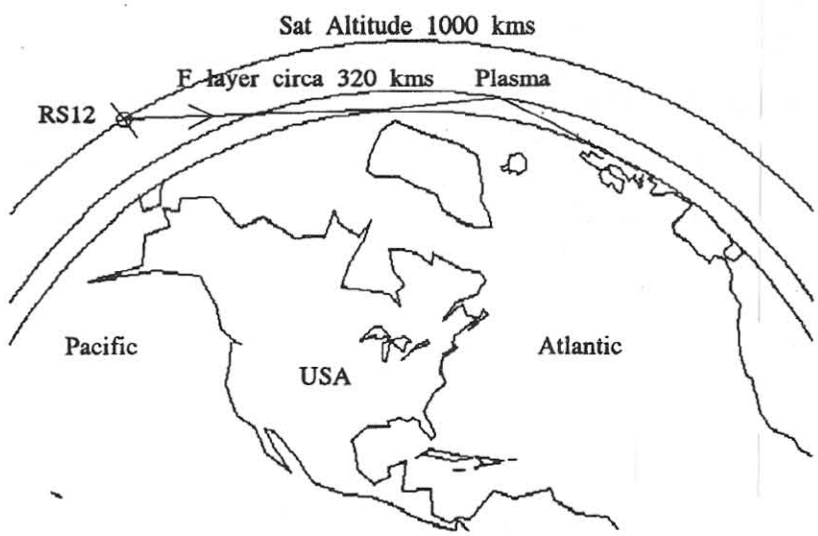
How is the Polar signal propagated? In Ref 5, Tromso radar reveals F layer plasma south of Svalbard at 75N 12E, whilst DMSP F10 sat reports density of > 1 million elect/cm ^{3} in the F layer.

Figure 7 Tromso radar and DMSP sat



How plasma in Fig 7 might permit RS 12 over Siberia to put a 29.408 MHz signal into UK

Figure 8



On numerous occasions in the winter 91/92 and 92/93 , signals from Radiosport satellites over A4 Alaska and Siberia were received in UK in the time slot 0830 to 1530 utc. As the scale drawing in figure 8 shows , this was possible provided the ionosphere beyond the pole from UK was thin enough to permit easy downward penetration of the RS signal , thereby allowing the signal to travel on over the pole at low altitude, then rise to meet the ionosphere north and east of Iceland. At which point the signal was refracted by the ionosphere , down to the receiving station in Scotland.

How does the Plasma get into the Polar arc ?

Figure 9 The Earth's Magnetosphere > > > > > > > > > >

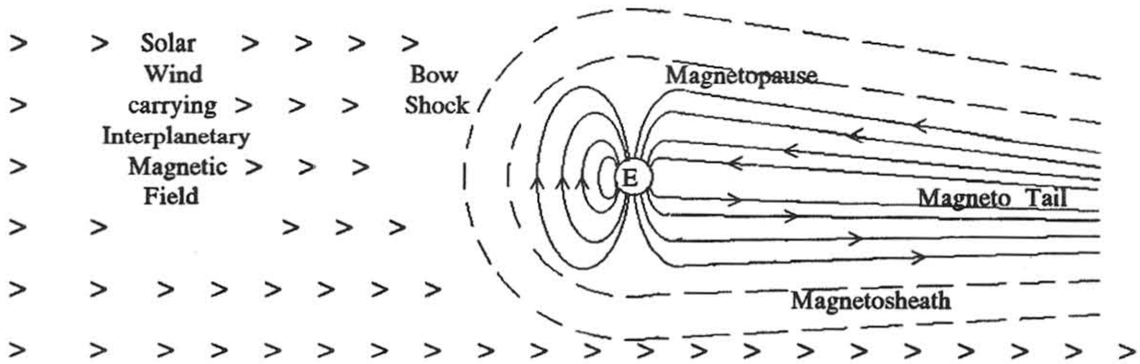
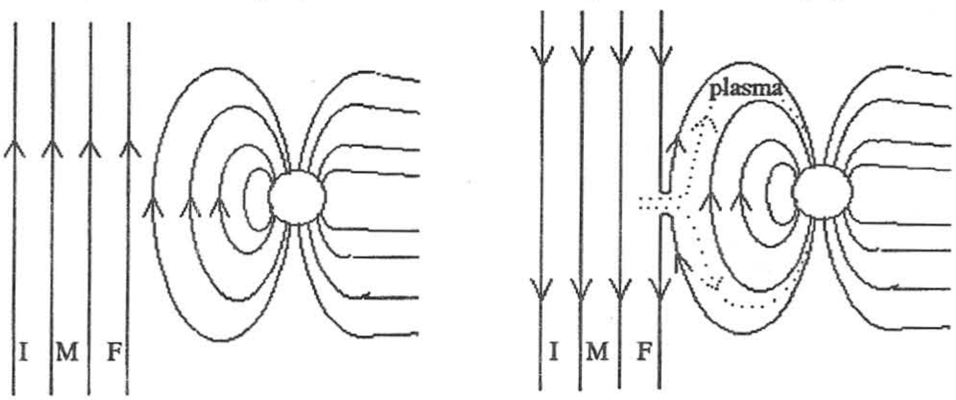


Figure 9 shows a side view of the Earth and its Magnetosphere. Coming in from the left is the Solar Wind composed of ionised gas/plasma, moving at high speed out from the Sun. Some Solar Wind plasma intercepts the Earth .The resulting collision between the Earth inside its magnetic field , and , the Solar Wind - a high speed "Electric Current" with its own built in mobile magnetic field referred to as the Interplanetary magnetic field (IMF), crushes the Sunward side of the Earth's magnetic field and flows around it to produce a tear drop shaped magnetic cavity delineated by the Magnetopause boundary, between the IMF and, the Earth's own magnetic field. In general,stations on the Earth's surface only notice the effects of the Solar wind when that wind is enhanced by the massive Coronal Ejections, or, the steady slower but still powerful output of Solar Coronal holes. When enhaced the Solar wind flows over and around the tear drop earth field causing major magnetic changes behind the Earth in its Magneto Tail. This Magneto tail interference from the Solar wind results in plasma in the magneto tail being fired back at the Earth into its polar regions producing Aurora. This is not the mechanism producing polar F layer plasma injection . Auroral effects are reported in later paragraphs.

Figure 10 Northerly IMF no Merging   Southerly IMF allows merging



The steadier Arctic plasma injection mechanism which provides Trans Arctic Propagation is not fully understood. But there is a strong clue whereby in certain states of the Solar Wind generated IMF, merging can provide a "hole" allowing some solar wind plasma to get into the Polar Ionosphere. Fig 10 shows two states of the IMF at the collision boundary with the Earth's magnetic field .The northern IMF and Earth's field cannot merge. But a southern IMF and , the Earth's field can merge

Repeated Plasma Injection Events

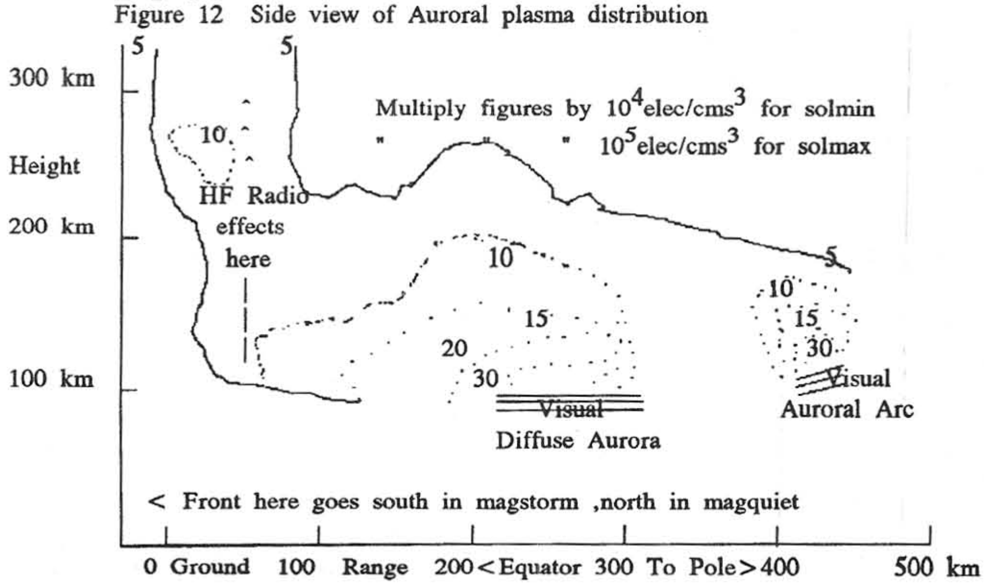
Once in the sub polar ionosphere there is evidence from radar that the plasma migrates quickly towards the north magnetic pole. Evidence from the radar and from observation of several successive orbits of HF satellites RS10 and RS12 suggests that individual injection events may only last for 30 or 40 minutes at most, but, on some days, there may be a sequence of injection events over several hours. Coronal hole activity has regularly produced events over several days with the 2nd day event series being of much longer duration than the rest. Figure 11 shows a series of satellite tracks whose signals propagated over the Arctic to UK in a 5 hour sequence roughly centred on local noon.

Figure 11 Subhorizon tracks 2 RS12 3 RS10 over a 5 hour period

Radio communicators should note two points. Firstly not all solar wind enhancement events produce plasma injection propagation . Perhaps because the Interplanetary Magnetic Field of the solar wind is the wrong polarity for coupling with the Earth Magnetic Field. Secondly , useful propagation over Arctic paths by way of plasma injection, is not confined to 29 MHz satellite users. There are several reports of terrestrial communications enhancement on trans arctic paths on 7, 14 and 21 MHz during plasma injection events. Typical examples include UK to Kodiak Alaska, and USA to Korea, via polar routes, when nothing useful by way of propagation was available elsewhere or by other paths. This type of propagation has been observed in both winter and summer as the solar cycle was moving down towards its sunspot cycle minimum with " normal" MUFs no higher than 12 MHz, in some cases.

Auroral Propagation Modes at HF

Figure 12 Side view of Auroral plasma distribution



Aggregations of plasma exist up to quite high altitude well above the E layer at 90 kms with electron densities capable of forward refraction propagation of 16 to 18 MHz signals even when solar wind enhancement is slight. Given the possible ten fold increase in electron density available in many auroras, MUFs up to 30 Mhz are readily attainable. Amateur radio has got so used to Auroral propagation by the rarer back scatter mode used at VHF , which depends for the most part on sharp unconformities in the plasma, that amateurs forget the potential for auroral propagation is much greater at HF.

Patches of radio propagating plasma are not continuous and do not form an oval structure roughly around the magnetic pole. Their discrete nature is due to their physical separation and to the somewhat episodic nature by which radio propagating auroral plasma gets into the polar regions. Radio propagating plasma is usually 200 or 250 kms further from the pole than visual auroral activity and it is much more widely spread as discrete patches , as well as lacking the pre local magnetic midnight format of visual auroral arcs which can stretch unbroken for 2000 kms.

Radio VHF user will be aware that they should not regard the presence of visual aurora as a sign that radio vhf auroral propagation is present. The two modes rarely coexist. HF auroral activity by contrast is often present when neither Radio VHF or Visual aurora is present , and because of its widespread nature , HF radio auroral propagation is sometimes evident in one part of the sky when visual aurora is present in another part.

Last but not least as Figure 12 shows the densest plasma is down near the E layer. This means that while VHF radio aurora is restricted to ranges below 1400 kms and often far less for most of the time. HF radio aurora using patches of plasma at higher altitude can give much longer communications ranges.

HF Satellite Auroral Signals

It is often the case that unless an operator has regular 4 hourly access to WWV , Boulder or Meudon reports of solar activity and magnetic storm onset, the first warning of a magnetic storm in progress comes to him via his own signal returns from distant HF satellites. This warning takes the form of the familiar roughening (broad banding) of the signal induced by doppler due to spasmodic motion of the auroral plasma. This auroral hiss can sometimes be heard on satellites over the Siberian arctic (where it is much later in the local day). Rough signals being apparent as early as 1000 ut in UK many hours before the evidence of auroral plasma above the UK horizon can be expected to appear. To get " Trans Auroral" propagation of satellite signals to your station needs a quite different alignment than that at 1000 ut. Indeed things rarely happen before 1600.

Figure 13 A typical "Trans Auroral " propagation event

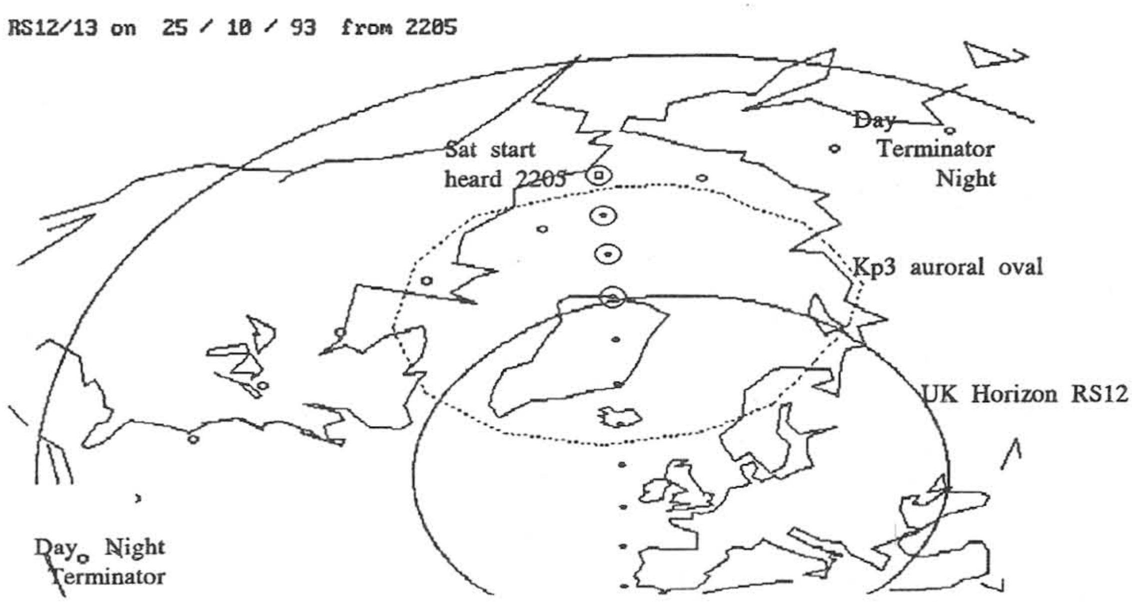


Figure 13 shows an example of a "Trans Auroral" event with the satellite one side of the aurora A7 propagating its signals through the aurora and on to the Scottish station on the other side of the aurora. This orbit was first heard as the satellite over flew the north coast of Alaska near the Bering Straits at 2205 ut. Its signal continued to be propagated sub horizon via the auroral plasma until it over flew the UK /RS12 northern horizon at 2211 ut. This pattern where the satellite is first heard as it enters above the farside of the auroral oval is a common one. The actual magnetic storm which produced this propagation was variously reported as Kp3 and Kp4 and it provided subhorizon reception of RS10 and RS12 orbits at 1610, 1646, 1951, 2019, 2135, and 2205 ut. . As is often the case this is not a complete orbit sequence . There is a gap where orbits at 1800 and 1830 produced no subhorizon extension. The reason for this gap is presently unclear. In addition to the trans auroral propagation, typical " plasma injection " propagation around local noon produced much longer (6000+ km) sub horizon reception events at 1110, 1140, and 1244 ut.

RS12 signal over the Pole trans Auroral to UK

Figure 14

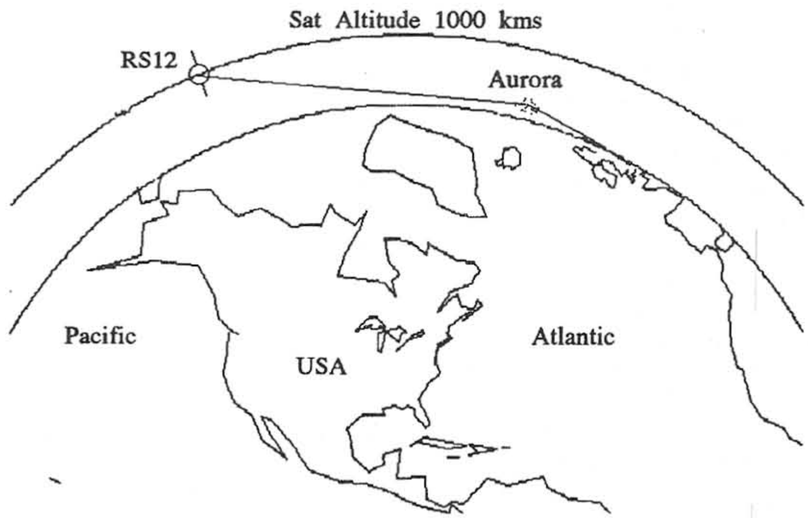


Figure 14 shows a side view of the Trans Auroral propagation route to UK in a Kp3 magnetic storm. Please note that not every Kp3 storm produces radio aurora for HF propagation . Only about 30 to 40% of Kp3 days actually feature auroral plasma capable of supporting HF propagation giving 40 to 50 opportunities each year of this sort. This same trans auroral propagation is available for communications between terrestrial stations at HF . OH9TEN beacon in Finland is sometimes the other side of the aurora from UK , giving a good indication of when that country is available on 28 MHz. Much less often similar auroral circuits to Northern Sweden and Finland provide opportunities for communications at 144 MHz VHF .

Other Modes of Propagation

Far less useful as compared with plasma injection or through the aurora propagation are VHF Radio Auroral Back Scatter propagation and, Sporadic E propagation. Back Scatter as it name suggests scatters your signal back on your side of the aurora so it is unable to help you on polar circuits, but Sporadic E SpE, can be useful at times when it occurs north of your station. Most radio amateur are familiar with summer time VHF SpE propagation but they rarely notice HF propagation by this route although HF FM operators will find it can be very useful in summer to and from Arctic locations. Equally important it should not be forgotten that HF communication does not require very dense SpE, so it is often available when VHF SpE is not. The Winter season in particular features quite a lot of HF SpE propagation , which often go unnoticed because fewer amateurs know there is a useful December/January winter season and even less appreciate that it is useful for extended propagation to satellites and , for very useful terrestrial communications links.
If you do use terrestrial HF at any time , please remember that 29.350 to 29.5 MHz is set aside for weak signal satellite work . So please keep your HF FM or SSB below 29.35 MHz.