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PROCEEDINGS OF THE AMSAT-NA

21st Space Symposium and AMSAT-NA Annual Meeting

October 17-19
2003
Toronto, Ontario
Canada

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Papers courtesy
AMSAT
PO Box 27
Washington, DC 20044

Published by:
ARRL *The national association for* ***AMATEUR RADIO***
225 Main Street
Newington, CT 06111-1494

Printed in USA

ISBN: 0-87259-910-8

ARRL Order Number: 9108

First Edition

K7RR

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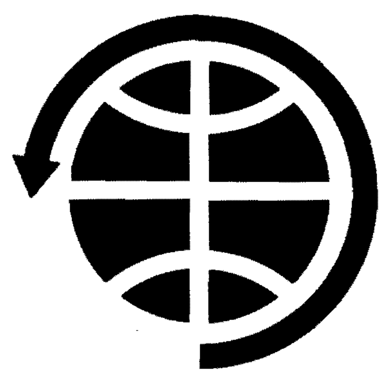


Welcome Back to Toronto

Six years ago, I had the pleasure of organizing the AMSAT annual meeting and Space Symposium here in Toronto, at that time I was a very nervous officer of the organization but enjoyed your company and determined that one day I would invite you back here again.

Well, that time has now come, and over the next few days, I look forward to renewing many relationships that were made six years ago.

On this occasion, however, Barry Delong, VA3BJD, has become Chair of the organizing committee and I would like to thank him and all the members of the committee and others who have assisted for their hard work.

During the Past year, I wondered several times if we should hold the Annual meeting in Toronto due to SARS, Economic slowdown and other factors, however it really does give me great pleasure to be able to say "Welcome" to you all.

At the time of writing this, I am pleased to advise that our latest Satellite "ECHO" is scheduled for launch at the end of March / early April 2004. Echo is a renewal of the Microsatellite Tradition of AMSAT-NA, only now we can package so much more into a Microsatellite satellite than we could 13 years ago. New integration and construction techniques have enabled the volume of the Microsats to remain the same while increasing both the capability and the power output of the bird.

I am delighted once more at the quality of the papers being presented this year, the ingenuity of the presenters never fails to amaze me and I thank them for the time and effort they put into each and every paper.

Finally I would like to thank you all for attending our meetings, your fiscal support of AMSAT and the building and developing of Amateur Satellites, it is this support that enables AMSAT to provide you with the satellites for the worlds best hobby.

Please keep up your membership and donations to the President's Club.

Robin Haighton, VE3FRH
President AMSAT-NA

AMATEUR RADIO ON THE INTERNATIONAL SPACE STATION—PHASE 2 HARDWARE SYSTEM

Frank H. Bauer; KA3HDO, Sergej Samburov, RV3DR, Lou McFadin, W5DID; Bob Bruninga, WB4APR and Hiroto Watarikawa, JJ1LYU

INTRODUCTION

The International Space Station (ISS) ham radio system has been on-orbit for over 3 years. Since its first use in November 2000, the first seven expedition crews and three Soyuz taxi crews have utilized the amateur radio station in the Functional Cargo Block (also referred to as the FGB or Zarya module) to talk to thousands of students in schools, to their families on Earth, and to amateur radio operators around the world.

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

The Phase 1 system hardware development which was started in 1996 has since been delivered to ISS. It is currently operational on 2 meters. The 70 cm system is expected to be installed and operated later this year.

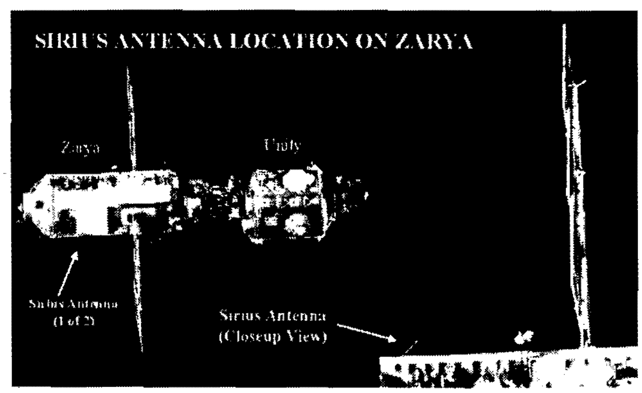
Since 2001, the ARISS international team has worked to bring the second generation ham system, called Phase 2, to flight qualification status. At this time, major portions of the Phase 2 hardware system have been delivered to ISS and will soon be installed and checked out.

This paper intends to provide an overview of the Phase 1 system for background and then describe the capabilities of the Phase 2 radio system. It will also describe the current plans to finalize the Phase 1 and Phase 2 testing in Russia and outlines the plans to bring the Phase 2 hardware system to full operation.

HAM RADIO EQUIPMENT SPECIFICS

Ham Station Location

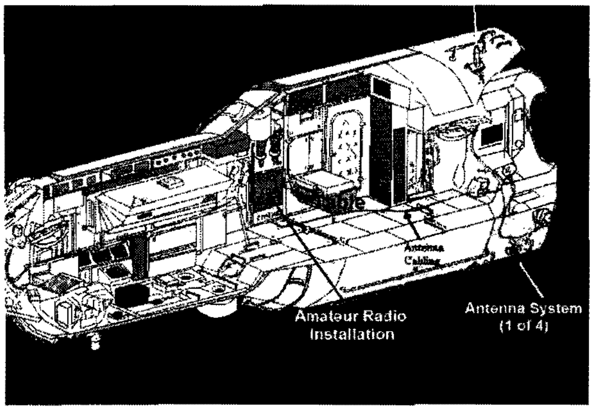
The ISS Ham radio equipment will reside in two locations inside the ISS and at least one location outside the ISS. 2-meter (144 MHz) operations will primarily be conducted inside the Functional Cargo Block (FGB), named Zarya, using antennas that supported docking of the FGB with the Russian Service Module. These antennas, designed for use near the 2-meter band, (see figure 1) no longer support docking



FGB 2 Meter Antenna Locations
Figure 1

and can be used by the ARISS team permanently. This is the current location of the 2 meter portion of the Phase 1 ISS ham radio station. The FGB radio system represents a minimal capability that allows the ARISS team to support school group contacts and packet communications on one band, the 2-meter band.

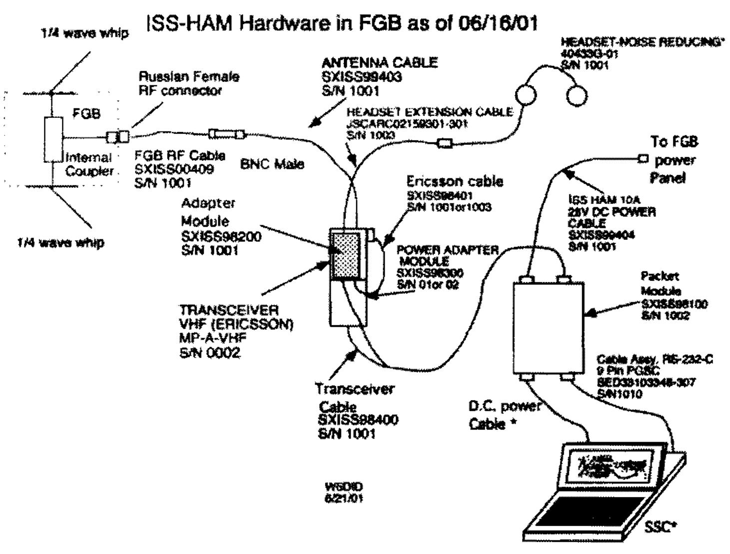
The ARISS team's vision of supporting several different international users at the same time on separate frequency bands and different modes (voice, data, television, etc) requires several different antenna systems. The ARISS-Russia team, led by Sergej Samburov, RV3DR,



ARISS Hardware in Service Module
Figure 2

provided this foundation through the installation of four ham radio antenna feedthrough ports on the Russian Service Module. With these antennas in place, the primary location of the ham station will reside inside the Russian Service Module (SM) named Zvezda. The ham station will be installed near the SM dining table. See figure 2. Simultaneous multi-band operations can be conducted with these two (SM and FGB) station locations.

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



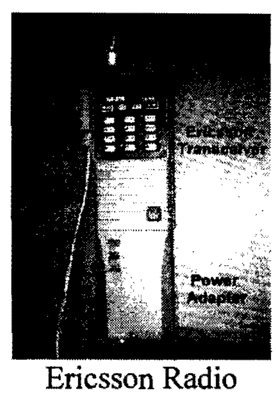
ISS Ham Phase 1 System in the FGB
Figure 3

Phase 1 Hardware Overview

The ARISS team has developed all the hardware elements for the Phase 1 radio system. These hardware elements have been flown to ISS on three Shuttle flights. The Phase 1 system supports voice and packet (computer-to-computer radio link) capabilities. Packet radio has several capabilities including an APRS Instant Messaging-type system and a Bulletin Board System that allows radio amateurs to store and forward messages and allows the orbiting crew to send e-mail to all hams or to individuals.

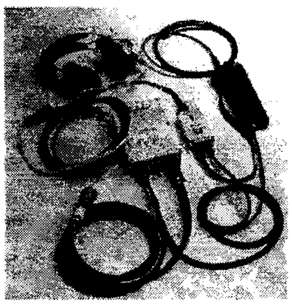
The Phase 1 ham radio system was developed primarily in the US. However, extensive testing and coordination with the ARISS-Russia team was required since it is installed in the ISS Russian segment. The initial portion of the Phase 1 ISS Ham radio system was launched on-board the STS-106 Space Shuttle Atlantis mission on September 8, 2000. This system consists of two hand-held Ericsson MP-A transceivers for 2 meters and 70 cm, a power adapter, an adapter module, an antenna system, a packet module, a headset assembly, and the required cable assemblies (see figures 3, 4 and 5).

This configuration can be operated in the attended mode for voice communications and either the attended or automatic mode for packet communications.



Ericsson Radio
Figure 4

Additional ARISS Phase 1 hardware was deployed during two additional Shuttle flights to ISS. This

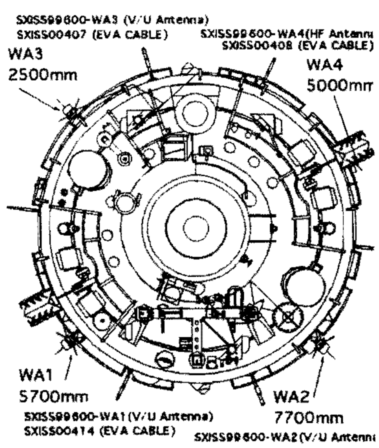


Phase 1 Hardware
Figure 5

hardware included an additional Packet Module on the STS-105 · Discovery flight on August 10, 2001 (see Figure 6), and additional cables and modules to support simultaneous 2 meter and 70 cm operation on the STS-108 Endeavour flight on December 5, 2001. Details of the Phase 1 system are described in reference 1.

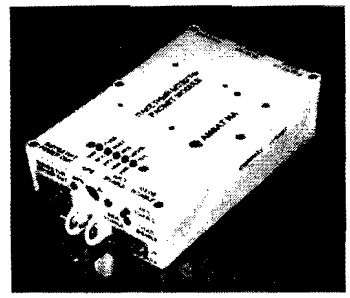
Antenna Assemblies

In 2002, a set of four antenna systems, developed by the ARISS team, were deployed during three Russian EVAs. These antennas will support the Phase 1 and Phase 2 systems in the Service Module. Once checked out, the specially designed antenna assemblies will permit operations on HF (20 meters, 15 meters & 10 meters), VHF (2-meters), UHF (70cm), and the microwave bands (L and S band) These antennas also permit the reception of the Russian Glisser EVA video signals (2.0 GHz). This dual-use (Ham/EVA video) capability is the primary reason the ARISS team received access to the four antenna feedthroughs located on the outside of the Service Module.



Antenna Location from End of Service Module
Figure 7

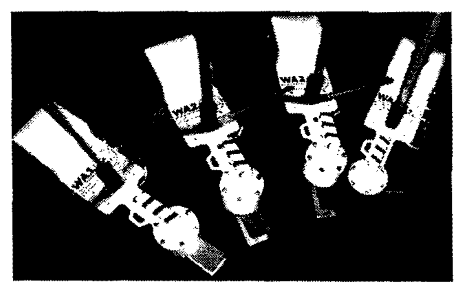
A total of four antenna systems were developed to get maximum use of the antenna feedthroughs. These were installed around the periphery of the far end of the Service Module. See figure 7. Three of the antennas (WA1-WA3) include a



Phase 1 Packet Module

VHF/UHF flexible tape antennas. WA4 includes a 2.5 meter flexible tape HF antenna. The antenna systems were developed by the U.S., Italian, and Russian ARISS partners.

Each antenna assembly consists of a mounting plate, spacer, a black striped handle, a Russian handrail clamp, an orange-colored VHF/UHF (or HF) metal flexible tape antenna with black delrin mounting collar, an L/S band flat spiral antenna with a white delrin radome cover, a diplexer (mounted underneath the plate) and interconnecting RF cables. See figure 8.



Antenna Systems WA1-WA4
Figure 8

The antenna systems were launched on the Space Shuttle Endeavour flight on December 5, 2001. The two up-looking (zenith) antennas, WA3 and WA4, were deployed by EVA (space walk) in January 2002 and the two down-looking (Nadir) antennas, WA1 and WA2, were deployed by EVA in August 2002.

Antenna installation EVA procedure development and training was led by Sergej Samburov from Energia with support from the ARISS-USA team.

PHASE-2 HARDWARE SYSTEM

Phase 2 Hardware Overview

The Phase 2 hardware system is expected to exploit the new antenna systems installed on the Service Module. Two new radio systems will be installed as part of Phase 2. These systems will augment the two Ericsson radio systems already on-board the ISS as part of the Phase 1 system. Combined, the Phase 1 and Phase 2 system will provide more capabilities for the crew and permit simultaneous, multi-mode operations by more than one crew member.

The Phase 2 development is a joint Russian, U.S. and Japan activity. Development was led by Russian team member Sergej Samburov, RV3DR. The Russian team was responsible for certifying the hardware for flight and providing the ride on the Progress launch vehicle. The Japanese team provided (donated) the Kenwood radios to the ARISS team and made specific hardware and firmware modifications to the radio system to prepare it for flight. The USA team, in conjunction with the Japan and Russian team, developed the Program Memory software that provides a powerful system with a very user-friendly interface for crew.

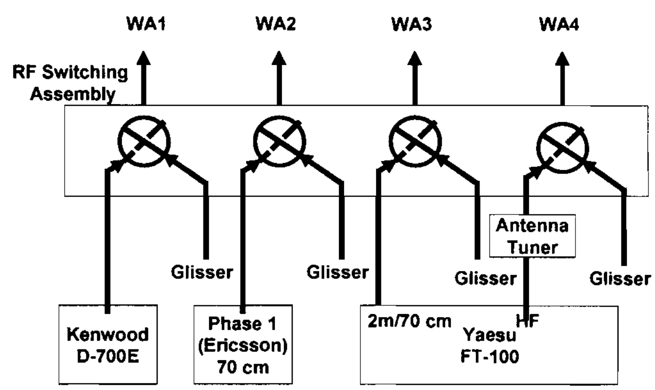
One of the two radios qualified for flight is a Kenwood TM-D700 radio. This radio supports 2 meter (144-146 MHz) and 70 cm (435-438 MHz) transmit/receive operation and L-band uplink operation. This radio provides a higher output power capability (10-25 Watts) than the Phase 1 radio system and can support FM and packet operations. The higher power capability should allow nearly horizon-to-horizon signal reception using simple hand-held radios or scanners.

The other radio is a Yaesu FT-100. This radio system will permit operation in the high frequency bands. Of particular interest is performing ionospheric propagation experimentation using the WA4 (high frequency) antenna and this radio. This radio also supports higher output power capabilities on 2 meters and 70 cm.

The entire set of Phase 2 hardware consists of the Kenwood and Yaesu radios, an RF tuning unit for the Yaesu radio system, interconnecting signal and RF cables, two specially developed Energia power supplies, a power distribution

Phase 2 Hardware Housed in
Velcro Table
Figure 9

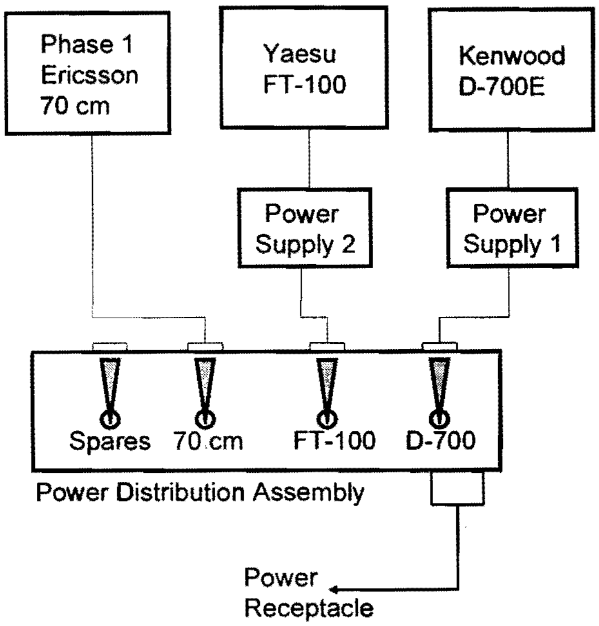
assembly developed by the USA team, a computer and the 70 cm Phase 1 hardware system. These will be mounted on a Velcro-backed table. See figure 9. These radio systems will be connected to the four Service Module antenna systems through a Russian developed antenna switching system. See figure 10. A schematic of the hardware configuration is shown in figure 11.



RF Layout of ISS Ham Radio Systems
Figure 10

Kenwood D-700 Specifics

The ARISS and Kenwood teams agreed that the Kenwood European model radio, D-700E, would



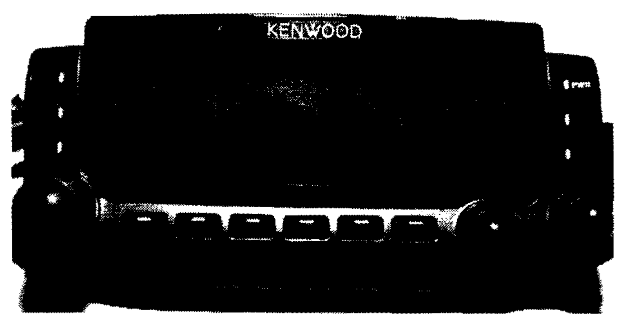
Power Distribution Schematic
Figure 11

be used for flight and ground operations. This radio was already certified by the Russian team.

Several modifications were made by the Kenwood Japan and Kenwood Moscow (Bermos) teams to prepare this radio system for flight. These included:

1) Developing a special Memory Control Program (MCP) to support reprogramming of the radio in the USA, Japan and Russia to ARISS specifications
2) Changing the packet radio default parameters, as specified by the ARISS team, in EEPROM memory
3) Enhancing the "repeater mode" of the radio system
4) Replacing the power cable and the microphone and control head cables with flight cables to allow certification of the hardware to the Russian requirements.
5) Reducing the maximum power output of the radio to 25 watts
6) Replacement of the 6-pin data connector with an 8-pin connector. One of the additional pins on this connector supports an 8 V DC output capability.
7) Incorporating a channel designator for the front panel as the default instead of the frequency information.

The architecture of the radio interface to the crew was carefully crafted by the USA and Japan team to make the D-700 a powerful radio system with a simple user interface. A set of 5 default options, or Programmable Memories, were embedded in the D700 to support ISS operations. See figure 12. The advantage of these five Program Memories (PM's) are that they can be restored with a two-button key press by the crew at any time. With the two hundred different frequency channels, the nearly one hundred TNC parameters, and the variety of applications for this radio on orbit, the default configurations are absolutely critical to being able to maintain communications with the crew under all conditions. These five configurations reduce operations to these fundamental configuration baselines:



Kenwood D-700
PM1 Crew Display
Figure 12

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

The PM's remember the following types of parameters for the radio:

- Default Channel for LEFT side and RIGHT side of radio
- Which side of radio the Microphone and PTT will activate
- Which side of the radio the TNC will RECEIVE and on which side it will Transmit
- The function of the several "soft keys" on the radio front panel

While the MCP program stores all 200 frequency channels in the radio, the PM's do not store any combination of channel frequencies other than the initial two defaults for the left and right side of the radio. This means, that once a PM has been selected by the crew, this only configures the radio to a known default pair of channels. The crew member can still tune to any channel after that. Thus, with a push of two buttons and a rotation of the main dial, the crew member can operate on multiple modes and different frequency pairs. While this architecture offers the ultimate in flexibility (millions of combinations), it also provides a user-friendly interface of the five PM's to always return the radio to a known initial state.

Each of the 200 memory channels can support separate TX and RX frequencies, offsets, and PL or CTCSS tones. The D700 is a dual radio system and although it only supports two channels at a time, it is very important to remember that each channel consists of both a displayed RECEIVE frequency and a separate TRANSMIT frequency. Thus, at any time, there can be up to four frequencies involved in radio operations. Since the Microphone and PTT (for voice) can be using one channel and the TNC can be using the same or the other channel, or even can transmit on one channel and receive on the other, there are many conventional (e.g. simplex, split) and non-conventional (e.g. crossband, repeater, CTCSS-enabled command uplink digital channels, etc) ways to use these combinations for ARISS.

Yaesu FT-100 Specifics

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

1. Replacing the power cable and the microphone and control head cables with flight cables to allow certification of the hardware to the Russian requirements.
2. Reducing the maximum power output of the radio to 25 watts
3. Replacing the PVC RF cables and connectors on the back of the radio with SMA connectors. Attached to these are Teflon coated RG-142 antenna cables with N connectors
4. Tuner cable replacement with flight cables
5. Replacement of 6-pin data connector with an 8-pin connector. One of the additional pins on this connector supports a 12 V DC output capability.

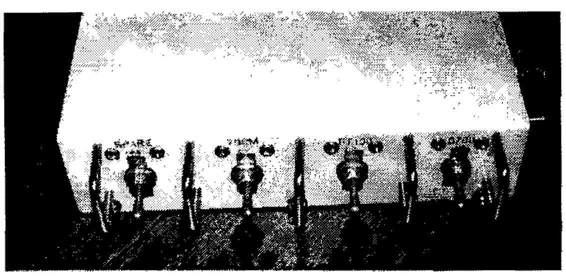
Since the FT-100 supports HF operation and the WA4 antenna is a single 2.5 meter vertical the ARISS team felt that it would be best to supply a tuner with the radio to minimize SWR concerns and optimize signal output. See figure 11. The ARISS USA team is working closely with the Yeasu team to modify their existing FT-100 auto-tuner for ham radio operations on ISS.

Development of the Yaesu system is on-going, but is expected to conclude in early November 2003.

Power Distribution Assembly

One of the primary issues in a household is sufficient and easy access to electrical receptacles. A similar issue exists on ISS. There just aren't enough receptacles where you need them. With the 3 radio systems being installed in the Service Module (Phase 1 70 cm, Phase 2 Kenwood and Phase 2 Yaesu), the need for electrical receptacles for the ISS ham radio system could become a major issue.

The power distribution assembly, see figures 11 and 13, resolves this problem and several other potential issues on ISS. The power distribution assembly allows the ISS ham system in the Service Module to be plugged into only one ISS receptacle. It also provides a power shutoff capability via switches and circuit breaker protection for each radio system. This not only provides an addition level of safety but also provides an additional shut-down feature that is critical for satisfying the ISS EVA safety requirements. With the power distribution assembly, there will be no need to plug and unplug ISS Ham items due to insufficient receptacles. Thus, this assembly serves to reduce wear and tear on the power cables, improving system safety.

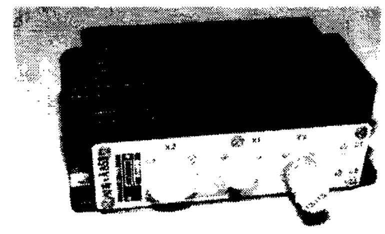


Power Distribution Assembly
Figure 13

The Power Distribution Assembly is being developed by the USA team with strong support from the Russian team. While the unit will be fabricated in the US, several of the parts, particularly the electrical connectors, are Russian supplied. The current plan for the Power Distribution Assembly is to fabricate the flight unit, certify it for flight in the US and in Russia and then fly it on-board the next space shuttle. Since the Yaesu system will not be deployed until the Spring of 2004, this development and delivery schedule appears to make sense.

Power Converters

Two fully redundant, flight certified power converters were developed by the Russian Energia team and were supplied to the ISS Ham team for use as part of the Phase 2 radio system. These power supplies convert the 28 VDC ISS power to 13 VDC for use by the Kenwood and Yaesu radio systems. Since the power converters are fully redundant, the ISS ham team will have adequate power capabilities for all the radio systems even if one of the power converters fail.



Power Converter
Figure 14

Phase 2 Delivery, Testing and Checkout

The final version of the flight MCP software was delivered to the Russian team by the USA team on July 17, 2003. Just prior to this, the Kenwood Japan team delivered the final firmware load to the Kenwood Japan (Bermos) team for installation into the D-700 radio. The Bermos team and the ARISS-Russia team, led by Sergej Samburov, completed the hardware and software modifications to the radio system in late July and readied the Phase 2 hardware system for flight. The initial set of Phase 2 hardware, including the Kenwood D-700 radio, interconnecting cables, power converters, and RF switching system were delivered to the Baikonur Cosmodrome in Kazakhstan in early August. The Phase 2 hardware was launched on the Progress 12P rocket on August 29, 2003 and docked with the ISS on August 31. The Velcro table is already on-board ISS and is awaiting equipment installation.

The Phase 2 equipment is currently "yellow tagged" meaning that we need to accomplish some additional tests prior to on-board hardware integration and testing. A series of tests are being planned for early November, 2003 at the KIS facility (Service Module engineering model equivalent) located at Energia in Korelev (Moscow area) Russia. The Russian and US team will be conducting tests in this Service Module equivalent to validate that the Phase 2 and 70 cm and 2 meter Phase 1 systems are compatible with the other electrical systems on the Service Module. We will also conduct some RF testing with the flight-identical antenna systems and the Phase 1 and Phase 2 hardware. Once these tests are successfully completed, the yellow tag can be removed and hardware installation can begin.

The current plan is for Mike Foale and Alexander Kaleri to install the Phase 2 and Phase 1 70 cm hardware on Expedition 8. The plan is to perform hardware installation and checkout in mid to late November 2003.

The remaining Phase 2 hardware, including the Yeasu radio system is planned to be launched on the Progress 14P flight that is planned for January 2004.

FUTURE HARDWARE DEPLOYMENTS

Follow-on Phase 2 Hardware

Two future projects are envisioned to improve the capabilities of the Phase 2 system. These include the development of the tuner for the Yaesu radio system and the certification of a Standing Wave Ratio/Power meter. These two projects will be developed and flight certified by the US team and flown on a future shuttle flight.

SSTV

In the near future, a Slow Scan Television (SSTV) system will be deployed on ISS. The SSTV system for the ISS ham radio station is currently in development. This system will consist of a software interface, developed by the MAREX-MG team and a hardware interface, developed by the AMSAT-NA hardware team. Prototype hardware and software systems have been developed and the flight system fabrication has started. The SSTV system will allow digital still pictures to be uplinked and downlinked in both crew-tended and autonomous modes. The ARISS team expects the SSTV system to be flown on Progress flight 14P in January 2004.

CONCLUSIONS

The ARISS-international team, with help from Kenwood and Yaesu, have developed the ISS Phase 2 ham radio system. The Kenwood system is currently on-orbit and will soon be operational on ISS. The team expects that the Yaesu system will be operational in Spring 2004. This multi-national development effort presented many challenges to the team. Despite these challenges, the tremendous teamwork and optimistic spirit resulted in an outstanding new capability on ISS that we expect to set the standard in space for years to come.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the tremendous support, teamwork and volunteer spirit of the ARISS-International team in making this hardware system come to fruition. Technical, financial and administrative support by the ARISS member organizations--the AMSAT organizations and IARU organizations (ARRL in the USA) continue to be crucial to the success of the program. Also special recognition is in order to NASA, Energia, Kenwood, and Yaesu. The ARISS team continues to be indebted to them for all their in-kind contributions and support. Together we are pioneering the new frontiers of amateur radio and educational outreach.

DEDICATION

This paper is dedicated to the memory of Roy Neal, K6DUE. Roy's tireless pursuit to make amateur radio on human spaceflight missions a permanent capability was an inspiration to us all. We feel privileged to have realized his vision on ISS during his lifetime. We have more solidly cemented that permanence with the delivery of the Phase 2 hardware system. Our thoughts are prayers are with you old buddy.

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For more information on the ARISS program, you are welcome to visit the ARISS web page at: http://ariss.gsfc.nasa.gov or http://www.rac.ca/ariss

AMSAT Oscar-Echo, SDR-1000, and higher speed FSK

Frank Brickle, AB2KT and Bob McGwier, N4HY

If all goes well, in May 2004 AMSAT-NA will launch its newest satellite on the Dnepr LV (converted SS-18) from a Russian launch site. The satellite has the ability to support several digital modes. They will be difficult to support using off the shelf conventional transceivers. Recently, a realistic candidate has emerged in the form of an affordable and easily usable software defined radio (SDR). In this paper we will describe the digital capabilities of AMSAT-ECHO, the new satellite, and how the software defined radio can be the ideal terrestrial station for exploiting those modes. We will discuss the changes and upgrades to the SDR, to be provided by the manufacturer, that will be necessary for this added functionality.

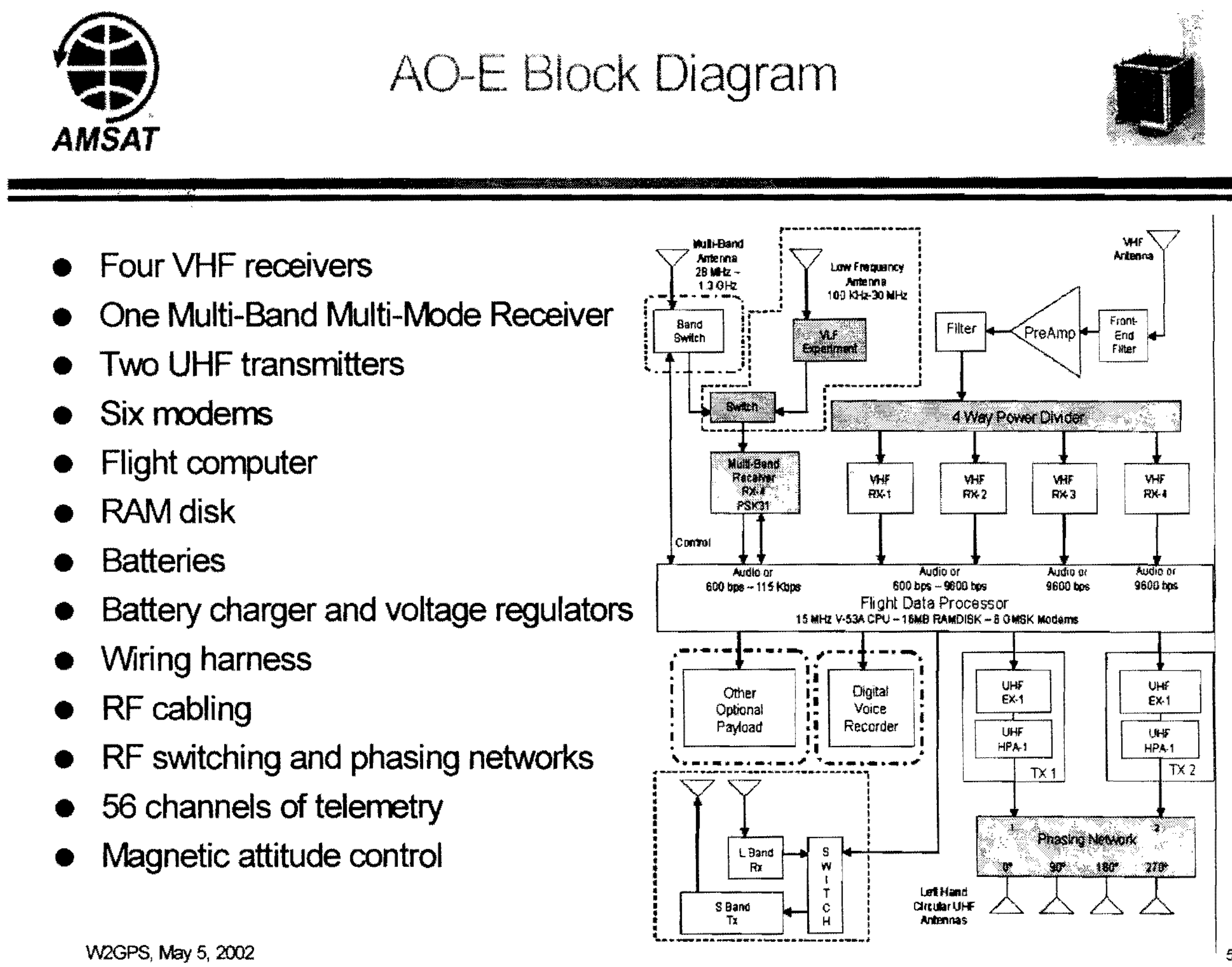
AMSAT Oscar Echo

In 1990, AMSAT-NA launched four Microsats: AO-16, DO-17, WO-18, and LU-19. Four subsequent satellites, the IO-26, AO-27, MO-30, and the SO-41, were designed and built based on these original Microsats, using technology licensed from AMSAT-NA. In early 2002 the AMSAT-NA board of directors entered into an agreement with Spacequest, Inc., which had been exploiting the Microsat concepts, to develop a spacecraft with their updated version of the technology. AMSAT-NA would create unique modules for the payload, and would carry out the integration jointly with Spacequest. It appears now that that the result will be launched in May 2004 on a Dnepr (converted Soviet SS-18). The new satellite will have a very digital flavor onboard along with the very popular "FM-sat/Easysat" mode.

The initial and primary operational mode for the new satellite will be Mode J (2 meter uplink, 70 centimeter downlink). It will carry four receivers configured either for FM audio or FSK-modulated data signals. Downlink will be provided by two high-power 70cm transceivers, each capable of 8 watts output. This is definitely no low-power satellite. On a typical pass, the link margin – the level of power in excess of what is required to complete a digital transaction with the satellite -- should be more than adequate to support the use of 0 dBd omni antennas for both uplink and downlink. The link margin for digital signals at 9.6 kbps at elevation angles above 10 degrees will be several dB.

The onboard computer will run the now well-known SCOS (Spacecraft Operating System) from Harold Price, NK6K. This computer has sufficient power to allow us to not talk to the fishes in the middle of the ocean (unless first called) and will greatly increase the power budget available for the high power transmitters over more populous areas.

In addition to the now standard 9600 bps FSK mode, the satellite will carry an L band receiver and an S band transmitter. Together these assets will enable downlink data rates up to 76.8 kbps. The L band receiver will be capable of receiving FSK data at rates up to 56 kbps. It should be clear this will not be enabled by a quick press of the data button on your favorite satellite or terrestrial radio. The interested reader is referred to a recent paper by the AMSAT executive VP and ECHO project manager W2GPS (1).



Software Defined Radio

In the July/August 2002 issue of QEX, Gerald Youngblood, AC5OG, gave us the first of four articles which introduced the outcome of a four year struggle to bring a real software defined radio transceiver with high performance to amateur radio. The performance of the nearly direct conversion receiver is due to a unique "mixer" at the front end. Youngblood calls it the Quadrature Sampling Detector (QSD for short). It is essentially a four-phase sample-and-hold, which, with outputs combined properly, produces a complex version of the received signal and mixes it down to the last IF at 11025 Hz. This last IF is passed to a general-purpose personal computer via the stereo line-in to its soundcard. This front-end hardware, together with the software designed to control the hardware and interface with the user, forms a complete system called the SDR-1000. It realizes a ham band transmitter and a general coverage receiver operating 11.025 Khz to 60 MHz. It currently uses a 44100 Hz sample clock. As is characteristic of SDRs, most significant changes in the capabilities of the system involve software and not hardware. We will return to this theme in a moment. A number of early users have been contributing to the improvement and enhancement of the SDR-1000 signal-processing software. Among the areas addressed are the complex or phasing detector for sideband, implementing AM, and CW modes on both transmit and receive, automatic noise cancellation and tone removal, etc.

The present authors, among others, are very interested in adding digital mode capabilities. This work is a high priority following the completion of noise-blanking algorithm and implementation.

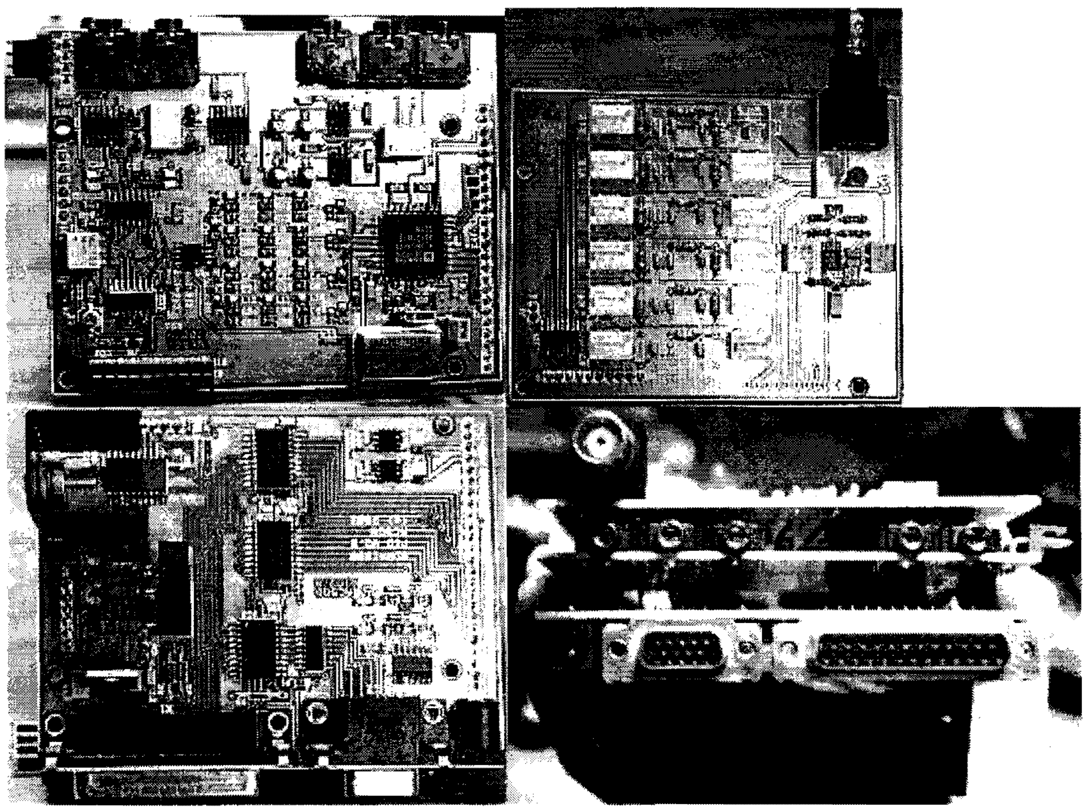


Fig.2 (clockwise from top left) Transceiver board, Filter/Amplifier board, Parallel I/O board, and the full stack.

The SDR-1000 as delivered comes with software written in Visual Basic 6, using Intel optimized signal processing libraries and DSP code the SDR project has written. The software is released GPL though it is based on commercial proprietary software which we hope to replace with libraries that do not have such restrictions. Figure 3 shows the current front panel. It is clear from looking at it why Gerald chose Visual Basic 6 since it made this level of detail easy to construct.

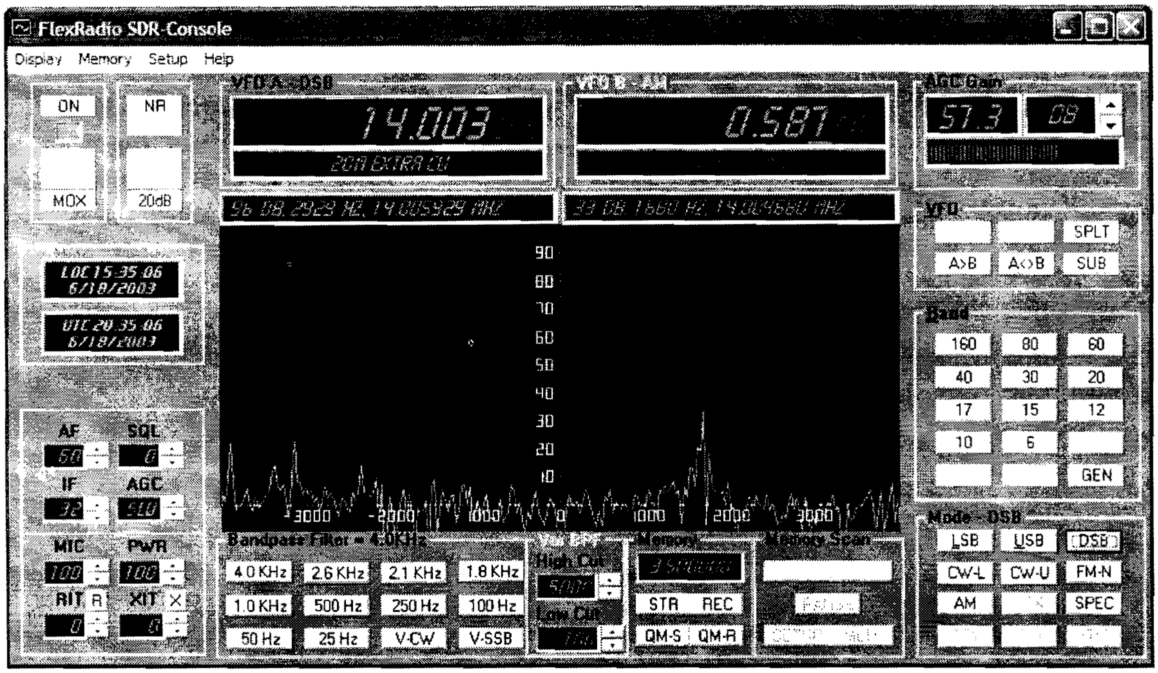


Figure 3 SDR-1000 "front panel" screen capture

Marrying SDR-1000 and AMSAT-ECHO FSK

As currently delivered, the SDR-1000 can handle 9600 bps but not 56 kbps. This limitation is being addressed on two fronts. The SDR-1000's "mixer" or sample-and-hold circuit works by charging a capacitor through the load presented by the antenna and bandpass filter combination. This "RC" network in the delivered model sets the front end Q to deliver a bandwidth of 40 Khz. A passband of at least 192 Khz will be required to accommodate occupied bandwidth of the FSK, Doppler, and other tuning inaccuracies. The SDR-1000 can be modified to handle this by a change of four chip capacitors! The other hardware change is likely to be the computer soundcard: to capture the necessary additional bandwidth, the sampling rate needs to be increased. There several audio cards out now that will allow sampling at a 192 Khz sample rate. A good candidate is the Lynx L22 (see http://www.lynxstudio.com/lynxl22.html) in a 24 bit A/D card. For 16 bits, the Turtle Beach Santa Cruz will serve well, although, while it uses an 18 bit A/D, it only delivers 16 bits. The Santa Cruz will not sample at 192 Khz, but should be more than adequate for the 9600 bps that will be used immediately following launch of the new satellite.

Youngblood has set up an official software exchange for the existing Visual Basic SDR-1000 code at Sourceforge. The present authors are working in parallel on Linux versions of the transceiver software, including that necessary to operate AMSAT-ECHO. If all goes well, a demo will accompany this talk.

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3) G. Youngblood, AC5OG, "A Software Defined Radio for the Masses: Part 2", *QEX*, Sep/Oct 2002, pp. 10-18.
4) G. Youngblood, AC5OG, "A Software Defined Radio for the Masses: Part 3", *QEX*, Nov/Dec 2002, pp. 27-36.
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Mode L/S: Suitcase Portable

Gerald R. Brown, K5OE
k5oe@amsat.org

Working AO-40 with minimal hardware can be a challenge. Working it with portable hardware that will all fit in a suitcase is something I have been thinking about since the first time I saw the W9AE portable system: an FT-847, an Arrow Antenna 7x2 beam, a G3RUH dish and patch, and a TSI 3731 downconverter. I worked W9AE when he used his innovative system in Guadelupe (FG). I later worked VE7DX from both Lesotho (7P8) and Swaziland (3D) while operating with the same gear. See the KK5DO web site (www.amsatnet.com) for pictures of the 7P8 setup.

Figure 1: The W9AE Portable DX Setup (QSL Card)

W9AE's system fits neatly into a small wooden box suitable to be checked as luggage. The FT-847 presumably goes in another box or as carry-on luggage. I looked around at what I had in the shack/garage and began to think small—real small. I wondered how much smaller a system could be. I wondered if my 18" DSS dish would fit in a carry-on suitcase. It does. I wondered if I could use it for both S-band downlink and L-band uplink with a dual-band feed: I recently acquired a microwave relic, a Microwave Modules varacter "trippler." I wondered if my FT-100 all-mode radio would drive the MML trippler with enough UHF power, converted to L-band, to work AO-40. Quick calculations indicated 18 dBi of receive gain from the dish, 10 W of CW power from the MML trippler, and 12 dBi of transmit gain from the dish. Could CW be worked with barely 100 W ERP and a dish half the "recommended" size? There is only way to know for sure.

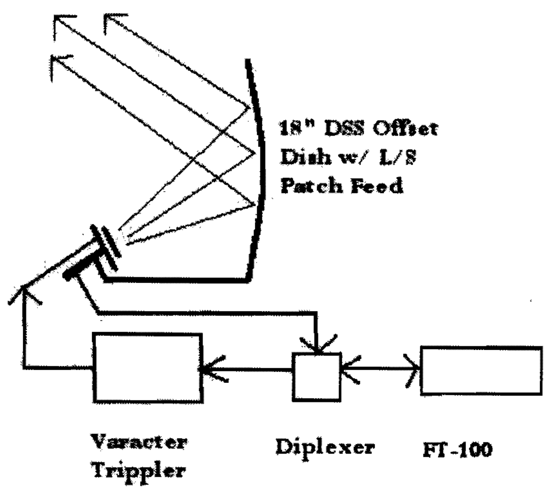

Figure 2: The Portable L/S Concept

The issue of using a non-full-duplex radio, the FT-100, to make analog satellite contacts is one I have been familiar with for a long time. Having lots of practice on Rs-12/13, FO-20/29, and even AO-10, I knew working AO-40 would be a little harder but certainly not impossible. While these other satellites' frequencies were quite predictable, allowing me to "guess" at the correct uplink frequency, AO-40 is anything but predictable with the combination of more than 50 kHz of Doppler shift and as much as 10 kHz temperature drift in the downconverter. If I put the FT-100 in QSK mode (no delay between transmit and receive), would I be able to hear my return "echo" from the AO-40 transponder? At apogee this delay is quite noticeable and I was counting on the T/R relay in the FT-100 to be fast enough to hear my own return on CW.

The FT-100 did need a slight modification, however. The MML frequency "trippler" needs an input of 423 MHz to obtain the requisite output at 1269 MHz. The stock transceiver does not transmit below 430 MHz, so I implemented the "expanded transmit" modification documented on the Internet. This simple procedure is a legitimate modification, even if not sanctioned by the manufacturer. It took all of 10 minutes and did not require re-setting the rig's memory.

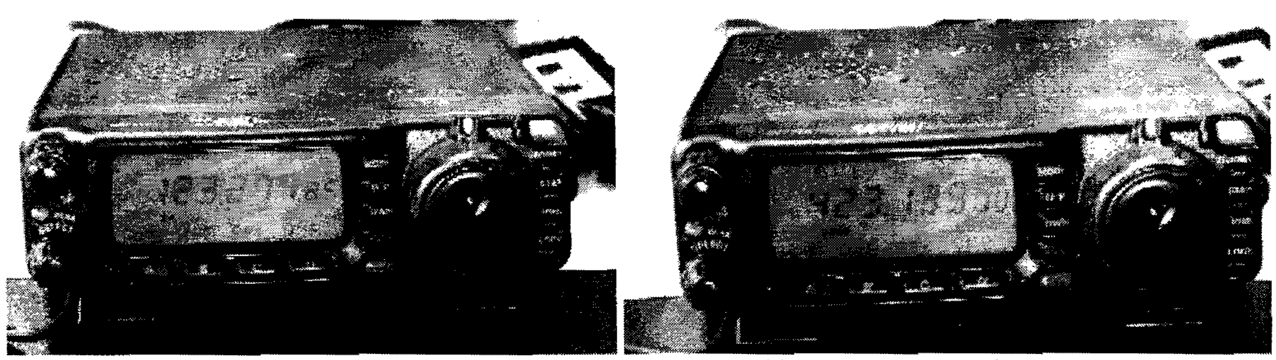

Figure 3: The Yaesu FT-100 in QSK Mode with Expanded Transmit

Upon testing the MMV-1296, I found it worked well at 432/1296 MHz (as one would expect), but had a 3:1 SWR on the input at 423/1269 MHz. This was an unanticipated problem. After having modified my transceiver, there was no turning back, so I got a screwdriver and opened up the MMV-1296--expecting to find some kind of tuning network I could adjust. Surprise! It had no "user serviceable parts" inside. I studied it for a while and guessed the bare wires running from the input connector to the diode were tuned transmission lines. Would lengthening them lower the resonant frequency of the input circuit? There was only one way to find out. I got lucky and it worked.

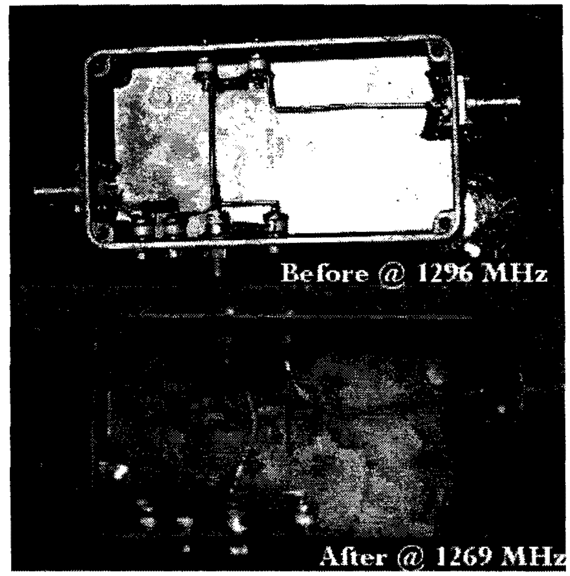

Figure 4: MML MMV-1296 Varacter Trippler

The first opportunity I had to test the system was an early Sunday morning with AO-40 to my west. I assembled all the parts and pieces on my driveway and easily found the beacon. Next came the test to find my own downlink. I set the transmit frequency at 423.137 MHz, producing 10 Watts at 1269.410 MHz. This uplink corresponds to a frequency roughly 30 kHz below the beacon. It took me just a few quick "dits" on my CW key to find myself by moving the receive frequency slightly after each trial dit. The return signal was about 3 kHz higher than I anticipated, but certainly within the accuracy of my manual system. It also sounded rough, slightly chirpy, on the FT-100.

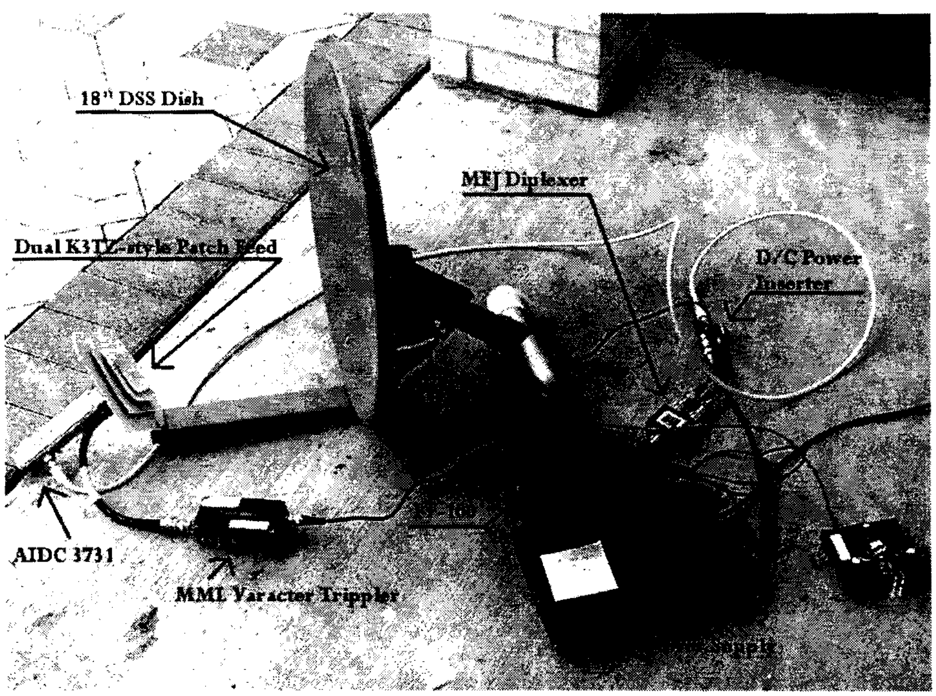

Figure 5: The Dual-Band Suitcase-Portable System

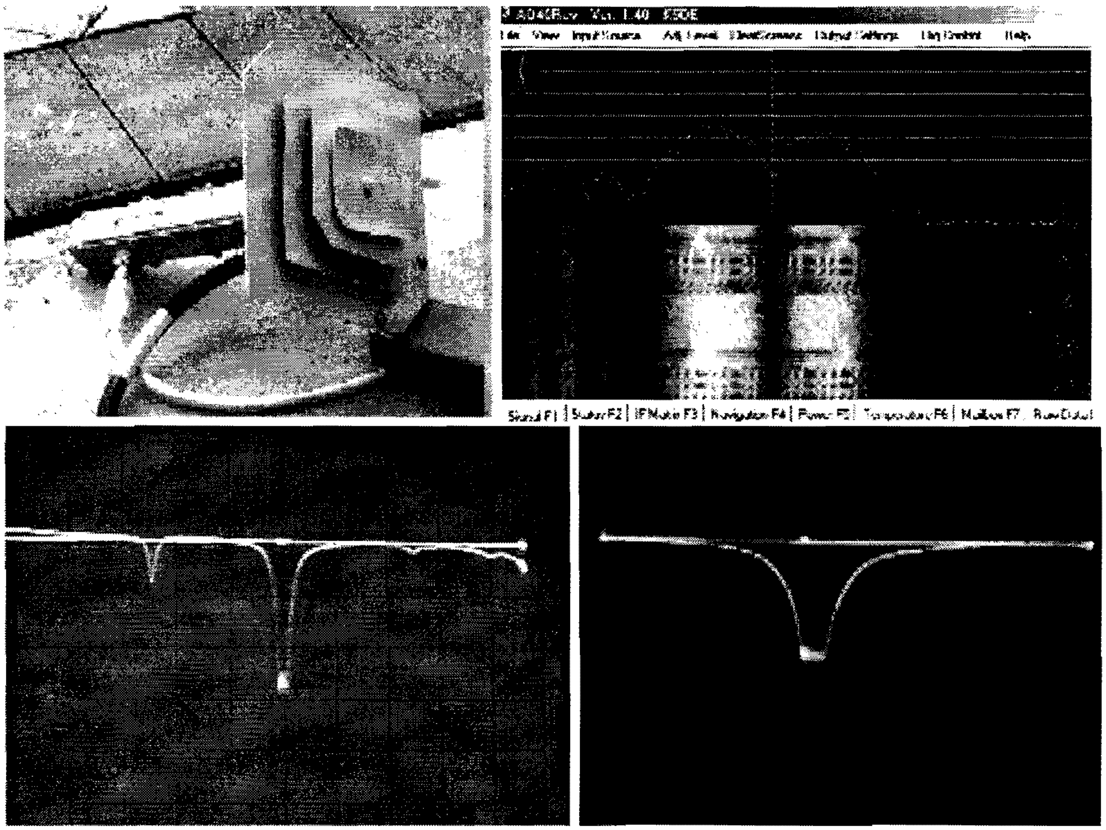

Figure 6: The Dual-Patch Feed: (clockwise) The K3TZ Design, AO-40Rcv
S-band Performance, The L-Band Patch at –28 dBi, The S-band patch at –23 dBi

I was eager to hear how it sounded on my "regular" home system, so I enlisted the assistance of my older daughter to stand on the hot driveway and send some CW dits while I went inside to listen. It took only a few seconds to find the test signal on AO-40's downlink. To my great relief it sounded just fine; a pure CW note. Then, out of nowhere, I heard the CW question mark right on top of the test dits. That could only mean one thing: somebody was hearing the test signal and wanted to QSO. I ran, literally, back out to the driveway and took over the CW key and quickly sent my call sign a few times. To my complete surprise, JA1BLC came back to me. He gave me a 579 signal report! We had a nice, long "rag chew" QSO. It was hot on the driveway and I was sweating profusely by the conclusion of that QSO, but I was elated with my unexpected success.

Several more tests followed on the back patio and on the driveway, including placing the system in the back of my pickup truck, setting the elevation manually, and then driving around on the driveway to peak the beacon. That was just plain fun! In all seriousness, though, that test was really about operating the entire setup from a vehicle's 12 Vdc power system. I wanted to test the system's ability to be powered from a rental car's battery. Again, success was fairly easy and I had a short QSO with W0OQC, who finished the QSO on phone and I had perfect copy throughout.

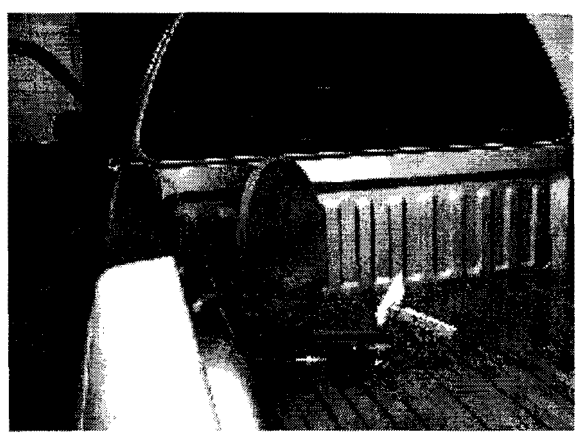

Figure 7: The Portable System Set Up Mobile

My planned trek to the University of Surrey a few weeks later for the AMSAT-UK Colloquium was an opportunity to test the concept. To prove it was truly suitcase-portable, I took the antenna system along. The DSS dish fit snuggly in my roll-on suitcase, angled up on one edge. The support bracket and the feed assembly fit underneath the raised edge. Since this was a short, weekend trip, this was the only luggage I carried on the flight.

Figure 8: Roll-on Suitcase Ready To Go

I did not take the FT-100 with me to London, as my goals were 1) prove the system was indeed suitcase-portable and 2) have it tested on the antenna test range—a popular feature of the Colloquium. The calculated 18 dBi of receive gain on S-band was slightly optimistic, as the testing proved out to 17 dBi. The L-band gain was not tested.

Overall, this was a fun experiment. I invested practically nothing in building the system: already owning the DSS dish, the varacter trippler (bought on ebay.com for about $50), and the FT-100 as my normal mobile radio. I demonstrated, to myself at least, a very small antenna with very little L-band power can reliably communicate on AO-40 under normal conditions. I also showed mode L need not cost a fortune as long as one is willing accept the limit of CW-only operation. I hope some of these ideas will spur others to take what they have in the garage and pack it with them on vacation. I have some business travel planned to the Northern Territories of Australia in the near future and hope to put VK8 on AO-40 with this system.

Figure 9: Testing At AMSAT-UK: G4DDK with the K5OE Dual-Band Antenna and G0MRF with the Feed Horn (and Umbrella)

C-C Rider

A new transponder concept for amateur satellites

Tom Clark, W3IWI
w3iwi@amsat.org

ABSTRACT: The Amateur Satellite Service has several microwave allocations in the 1-10 GHz range. AO-40 and the planned Echo satellite makes use of the L/S combination permitted by combining the Amateur Satellite uplink allocation at 23 cm (1260-1270 MHz) with the 13 cm (2400-2450 MHz) band. Unfortunately, the FCC's "Part 15" and ISM rules have caused the 13 cm band to be seriously compromised by unlicensed consumer devices – microwave ovens, 802.11b and 802.11g wireless LANs, cordless telephones, video relay, etc.

Another very desirable amateur band is C-Band (5 cm) where the Amateur Satellite Service has a pair of 20 MHz wide allocations: 5650-5670 MHz is set aside for uplinks, paired with 5830-5850 MHz for downlinks. This spectrum is also at considerable threat; it is already experiencing the intrusion of 802.11a LANs, cordless phones and other unlicensed applications and has been targeted for expansion by a number of new wireless services. Unless we begin to use this band very soon, it may become a bigger sewer than the 13 cm band has become.

This paper presents a conceptual design for an "in band" transponder making use of the pair C-band allocations. Although microwave frequencies imply huge doppler tuning problems for narrow-band signals typical of most amateur satellite activity, by placing a single local oscillator midway between the pair of frequencies (5750 MHz) we cancel 97% of the doppler shift, equivalent to operating at the difference frequency (180 MHz).

Until satellite resources can be deployed, low-cost versions of the transponder can be deployed at terrestrial locations as a wide-band "bent pipe" transponder with bandwidths capable of supporting many digital applications. These terrestrial developments could be a logical expansion of the ARRL's 13 cm "HSMM" "Hinternet" effort which makes amateur use of off-the-shelf low-cost commercial hardware.

THE MICROWAVE SPECTRUM: Let us begin by examining the amateur frequency allocations between 1 and 10 GHz in Table 1[1]:

Table 1: United States Microwave Allocations			
Amateur Service		Amateur-Satellite Service	
Band (MHz)	Bandwidth (MHz)	Band (MHz)	Bandwidth (MHz)
1240-1300	60	1260-1270 ↑	10
2300-2310 2390-2450	10 60	- 2400-2450	- 50
3300-3500	200	3400-3410	10
5650-5925	275	5650-5670 ↑ 5830-5850 ↓	20 20
10000-10500	500	10450-10500	50
24000-24250	250	24000-24050	50

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

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[1] Thanks to Paul Rinaldo, W4RI for supplying an early version of this table.

One sad lesson we have all learned from recent S-Band (2.4 GHz) experiences is that amateur activities have been seriously compromised by unlicensed users — 802.11b & g,WiFi, BlueTooth, cordless telephones, room-to-room TV links, microwave ovens, etc. We have learned that "listen only" and weak-signal services like the AO-40 downlink and EME are nearly powerless to convince millions of unlicensed users that our needs "trump" their usage. Since our applications are listen only (or mostly), we don't even announce our presence[2]!

Realizing that many future amateur activities will want more bandwidth, the ARRL has formed the High Speed MultiMedia (HSMM) working group to explore ways to adapt low-cost commercial wireless computer widgets for use in amateur applications. The HSMM working group is headed by John Champa, K8OCL (an AMSAT Director and Executive Vice President in the late 1980's). You may get more information on HSMM on the ARRL website[3] and an excellent article on HSMM by N5KM is in the April 2003 QST[4]. The ambient RFI level from unlicensed devices has proven to limit coverage on HSMM links and I understand that the HSMM group and TAPR have begun efforts to figure out ways to QSY from 2400 MHz to either the 902-928 or 3300-3500 MHz amateur bands[5] in order to improve operating range.

In this paper, I plan to concentrate on the idea of making a "fresh start" using the pair of C-Band Satellite allocations seen in Table 1: 5650-5670 MHz (uplink) and 5830-5850 MHz (downlink). Time is short -- C-band has begun the process of becoming another S-band-like "sewer" with 802.11a wireless LANs, cordless telephones and the like. On the CISCO website one can find details[6] of the current 802.11a WLAN channelization. At present, the 802.11a activity is confined to WiFi channels[7] 149-157 in the 5740-5790 MHz range[8]. This segment is in the middle of the 5655-5925 MHz amateur allocation, but it has no overlap with either of the 20 MHz-wide Amateur Satellite allocations, as seen in Figure 1.

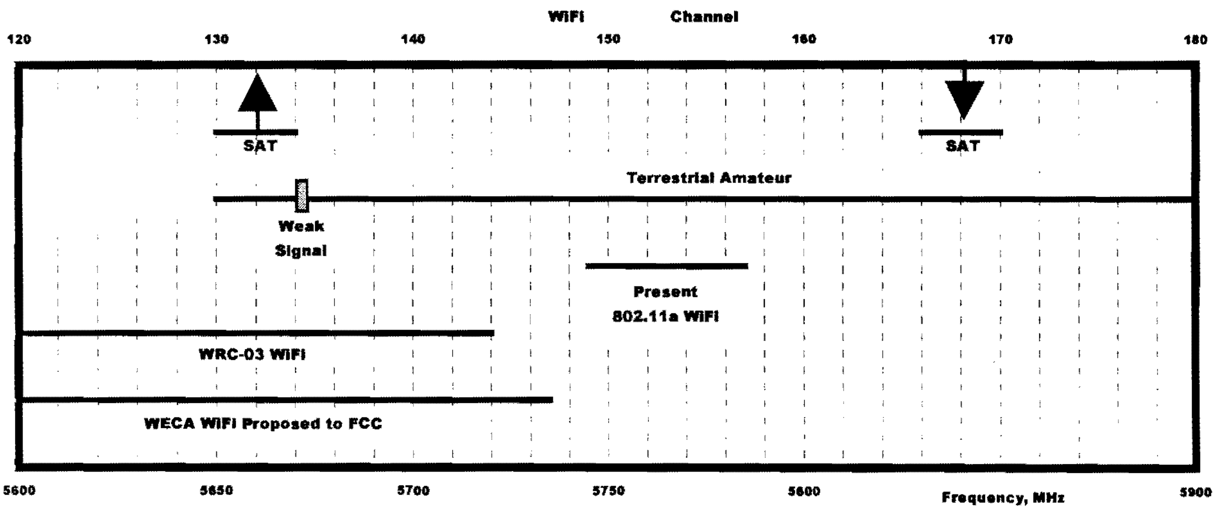

Figure 1: The 5600-5900 MHz C-band Microwave Spectrum

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[2] One exception: some S-band amateur TV repeaters have had some success in making life quite unpleasant for WiFi and BlueTooth users although this was not the intent of their activities.

[3] See http://www.arrl.org/hsmm

[4] See http://www.arrl.org/tis/info/pdf/0304028.pdf

[5] In point of fact, even the unlicensed users are starting to feel the pollution of the microwave spectrum. One (unconfirmed) report I have heard – in a small city in the Pacific Northwest, a wireless LAN installed a few years ago has become useless; the proliferation of unlicensed devices has raised the background noise level by some 67 dB!

[6] See http://www.cisco.com/univercd/cc/td/doc/product/wireless/airo1200/accsspts/ap120scg/bkscgaxa.htm

[7] WiFi channels are 5 MHz wide and are defined as Channel ## = (frequency-5000)/5

[8] In the USA, 802.11a also uses Channels 34-66 in the 5170-5330MHz range.

The wireless industry has formed the Wireless Industry Compliance Association (WECA) to promote the development of WiFi hardware[9]. WECA has petitioned the FCC for a large chunk of spectrum spanning 5470-5740 MHz (Channels 95-147). The recent WRC-03 has set aside the range 5150-5720 MHz for low-powered wireless usage on a worldwide basis. It appears that we must concede that the uplink region will soon be over-run. For C-C Rider to work, we need to be certain that the aggregate of all these low-powered signals will not overwhelm the distant satellite.

What is important to note is that, while the 5650-5670 MHz Amateur Satellite uplink band will soon be occupied by unlicensed wireless services, the 5830-5850 MHz downlink band is not under the same pressure (yet). We need to conduct some detailed RFI surveys of the existing environment. It is my hope that we will be able to make enough noise so that they can hear our uplink signals, and that our downlinks will be in the clear!

The rest of this paper will explore what we might do with our valuable and untapped resource – the matched pair of C-band allocations.

A CAVEAT: I want to stress that **none** of us have suitable C-band equipment in our shacks. Any program to develop satellite hardware will need to be matched with a parallel development of user hardware. These developments will undoubtedly make use of bits and pieces developed for consumer-grade applications, but I doubt that the consumer hardware *per se* will be suitable.

C-C RIDER[10] – A PROPOSAL: This proposal suggests a new concept – a **single-band in-band[11] transponder**. By "in-band" we mean that uplink and downlink will use the same frequency band – in this case, the pair of C-band allocations seen in Figure 1. These two allocations are separated by 180 MHz, so the equivalent "Q" of the band separation filters needs to be ≈ [5800/180] = 32. [12]

In Figure 2, I show a simplified block diagram of a possible "C-C Rider" transponder. One thing to note is that the design uses a **SINGLE** local oscillator at 5750 MHz; this frequency is midway between the uplink and downlink bands (separated by 180 MHz), and results in a 90 MHz IF. Note that this configuration has the LO above the receive passband, and below the transmit passband to create an inverting transponder. This has the interesting property that Doppler offsets are nearly cancelled – I say "nearly" because the Doppler on the uplink and downlink happen at frequencies that differ by 180 MHz. The net Doppler effects are the same as they would have been if the satellite were to operate at 180 MHz. Imagine – a microwave satellite with Doppler rates only one-third of those we have learned to tolerate since the 1970's Mode-B and Mode-J satellites![13]

As with any other satellite program, the selection of a suitable orbit is a prime concern. The possibilities generally sort into two categories: LEO (Low Earth Orbit, with altitudes below about 1000 km and orbital period in the 90-120 minute range) and HEO (High Earth Orbit with altitudes greater than 10,000 km and periods longer than about 6 hours). By these broad definitions, the HEO category includes **GTO**

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[9] See http://www.wi-fialliance.org/OpenSection/pr/pr_pdf/Wi-Fi_Fall_01_Briefing.pdf

[10] The song "***CC Rider***" (sometimes called ***See See Rider***") was one of more than 100 songs written by the great jazz/blues singer, Ma Rainey (http://www.redhotjazz.com/rainey.html) in 1925. In addition to Ma, it was made famous in versions by Mississippi John Hurt, Big Bill Broonzy, Ray Charles, Bruce Springstein, Elvis Presley, Ian & Sylvia and even the Kingston Trio. I take the blame of picking it as a name for this project!

[11] Actually, OSCAR-III in 1965 carried a 50 kHz wide 2 Meter in-band transponder with a 145.9 MHz uplink and 144.1 MHz downlink.

[12] Contrast this with a conventional 2 Meter repeater which requires a "Q" ≈ [146/0.6] = 243, a technical challenge ≈ 7.5 times harder.

[13] Instead of having Doppler effect the frequency, the entire passband "slides", much like the Passband tuning on an HF radio. Thus stations near the passband edges may "fall off the edge" as the satellite goes from "away" to "towards" as it moves in the orbit.

(Geostationary Transfer Orbits), **GEO** (Geostationary orbits), **Molniya** (high inclination but otherwise similar to GTO), and the 12-hour orbits used by GPS and GLONASS navigation satellites.

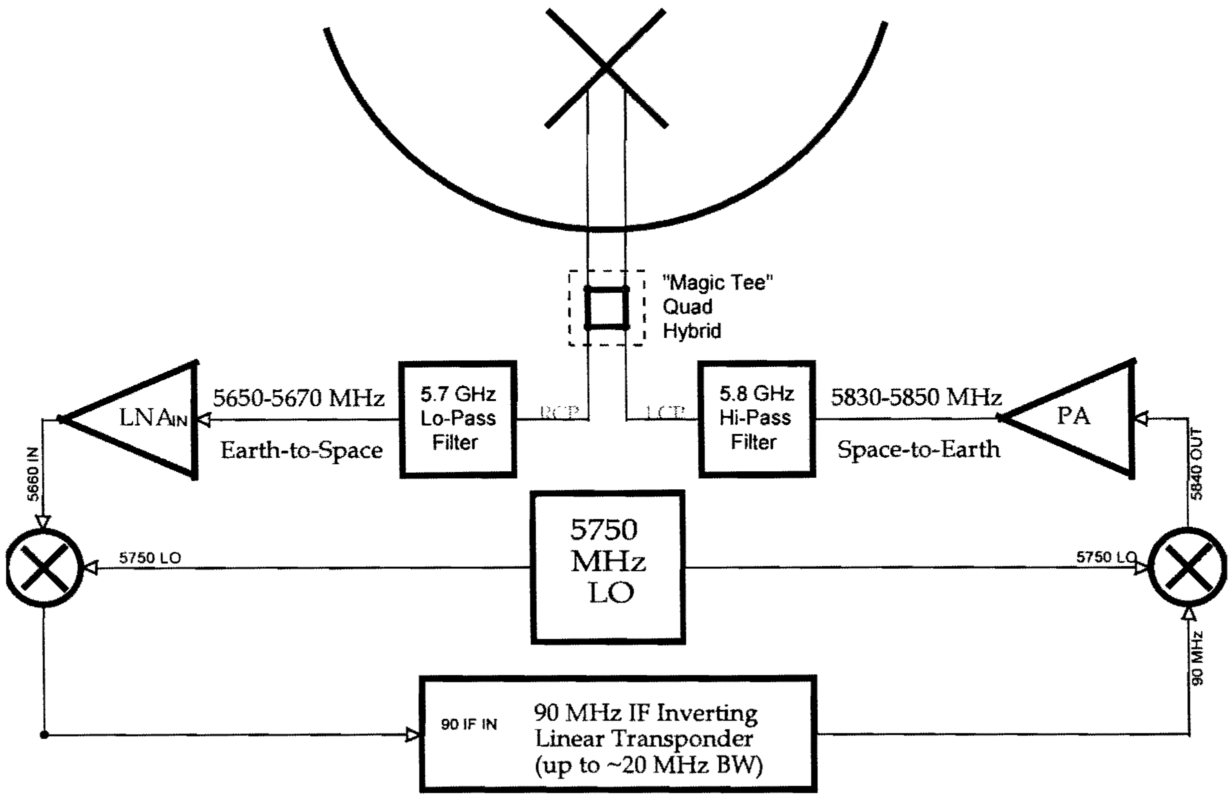

Figure 2: Simplified design of C-C Rider Spacecraft Transponder

LEO: If C-C Rider were to fly on a LEO satellite (~800 km), the Earth (and hence the users) fills much of the "down" half of the sky. A low-gain, wide beamwidth antenna is needed, like a small patch antenna (~6 dBiC gain). Computing the link budget[14] we find that the both the uplink and downlink path loss is about 175 dB. Let's put about 2 watts (output) of transmitter on the satellite.

On the ground, let's use a 30 cm dish (or a 3x3 phased array of patch antennas, as we discuss later) and a 70K LNA. Under these conditions, the downlink will just support a 64 kb/sec digital link (or a 64 kHz analog passband) without the addition gain that would result from coding and error correction. The use of these techniques could push the digital rate up to ~100 kb/sec. The user uplink will require about 5 watts of transmitter.

The 26 dBiC up/downlink antenna has a beamwidth ~12 degrees. This will need to be pointed at the spacecraft (mechanically or electronically) at levels of 2-3 degrees. An overhead satellite pass will produce peak satellite motion in the ½°/sec range, so the antenna will need to point very rapidly! In a later section I propose a possible "no moving parts" solution to this problem.

HEO: We all had a lot of hope in the promise of AO-40. Alas, the mission was only partially successful. We all have great hopes for AMSAT-DL's P3-E satellite and AMSAT-NA's Eagle satellite. Let's now look at how CC-Rider might work on Eagle.

[14] I used an Excel spreadsheet template provided by Jan King, W3GEY for LEO mission planning.

To evaluate a typical HEO link, I assume a GTO or GEO satellite at ~36,000 km range. From that altitude, the one-way C-band path loss is 200 dB, 25 dB more than the LEO case we considered earlier. We also find that from the spacecraft, the earth now has a diameter of about 17°. To achieve a 17° beam, the downlink antenna can have only ~22 dB of gain, corresponding to an aperture of about 20 cm (i.e. about 3.5λ). Finally, I assume that we can generate 5 watts of RF.

On the ground I assume a 30 cm aperture (probably a phased array for reason described later), 70K LNA and 10 watts of transmit power.

Using a different link budget analysis tool[15], we find that the C-C Rider could handle ~120 kb/sec of data without regeneration[16], or about 600 kb/sec with regeneration. This could be apportioned out to multiple users for digital data or voice use following the model suggested by Phil Karn, KA9Q.

HEO ANTENNA IDEAS: I envision that the same antenna will be shared by the uplink and downlink. Figure 2 showed how this might be done with a dish antenna. The inherent problem with this scheme is that the antenna's mechanical structure must be mechanically stabilized to levels of about ¼ of the beamwidth. In the case of a LEO ground station, and for both the spacecraft and ground stations for HEO, antenna gain in the 20-25 dBiC range ends up imposing a requirement of a few degrees on the antenna pointing. But with CC-Rider we have the interesting situation: The receive and transmit antennas share a common physical structure, and we want the two antenna beams to point in the same direction.

It is common practice in the professional spacecraft world to use a "monopulse" feed. At the focus of a dish antenna we find an array of 4 antenna feeds which we might denote LEFT, RIGHT, UP and DOWN. Four separate receivers compare the RF phase of the signals seen by the L-R-U-D antennas. The antenna is then mechanically steered for zero phase difference. Then a 5th receiver makes use of the sum of all 4 antennas to get the full antenna gain.

Figure 3 shows a "no moving parts" approach we might use at C-band. I show 9 antennas arrayed in a 3x3 square (although a 4x4 or 5x5 array might be used if more gain is needed). On the receive side, each antenna is connected to a separate LNA and mixer, and then into a separate receive IF channel. The data from all 9 (or 16 or 25) is compared to measure the offset of the array from "boresight" relative. All the channels are summed to generate the low-noise signal needed by the transponder. As you can see, this is a phased array implementation of the traditional monopulse feed.

The receive signal processor has now determined how to point the antenna to optimize the received signal; the desired transmitter direction is precisely the same as we "peaked" the receiver! So the same processor knows how to generate the phasing data needed to point the transmitter in the same direction.

I envision that the transmit phased array will use a separate power amplifier for each antenna. This makes it feasible to use multiple low powered transmit elements, like those already available in the consumer marketplace[17].

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[15] Also by Jan King, W3GEY, designed for the evaluation of the "KarnSat" digital payload for Eagle.
[16] The uplink signal is demodulated at the spacecraft, applying the gain of error correction. The "clean" signal then remodulates the downlink. This provides for a significant improvement in end-to-end sensitivity
[17] Some very interesting, low cost ½ watt 5.8 GHz amplifier chips costing < $10 are available from Hittite: http://www.hittite.com/product_info/product_specs/amplifiers/hmc408lp3.pdf (thanks to Grant, G8UBN for the pointer).

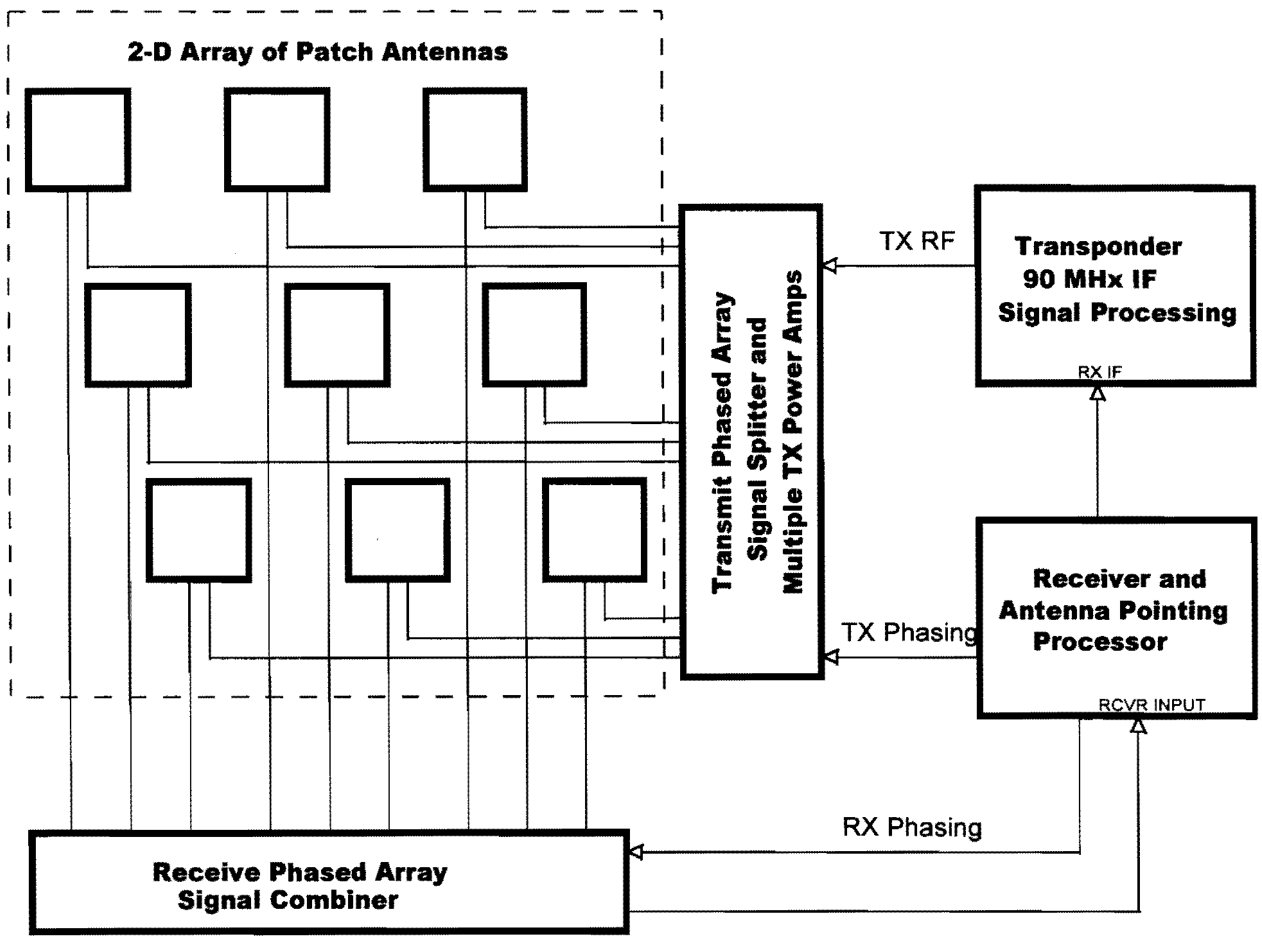

Figure 3: Using an Array of Patch Antennas instead of a Dish.

The use of separate receive LNAs and transmit power amplifiers for each antenna element provides a useful measure of reliability. If one of N elements should fail, then the array performance only drops by a factor of 1/N. Depending on spacecraft real estate, some extra elements could be flown to provide for the need for extra gain in an emergency. The amplitude illumination of the individual elements can be trimmed to provide active control of beams shape.

Some Other Ideas: So far I have not discussed any details of the inner transponder "guts". Figure 2 shows only a basic linear transponder. Certainly this could be made to work, and we could have a microwave replacement for Mode-B (or Mode-L/S). The interesting numerology of the two C-band channels causing Doppler to (nearly) cancel is neat. But we must ask if there might be alternate uses that make sense.

In thinking about these ideas, I asked myself a rhetorical question: What will be the thrust of Amateur Radio (and by implication Amateur Satellites) in the year 2018? Such a long vision is needed because it would take a few (let's guess 5) years before a new concept could fly. What will be the "hot button" technology in 2008? Then we hope that any satellite we build will continue to be a viable, exciting, living entity for at least a decade if not more.

Let me use historical hindsight to think about the implications of the need for long-range vision.
Back in the early 1970's, when we had OSCAR-6 flying, our members yelled that Mode-A was what they needed. Everyone had 10M capability; and a 2M TX was technically tough but possible. Many said "Why

even consider Mode-B in OSCAR-7? -- 70cm is like microwave and we mere mortal amateurs should not venture there!" Little did they know about all-mode, all-band radios!

In the early 1980's, as we were preparing Phase-3A, I saw the need for software to track elliptical satellites, so I wrote and published an "open source" ORBIT program. The naysayers said "Don't waste space in the AMSAT magazine – amateurs will never have their own computers". Little did they know that we would all have PCs connected to the Internet a decade and a half in the future.

The 1990's saw the birth of amateur digital satellites. AO-40 proved that L/S microwaves really are now in the grasp of amateurs. The folks planning missions now need to think about where amateur radio will be in the 2010's.

One of the imaginative views of the future has come from Phil Karn, KA9Q. His thinking is based on the success of creative mixtures of RF, digital and signal processing like we have seen with modern cell phones and the satellite phones used by correspondents in the middle-east which operate in the L/S band spectrum. DirecTV and similar systems at 12 GHz have shown that satellite-based microwave hardware can be combined with sophisticated digital coding and signal processing to provide robust, low-cost one and two-way wireless paths.

Phil asked if we couldn't make similar capabilities for amateurs. Many urban amateurs have problems erecting antennas: can't we invent a system that could use technology developed by amateurs to provide the functional characteristics of 20 meters to the amateurs living in apartments?

Various AMSAT people have thought a lot about these ideas and have concluded that the answer is YES. We could augment Eagle to include some of the needed technologies. Let's morph Figure 2 into Figure 4 to see what the spacecraft might look like[18]. Here we see that the IF portion of C-C Rider has been replaced by three packages: a linear transponder, a "KarnSat" digital transponder and a 3rd package called (for historical reasons) RUDAK.

On the Ground – As seen from the User's Point of View: As I noted earlier NOBODY has the hardware that a ground-based user might need. If we build CC-Rider, we **must** develop the ground-based hardware at the same time. Figure 5 shows a view of what a user terminal might look like.

If you compare Figure 4 and 5, you will see few differences, except that the transmit and receive roles are reversed. Transmit filters become receive filters, upconverters become downconverters, etc. I envision that the microwave part of C-C Rider (inside the dashed lines in both Figures 4 and 5 on the next page) would be constructed on 2-3 microstrip boards and there is little difference between the user terminal and the spacecraft – we can get double duty from a good RF design. This would also be possible with the phased-array alternative.

[18] Of course, the antenna might be a phased array instead of a dish following the ideas in Figure 4.

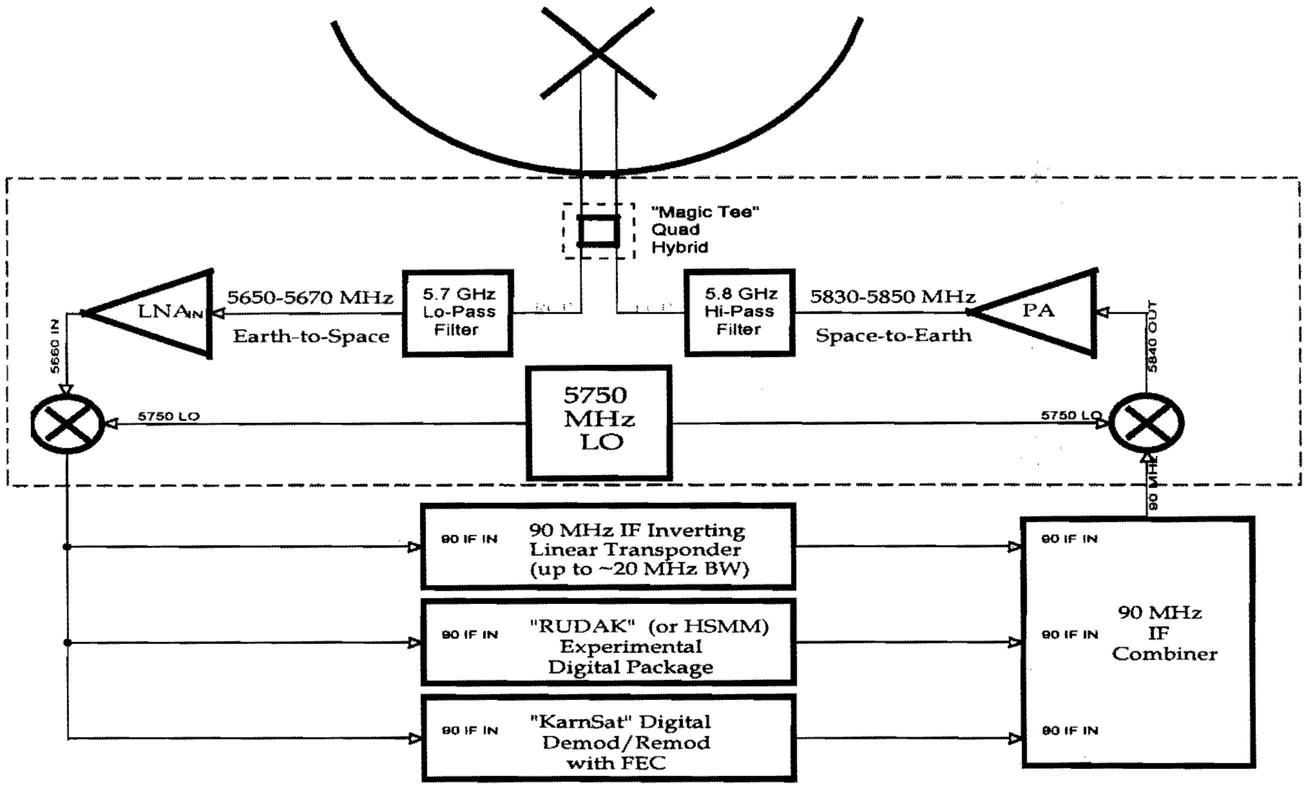

Figure 4: A possible C-C Rider Spacecraft Transponder for Eagle

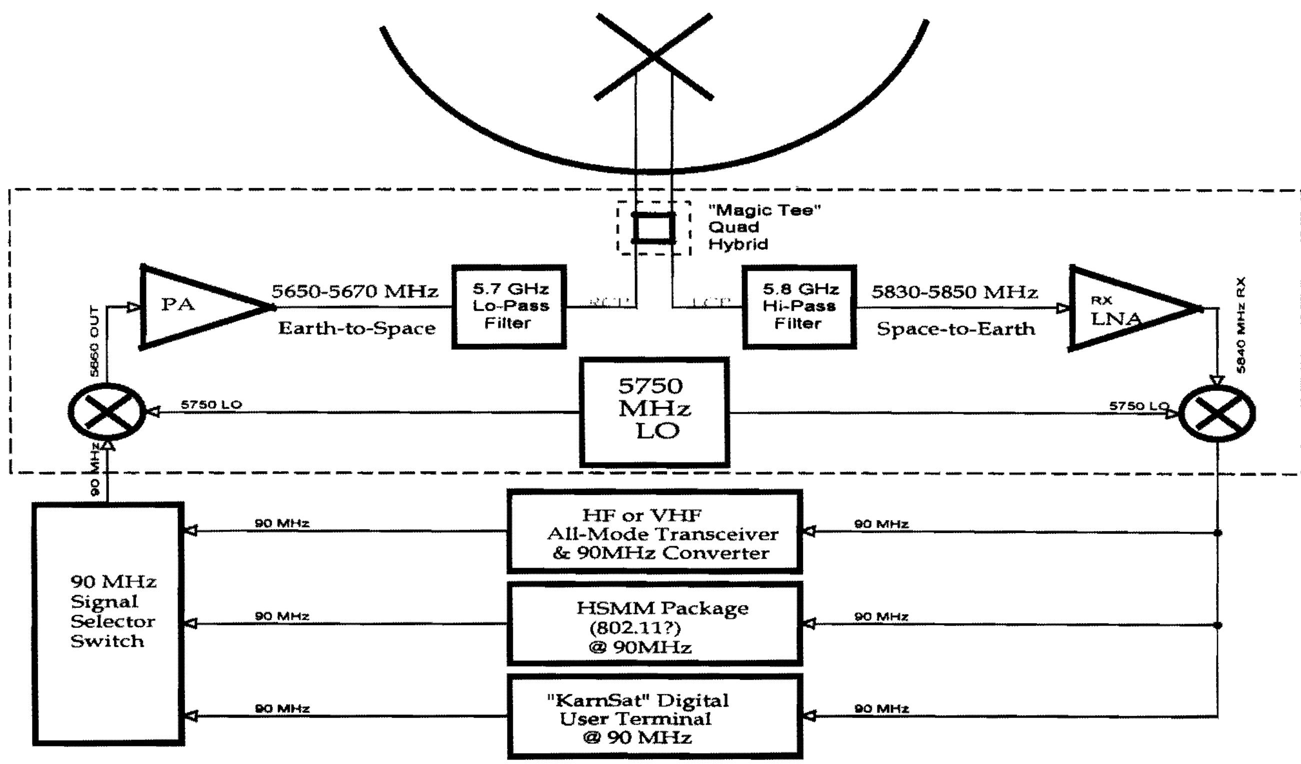

Figure 5: A C-C Rider Ground-based User Terminal

Terrestrial Possibilities: I mentioned earlier that the ARRL's HSMM effort has concentrated on the use of 2.4 GHz WiFi hardware, but that activity might want to try C-band. If some good RF hardware is developed that is suitable for both space and ground use, there is no reason that it should not serve as a technology resource for terrestrial use. "Dummy spacecraft" on mountain tops seem a logical development. Some low cost terrestrial hardware is already available.[19] So far, the "Hinternet" activity is based on 802.11x protocols, which in turn are derived from Ethernet; therefore they look a lot like packet radio. They require a timely packet-by-packet acknowledgement in order to achieve a good data thruput. These protocols look very different from a satellite link with light-travel-time limitations. So, while terrestrial and satellite applications might share a lot of hardware, they will probably require different software. But after all, that's not a serious limitation – there is an old adage:

It's only $oftware! It's the Hardware that's Hard.

In Conclusion: In this paper I have tried to present the radical idea – the Amateur Satellite folks need to lead the rest of Amateur Radio in the preservation of a valuable resource – our Microwave spectrum. We have already seen our 2.4 GHz turn into a "sewer" as unlicensed users move in to grab spectrum for their needs. Unless we begin a program to preserve our resources at C-band, they too will fall under the guillotine of consumer technology.

Let's not sing the blues[20] "Might not be comin' back at all" to our precious microwave allocations. Let's carry thru on the upbeat note "Just might find me that good girl, and everything would be alright".

Tom Clark
August 2003

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[19] Off-the-shelf ½ watt C-band amplifiers (intended for terrestrial WLAN use) are available at http://www.hyperlinktech.com/web/amplifiers_5800.html

[20] One version of Ma Rainey's CC Rider goes something like this. Note the highlighted lines:

CC RIDER

Well now see, C.C. Rider
well now see, see what you have done
Well now see, C.C. Rider
well now see, see what you have done
Well you made me love you woman
Now your man has come

So I'm goin' away now baby
And I won't be back till fall
I'm goin' away now baby
And I won't be back till fall
Just might find me a good girl
Might not be comin' back at all

Well now see, C.C. Rider
See now the moon is shining bright
Well now see, C.C. Rider
See now the moon is shining bright
Just might find me that good girl
And everything would be alright

Orbit Determination for *AMSAT* Spacecraft

By Ken Ernandes, N2WWD
n2wwd@amsat.org

ABSTRACT

Orbit Determination (OD) in the early phases of the AMSAT OSCAR 40 (AO-40) mission coincided with upgrades to a commercial satellite mission planning software program named AstroDynamics Environment (ADE). This unique timing provided opportunities for real-time mission support to the AO-40 Command Stations during some critical stages. ADE's capability has since further matured and is currently the baseline orbit determination software for the NAVSTAR Global Positioning System (GPS) Launch and early orbit, Anomaly, and Disposal Operations (LADO). The author, being one of the primary developers of ADE, has unlimited personal use of the software. Thus the availability of this robust capability offers AMSAT the opportunity for more timely and accurate OD support for current and future spacecraft missions.

BACKGROUND

Ken Ernandes, N2WWD was engaged as a consultant for Braxton Technologies, Inc. (http://www.braxtontech.com) in early 1999 to augment the orbit computation capability in their various Microsoft Windows-based satellite ground station software programs. Early on, Braxton president Bill Simpson indicated the desire for a more significant astrodynamics capability from within the company. The process began with ADE growing out of an earlier Braxton product (the tracking Observation Editor) in which we added an OD capability to support the Air Force Satellite Control Network (AFSCN) Operations Improvement System (OIS). The initial ADE OD capability used the Simplified General Perturbations version 4 (SGP4) orbit propagator, commonly resident in most satellite tracking software, for orbital modeling. This provided the base platform for statistical orbit computations that ultimately supported the AO-40 Command Team in the early phases of the mission.

Prior to the AO-40 launch, the Braxton Advanced Computation Equipment® (ACE) Telemetry, Tracking, and Commanding (TT&C) software product line had been selected for the GPS LADO program. The LADO contractors also selected ADE to generate mission-planning reports to augment the NASA Goddard Trajectory Determination System (GTDS) software, which was the baseline for GPS OD. However, Braxton and N2WWD were challenged to increase ADE's capability to provide a high precision OD capability equivalent to that of GTDS. Among the success criteria was demonstrating that ADE's precision Special Perturbations (SP) orbit propagation predictions would match that of GTDS within one meter over a continuous 30-day time interval, using a full GPS LADO force model. ADE ultimately met this challenge, deviating from GTDS by a maximum 0.6 meters over the 30-day interval. This led to ADE being selected to replace GTDS for the GPS LADO OD process and becoming the baseline Mission Planning software.

OD PROCESS

Some AMSAT members may be familiar with N2WWD providing early mission OD (i.e., computing the "Keps"), beginning with Radio Sputnik 15 (RS-15). While most have been content to just get the Two-Line Elements (TLEs), others have asked about how the process is done. While a complete explanation would be beyond the scope of this paper, I shall briefly summarize the process.

ADE uses a standard process called a least-squares batch differential correction (DC) to determine the statistically most likely orbit, starting with an initial (a priori) estimate of the trajectory that is refined against observations. A DC differs from a standard linear regression computation in that fitting an orbit to tracking data is a very non-linear problem. This requires not only special techniques to ensure the stability of least squares filter, but also that the problem be re-formulated as an approximate (linearized) correction to the current estimate (starting with the a priori orbit). Because of the linearization approximation, the process is iterative, with the filter providing ever-closer estimates, until a point of diminishing improvements between successive estimates of the actual orbit is achieved (i.e., convergence).

TRACKING DATA

ADE is currently set up to accept any subset of time-tagged Azimuth, Elevation, Range, and Range Rate data as observed by a fixed, Earth-based tracking site. Data is ingested in the format provided by the AFSCN sites.

The AO-40 Command Sites have the capability to measure range by sending pseudo-random codes through spacecraft transponders as discussed in reference 1. This is quite similar to the range measurement process performed by the AFSCN sites. James Miller, G3RUH was most cooperative in sharing AO-40 ranging data and encouraged N2WWD's feedback to Command Team orbital data requests.

While ranging observations are the most accurate measurements, they are only generated by Command Sites actively sending signals through the spacecraft transponder. However there are other sources of useful measurements, many of which were received from the general AMSAT membership. The types of useful measurement reports received were Acquisition of Signal (AOS) and Loss of Signal (LOS) times and the reversal times on the Doppler shift. The AOS/LOS times approximate spacecraft zero elevation angles and the Doppler reversal approximates the time of zero range rate. These measurements may all be made passively by tracking the spacecraft beacon. The only other information required is an accurate measurement of the observer's location, determined typically by a GPS receiver.

While some may question the usefulness of relatively coarse measurements such as the approximate times of AOS/LOS and of Doppler reversals, these have been used effectively in the past. A least squares DC allows for proportional weighting of all measurements, typically using the reciprocal of the measurements' statistical variances. Thus the less accurate data does not adversely affect the solution. In the early orbits following launch (prior to transponder activation), such measurements have proven to be quite instrumental in refining pre-launch orbital estimates into quite useful Keplerian element sets.

AO-40 EARLY ORBIT

AO-40's pre-launch orbit estimates were based on performance and payload injection information provided for the Ariane 5 launch booster and using the techniques described in reference 2. While the Ariane booster provided a nominal injection, even a very slight difference in planned position and velocity will accumulate over just a few orbits. Thus the nominal Keplerian estimates were a "perishable" commodity. But the estimated Keplerian elements were adequate for AMSAT members around the world to provide AOS/LOS observations that facilitated refinements and thus the computation of updated Keplerian elements. Having observers distributed throughout the World made for an excellent geometric data distribution; observers collecting at various times also facilitated a temporal data distribution. Both geometric and temporal distribution of the data is important for the OD mathematical algorithms optimal performance.

COMMAND TEAM RANGING DATA

The AO-40 command team measures ground site to spacecraft ranges through a spacecraft communications transponder. But unlike the AFSCN sites, the AMSAT command stations do not have the ability to automatically track the spacecraft following acquisition and thus provide measured azimuth and elevation angle measurements to augment the tracking data. While this would normally be of low significance, the angular data may have been helpful to the OD in reducing ambiguity in the AO-40 orbit's low inclination angle (i.e., orbital plane tilt relative to the equator).

The Command Stations providing AO-40 ranging data were:

DJ4ZC	Marburg Germany
DB2OS	Hanover Germany
G3RUH	Cambridge England
VK5AGR	Adelaide Australia
W4SM	Charlottesville USA
ZL1AOX	Auckland, NZ
ZL1BIV	Auckland, NZ

Figure 1 shows ADE's observation data select dialog box. In the upper left corner is AO-40 selected, plus the all the AMSAT Command Stations checked on for observation selection. The upper right corner shows the a priori Keplerian elements. While these data were (in this case) extracted from the previous solution on the database, these values may alternatively be manually entered or imported (from TLE or vector files). The a priori data may also be manually entered as Cartesian position and velocity state vectors or as spherical elements.

The "Light Time" correction was selected to correct the observation time for the propagation delay from when transponder sent the message to when the ground site received it. No refraction corrections were used as ADE only currently has an S-band model. At the bottom of the dialog are the data log files (converted to AFSCN format), containing the sites ranging data for various times.

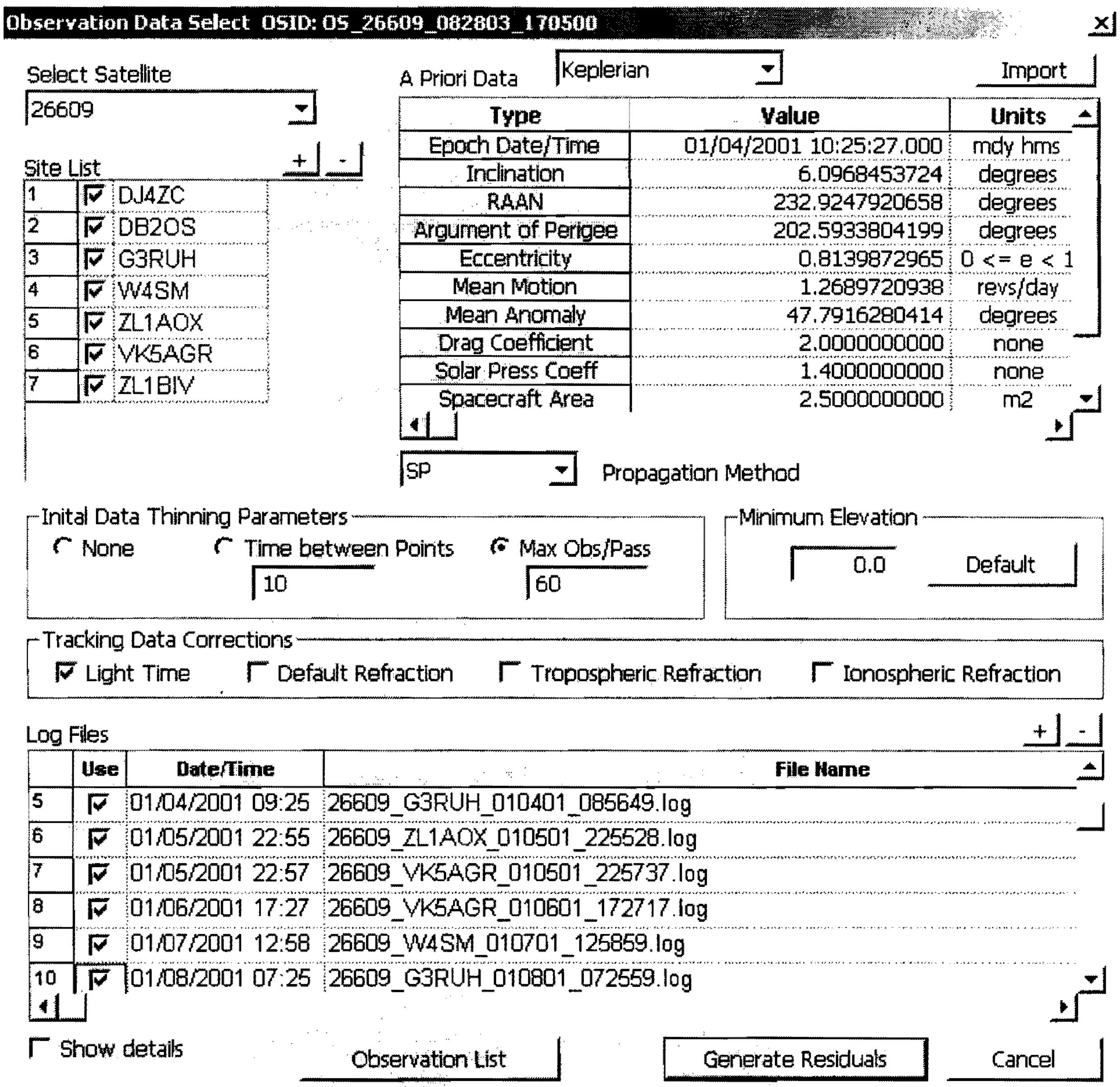

FIGURE 1. ADE OBSERVATION DATA SELECT DIALOG

Once the tracking data files are selected, the user would then choose the "Generate Residuals" button to proceed to the next step in the OD Process. Residuals are the difference between an actual observation and what the observation would have been as computed from the current orbit estimate. Given perfect observations, a perfect orbit estimate, and perfect prediction model, the residuals would all be zero. With the SP propagator we have endeavored to create an extremely accurate orbit prediction model. The observations, however, are good (at best) to 10 km using current AMSAT Command Station equipment. Therefore, the OD process must adjust the orbit estimate as best as possible to minimize the residuals and evenly distribute them about the zero (orbit prediction) line.

INITIAL RESIDUAL PLOT

Figure 2 show's ADE's plot of the range residuals against the a priori orbital estimate. For this example, a previous OD had been performed using the data on the left side of the plot. However, subsequent tracking data was added to the previous fit interval, in the interests of getting a wider temporal (and perhaps better geometric) resolution – i.e., additional bandwidth for the OD process.

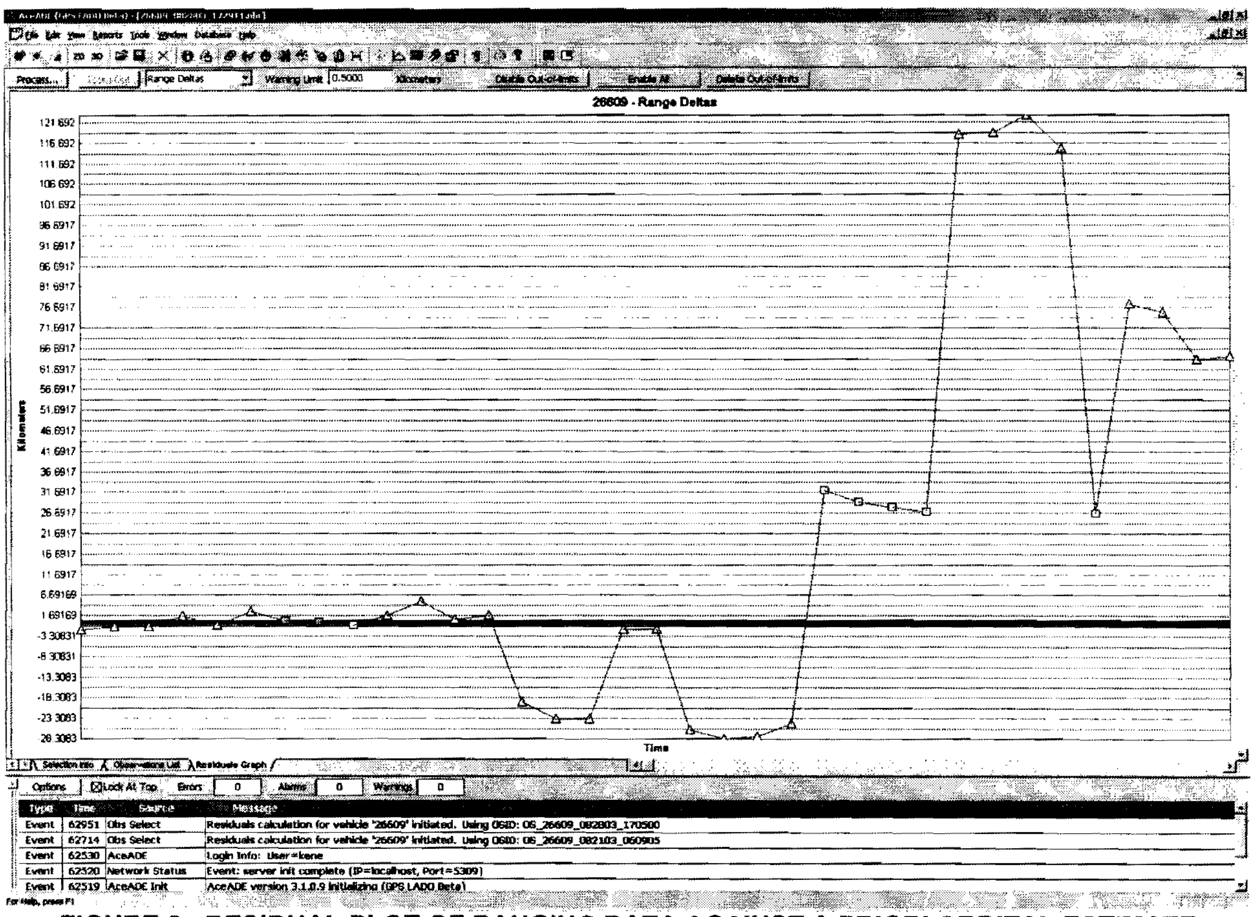

FIGURE 2. RESIDUAL PLOT OF RANGING DATA AGAINST A PRIORI ORBITAL ESTIMATE

It's worth noting is that the vertical scale has maximum ranges on the order of 120 km, indicating the a priori estimate to have deteriorating prediction accuracy at the times toward the end of the data span.

It should also be noted that the residual plots (also provided for Azimuth, Elevation, and Range Rate observation components) allow graphic editing of outlier data using a variety of tools. However for this example we shall allow ADE's OD algorithm to determine automatically if data should be edited out.

OD PROCESS INITIATION

Figure 3 shows ADE's OD Generation Dialog. What is most significant for this example are the Orbit Determination Controls and the Parameter Correction Subset. The Orbit Determination Controls govern the OD process in terms of the maximum number of iterations (i.e., sequential linearized correction steps) that may be made, the convergence criteria (the point of diminishing improvement between two successive estimates), and the automatic residual editing threshold (in numbers of standard deviations from the mean residual value).

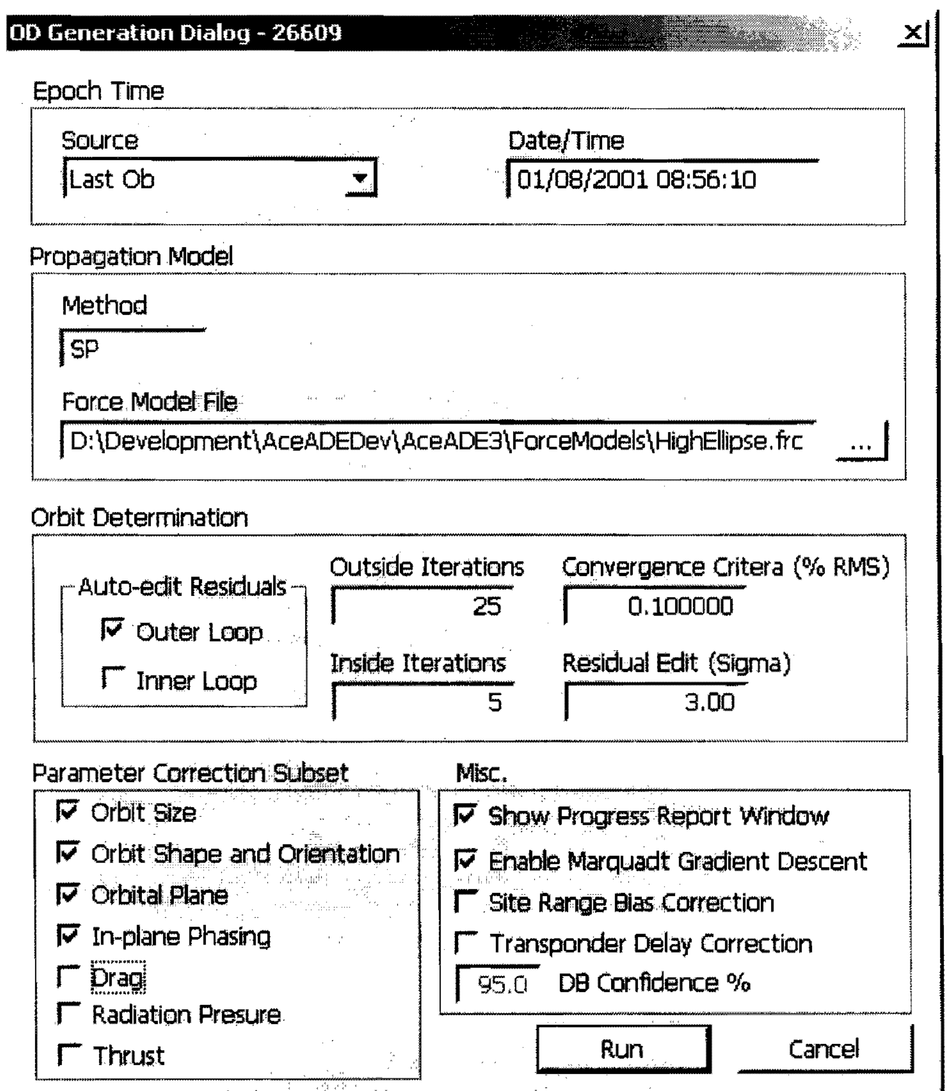

FIGURE 3. OD GENERATION DIALOG BOX

The Parameter Correction Subset controls have the basic constituents of a Keplerian element set selected, but are not correcting the drag or solar radiation pressure coefficients, nor are they solving for an included thruster firing event. This example has also chosen not to attempt updating site range bias values or the transponder delay value.

POST OD RESIDUAL PLOT

Figure 4 shows the post-correction range residual plot, updated to the orbit computed by ADE's OD algorithm. One should note that for the OD solution, the range points are now evenly distributed about the zero line throughout the time interval. The typical range residual is on the order of 12 km, essentially consistent with the expected data measurement accuracy.

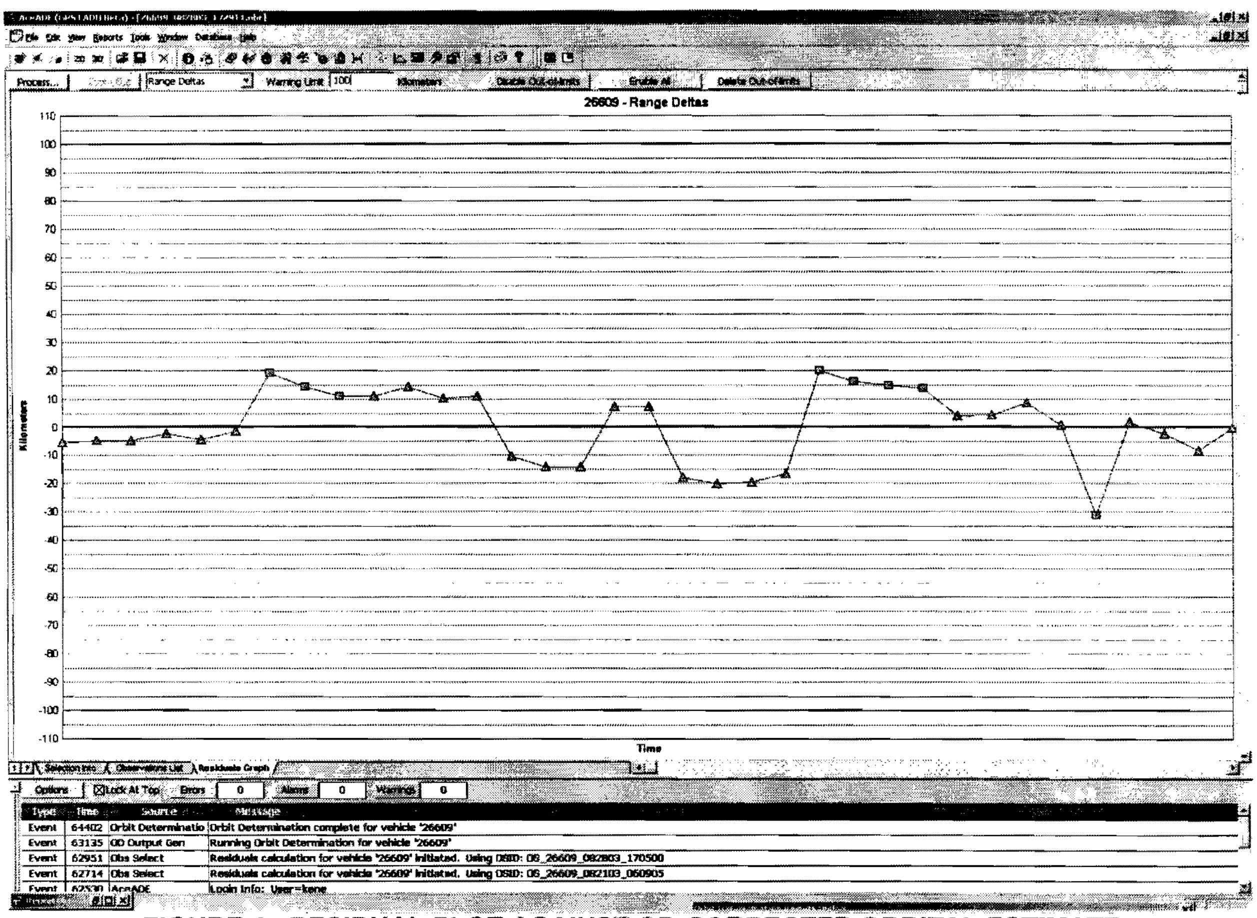

FIGURE 4. RESIDUAL PLOT AGAINST OD-CORRECTED ORBITAL ESTIMATE

A 12 km accuracy over the 5 day fit interval is a most satisfactory result for tracking the spacecraft. However, one might be concerned that the typical residual is greater than the expected 10 km accuracy of the ranging data. This may be explained, at least in part, by the fact that the spacecraft was, at the time, experiencing a leak that would correspond to a mass expulsion from the 400N thruster's nozzle. Hence the significant shift to the orbit and the challenge of this particular example. (By contrast, typical ADE post-OD range residuals for GPS satellites using AFSCN data are usually below two meters.)

CORRECTED KEPLERIAN ELEMENTS

Figure 5 provides a comparison of the a priori (Old Value) Keplerian elements versus the OD-corrected (New Value) elements. There are significant shifts to the inclination angle (tilt versus the equator), the eccentricity (the orbit's shape), and the mean motion (orbital frequency).

Orbit Determination Results Dialog

Vehicle 26609 Date/Time (240) 08/28/2003 17:53

a-b Keplerian Compare | Cartesian | Spherical | Quality | Site Bias

	Old Value (TOD)	New Value (TOD)	Info
Epoch Date/Time	01/08/2001 08:56:10	01/08/2001 08:56:09	mdy hms
Inclination	6.0377033086	5.9342507848	degrees
RAAN	231.8652390770	232.8276071112	degrees
Argument of Perigee	204.4792063513	203.9321911891	degrees
Eccentricity	0.8140700956	0.8144883813	0 <= e < 1
Mean Motion	1.2690954974	1.2692090426	revs/day
Mean Anomaly	46.7785209010	46.9140584931	degrees
Drag Coefficient	2.0000000000	2.0000000000	none
Solar Press Coeff	1.4000000000	1.4000000000	none
Spacecraft Area	2.5000000000	2.500000	m2
Spacecraft Mass	400.0000000000	400.0000000000	kg

Export | Commit | OS_26609_082803_175322 | Retire Logs | Done

FIGURE 5. A PRIORI VERSUS OD-CORRECTED KEPLERIAN ELEMENTS

Figure 6 has the OD output Keplerian elements from figure 5, deosculated by the export process to mean elements in NORAD TLE format. This is the product typically used by AMSAT members in computerized tracking software to direct antenna azimuth and elevation as well as for Doppler shift compensation corrections to the transceiver uplink and downlink frequencies.

26609_082803_175730.tle - Notepad

File Edit Format Help

```
AO-40
1 26609U 00072B   01008.37233796  .00000000  00000-0  00000-0 0 00014
2 26609 005.9330 232.8318 8145867 203.9282 046.9059  1.26892397000016
```

FIGURE 6. CORRECTED MEAN KEPLERIAN ELEMENTS EXPORTED TO TLE FORMAT

OUTPUT VECTOR DATA

Figure 7 provides the OD-corrected orbit in Cartesian position and velocity vector format. Note also that the data is displayed in both Earth-Centered Inertial (ECI) and Earth-Fixed Greenwich (EFG) coordinate frames and that it may display either kilometer or feet length units.

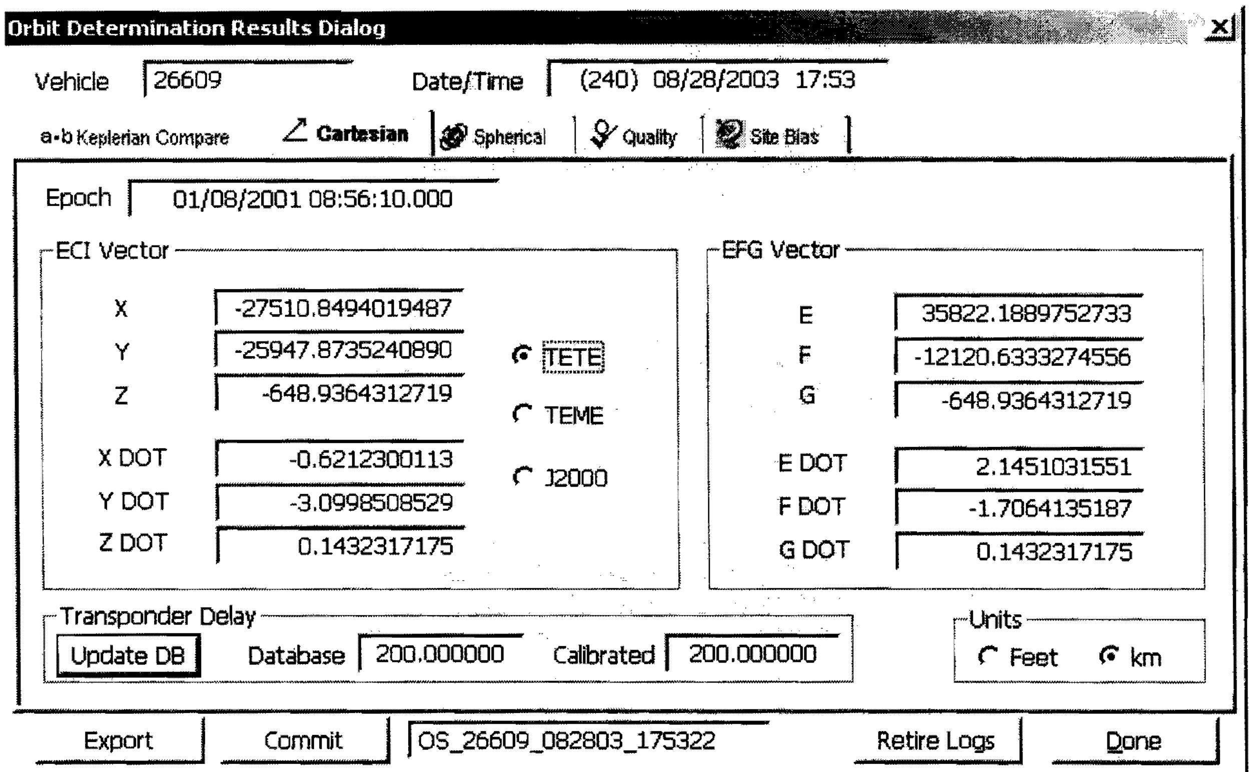

FIGURE 7. OD-CORRECTED ORBIT IN CARTESIAN POSITION AND VELOCITY VECTOR FORMAT

WHERE WE STAND TODAY

The ADE OD process, while retaining the legacy SGP4 capability, now benefits from the addition of a precision SP orbit propagator designed initially to accommodate the requirements of the GPS LADO mission. The user may tailor the SP force model to the application at run time. The modeling includes the following effects and force options:

- Integration Methods – the net acceleration vector, resulting from the sum of forces selected below is integrated numerically to update the spacecraft velocity and position vectors. Various integration methods have different advantages and disadvantages in the areas of speed, accuracy, and tolerance to abrupt changes in force. ADE currently has three choices of numerical integration methods:
    - Gauss-Jackson (4^{th} to 12^{th} Order) – A recursive method that has the best performance in terms of speed and accuracy, but has the lowest tolerance to abrupt force changes. The latter problem is overcome by automatic switching to Runge-Kutta integration when discontinuous forces (such as thrust events) are encountered.

- Runge-Kutta (4th Order) – A basic integration capability that is reasonably fast and accurate.
- Runge-Kutta (8th Order) – A more accurate Runge-Kutta integrator that is slower than the fourth order method. However, the eight-order method has adaptive step size control to help compensate for the slower processing speed.

- Earth Gravitational Modeling – ADE models the Earth's gravitation acceleration due to asymmetries and mass concentrations using spherical harmonics, up to 70th-order, 70th-degree. The spherical harmonics include terms that are latitude-dependent (zonal), longitude-dependent (sectoral), and terms that depend on both latitude and longitude (tesseral).
- Earth Precession and Nutation – ADE models the combined effects of lunisolar and planetary precession and nutation. Lunisolar precession (due to torques from the Moon and Sun) is the smooth long-periodic drift of the Earth's mean pole about the ecliptic, which has a gyration period of approximately 26,000 years. Planetary precession is an additional effect on the mean pole due to gravitation action by the planets. Nutation is a short period oscillation of the true pole about the mean pole, that has about a 9 arc-second amplitude and periods up to 18.6 years. The interested reader may get additional information from reference 3.
- Earth Rotation Irregularities – Variations in the Earth's rotation rate and polar wander are input using Earth Orientation Parameters (EOPs) from the International Earth Rotation Service (IERS) bulletins (http://hpiers.obspm.fr/) which are also available also from the United States Naval Observatory (USNO) http://maia.usno.navy.mil/. The specific EOPs used include the leap second differences between Atomic Time and Coordinated Universal Time (UTC), the differences between UTC and the Earth's actual rotation (UT1), and the Earth's polar wander offsets over time. ADE predicts the EOPs when the bulletin values are not available on the database.
- Third Body Gravitational Modeling – ADE allows the inclusion (or exclusion) of gravitational perturbations from the Sun and Moon. These bodies are treated as point mass gravitational disturbances. These forces are most significant for spacecraft orbiting wholly or partially at altitudes 5,000 km or more above the Earth's surface.
- Atmospheric Modeling – ADE allows for the inclusion (or exclusion) of atmospheric drag forces. The effects of atmospheric drag are most significant for spacecraft orbiting wholly or partially within 1,000 km of the Earth's surface. ADE provides a choice between two atmospheric density models:
  - Static – This is equivalent to the SGP4 atmosphere in with a power density that decreases with altitude above the Earth's surface.
  - Jacchia-Roberts – A dynamic atmospheric model that includes the effects of a diurnal bulge in the atmosphere (due to solar heating) and seasonal effects. Density modeling is tied to the measured effects of 10.7 cm solar and geomagnetic flux values. The flux data may be downloaded from the National Oceanic and Atmospheric Administration (NOAA) from: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/

- Solar Radiation Pressure Modeling – ADE allows for the inclusion (or exclusion) of the pressure induced by photon impact from solar radiation. When selected, radiation pressure is directed outward from the Sun, except at times when the spacecraft is in eclipse.
- Thrust Modeling – ADE allows for the modeling of finite duration thrust events, using a propulsion model that includes pressurized propellant tanks, propellant flow and mass expulsion rates based on current pressurization, propellant specific impulse, and thruster efficiency.

SUMMARY

AMSAT has available, with ADE, an indigenous OD capability developed to meet the requirements of a high profile, government-sponsored satellite program. ADE has demonstrated its ability to accurately compute AO-40's orbit for both the general AMSAT membership as well as providing orbital data useful to the AO-40 Command Team. Given the capability to make any subset of Azimuth, Elevation, Range, and Range-Rate measurements from calibrated tracking site locations, all AMSAT missions can benefit from precise and timely orbit computations. To fully realize this potential benefit, the spacecraft command teams will need to have an infrastructure, as was done with AO-40, in which accurate ranging or other tracking measurements may be made.

ACRONYMS

ACE	Advanced Communications Equipment®
ADE	AstroDynamics Environment
AFSCN	Air Force Satellite Control Network
AO-40	AMSAT OSCAR 40
AOS	Acquisition of Signal
DC	Differential Correction
ECI	Earth-Centered Inertial
EFG	Earth-Fixed Greenwich
EOP	Earth Orientation Parameters
GPS	Global Positioning System
GTDS	Goddard Trajectory Determination System
IERS	International Earth Rotation Service
LADO	Launch and early orbit, Anomaly, and Disposal Operations
LOS	Loss of Signal
NASA	National Aeronautics and Space Administration
NAVSTAR	Navigation System using Timing and Ranging
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
OD	Orbit Determination
OIS	Operations Improvement System
OSCAR	Orbiting Satellite Carrying Amateur Radio
SGP4	Simplified General Perturbations version 4
SP	Special Perturbations (i.e., higher-order modeling)
TLE	Two-Line Element
TT&C	Telemetry, Tracking, and Commanding

USNO	United States Naval Observatory
UTC	Coordinated Universal Time

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L BAND HELIX ANTENNA ARRAY

Clare Fowler, VE3NPC
ve3npc@rac.ca

Abstract

For 23 cm (1269 MHz) SSB operation on AO-40 a nominal 1500 watts ERP of up link power is required. This can be obtained with a low gain antenna driven by a power amplifier or alternatively with lower power into a higher gain antenna. Following classical standard textbook design, and utilizing available hardware and shop tools, the author has constructed four helical antennas in a square array, driven through a four-way power divider. Chain link fence fibreglass tension bars are used for the antenna and bracing frames. Aluminum ground wire is used for the helix conductor. This design provides an inexpensive durable lightweight array with relatively low wind loading. With a maximum input power of 10 watts into a feed line with about 2db total loss, this antenna array has performed well, both operationally and mechanically, for over two years. A novel implementation of the quarter wave matching section makes for simplified adjustment of the SWR. Construction material, dimensions, assembly and testing are covered.

Introduction

The helix is a relatively broadband antenna and small dimensional irregularities have little effect on performance. This makes it an ideal antenna for home construction. An antenna array comprised of four identical 27-turn right hand polarity helix antennas provides sufficient gain for L band operation into AO-40 with 10 watts of RF drive.

Aluminum ground wire, carried by the local electronic chain store, is used for the helix conductor. Chain link fence fiberglass tension bars are used for the helix support boom and antenna cross bracing. These bars may be obtained in the fencing department of hardware and building stores. Aluminum sheet it used for the reflector. Sections cut from aluminum angle stock are used for support brackets. Stainless steel machine screws and nuts are used to prevent corrosion. To minimize losses, type N connectors are used on each helix, the four-way power divider and interconnecting cables.

Helix Antenna Match

The feed point impedance of a helix antenna is in the order of 140 ohms. A quarter wave matching section may be used to transform this to 50 ohms. To match 140 ohms to 50 ohms the quarter wave matching section must have an impedance (Z) of 84 ohms where Z is the square root of 140 x 50. The impedance of a circular conductor above a ground plane is defined by the formula: $Z = 138 \log 4h/d$; where h is the height of the conductor above the ground plane, and d is the diameter of the conductor. Placing a conducting metal ground plane under the first quarter turn of the helix conductor provides a suitable quarter wave matching section. The width is not critical but should be several times the width of the helix conductor.

Quarter Wave Matching Section Construction

The ground plane for the quarter wave matching section is cut from a piece of hobby shop brass sheet. See Fig 1. With a compass draw two concentric 90-degree arcs on the brass, the first with a radius of 27 mm and the second with a radius of 52 mm. From the compass center mark draw two lines across the concentric arcs with a 90-degree angle between them. These four lines define a 59 mm length quarter circle ground plane that will be mounted directly under the helix. Cut or file a semi-circular notch in one end to clear the pin base of the N connector. Drill holes on each side of the notch to match the N connector mounting holes. The off-axis N connector location and orientation on the reflector plate is required for installation of the ground plane. For the ground plane to function, both ends need to be shorted to the reflector plate. A short loop of brass sheet or a piece of coax braid is soldered to the end of the ground plane. The other end of the loop is fastened to the reflector plate with the machine screw that holds the boom angle bracket.

Helix Antenna

The helix dimensions are determined using the formula by Kraus in *The Satellite Experimenter's Handbook.* The circumference is equal to one wavelength and the pitch angle is 12.5 degrees. Construction details are shown in Figs 1 and 2.

Two five-foot length fiberglass tension bars are used for the antenna boom frame held apart with cross braces cut from another bar. See Table I for positioning. The ends of the boom frame rails are fitted through cuts in the aluminum reflector plate. Each boom rail is held in place by two angle brackets, one on each side, cut from ¾" aluminum angle stock. A chain saw file is used to file angled notches in the boom rail bars into which the aluminum helix wire is fitted. To avoid cumulative errors, mark the position of each notch measuring from the reflector plate as indicated in Table II. Size the aluminum coil diameter by close wrapping it around a 65-mm diameter form. Wind the aluminum wire off the coil directly onto the form, without straightening it first. This way it stays pre-stressed, and will later spring out to the required 75-mm diameter when stretched to the correct helix length. Using a hammer, flatten the first 1 cm of the helix wire and drill a hole in the center of the flattened end to clear a 4-40 screw.

Trim off the half lip from the female chassis type N connector solder contact pin. Cut the head from a 4-40 brass screw. Dress one end to fit into the N connector pin by putting the screw into a power drill chuck and holding the edge of a flat file against it while it is turning. Solder the screw into the N connector contact being careful to not get excess solder up into the screw threads.

Bolt the N connector and the quarter wave ground plane section to the reflector plate. Extra screw nuts are used as spacers on the N connector so the first quarter turn of the helix is close to the ground plane and the reflector.

Using the brackets, mount the rails to the reflector plate. Stretch the helix to its approximate length. With the rails adjacent at the outer end, slip the helix coil over the rails and bolt the end of the helix to the screw that is soldered into the end of the N connector. While fitting the helix loops into the notches bolt the cross braces into place starting at the feed end. Omit the third cross brace. Initially the spacing between the helix first quarter turn and the ground plane should be adjusted to about 3 mm by bending the ground plane.

Four-Way 23 cm Power Divider

Theoretical and structural details for quarter-wave power dividers are covered in many of the microwave handbooks. Construction details are shown in Fig 3. Four type N female chassis connectors are fastened with #4 x ¼ in self-tapping screws, one on each side of a 1-inch square piece of aluminum tubing cut 207-mm long. A 177-mm length of ½" copper water pipe is used for the center conductor. File four equally spaced notches into the ends of the four N connector center pins to accept the end of the copper pipe. The notches should be just deep enough so that the end of the pipe reaches to the center of the N connector pins. A fifth N connector is screwed to one side of the square tubing with the center pin spaced 177 mm from the center pins of the other four. A notch in the copper pipe fits halfway over that center pin. Center the copper pipe and solder the five pins to the pipe. Square plastic plugs can be used to cover the open ends of the power divider.

Joining Cables

To minimize the effects of any impedance mismatch, the lengths of the four cables and connectors that connect each helix antenna to the center conductor of the power divider should be a multiple of an electrical half wavelength. RG-8 or RG-213 coax cable has a velocity factor of 0.66. A cable of four wavelengths at 1269 MHz (23.64 cm) will have a physical length of 624 mm (23.64 x 0 .66 x 4). Allowing for the female chassis connectors at the helix and the power divider, the interconnecting cables should be 600 mm long overall, measured from the open end of each male cable connector.

Helix Array Structure

The helix antennas are arranged in a square 640 mm apart as shown in Fig 4. The four antennas are all oriented in the same way with the position of the N connectors all being in the same relative position so that the output from the antennas will combine in phase. Two sections of tension bars, bolted one on each side of the helix antenna booms, support two helix antennas one above the other. By replacing the third cross brace of each helix antenna with the support bars, the array will be suspended near the balancing point. An H frame using two more sections of tension bars is used to join the double helix antenna sections. A mounting plate made from 3/8" Lexan plastic is used to attach the array to a non-conductive cross boom with muffler clamps. Additional support is provided by bolting sections of tension bars to the rear reflectors. The power divider is fastened to sections of tension bars going between the rear support and the middle H frame.

SWR Adjustment

The quarter wave matching section on each antenna should be adjusted individually for 1:1 SWR with an SWR meter connected directly to the antenna, using a coaxial barrel adapter. With a plastic tool, adjust the ground plane spacing. As the spacing is pushed from close to the wire to farther away a position should be found where the SWR decreases to 1:1.

If an SWR meter for 23 cm is not available an alternative method is to use a field strength meter and adjust for a maximum reading. The construction of a very simple FS meter is shown in Fig 5. The dimensions of the 2 ½ to 3 turn helix are non-critical, but keep the leads of the 1 k resistor, the signal diode and the bypass capacitor as short as possible. A 20 kilohms per volt analog multimeter set to the 50 microamp position may be used for the meter. Position the FS meter helix two or three meters in front of, and facing the 27-turn helix being adjusted. Apply a 1296 MHz signal from the transceiver to the 27-turn helix. Only a small amount of power should give a good meter reading. Adjust the ground plane spacing for maximum field strength meter reading. To facilitate reading the meter while making adjustments the multimeter connecting wires can be extended. Adjust each antenna matching section individually and make no further adjustments.

Feed Line

For this antenna array to provide good L band operation on AO-40 with a drive of 10 watts from the transmitter, the feed line must have a total loss of no more than 2 dB, preferably less. This requires a relatively short low loss feed line e.g. 10 meters or less of hard line with 1.5 meters or less of low loss flexible coax at the antenna and in the shack.

Variations on a Theme

Assuming a low loss feed line, 20 watts of power driving an array of two helix antennas would provide equivalent performance. A two-way power divider will be required in place of the four-way divider. A two-way divider requires a center conductor with an OD of 98-mm (use 13/32 in. brass tube) with the length remaining the same.

With a drive of 40 watts or more a single 27-turn helix will give good performance with 2 dB or less feed line loss.

If the feed line has a total loss of more than 2 dB, performance can be maintained by increasing the driving power using an amplifier in the shack or at the antenna.

23 cm Helix Antenna Specifications

Frequency = 1269 MHz
Circumference = 1 wavelength
Number of turns = 27
Pitch angle = 12.5 degrees
Ant gain = 19 dB
Spacing between turns = 52.4 mm
Helix diameter = 75 mm
Beam width = 21 degrees
Reflector side = 200 mm

Theoretical array gain = 25 dB
Probable gain = 23dB
Theoretical beam width = 11 degrees

Working with Fibreglass

Some people are adversely affected by fibreglass. In any case, precautions should be taken when cutting drilling or filing fibreglass to protect against the dust. Wear glasses, a mask and gloves. Wash areas where the dust comes in contact with the skin.

mm to inch Conversion

inches = mm/25.4

Acknowledgments

Thanks are due to Gordon Grant, VE3DY for all of the drafting.

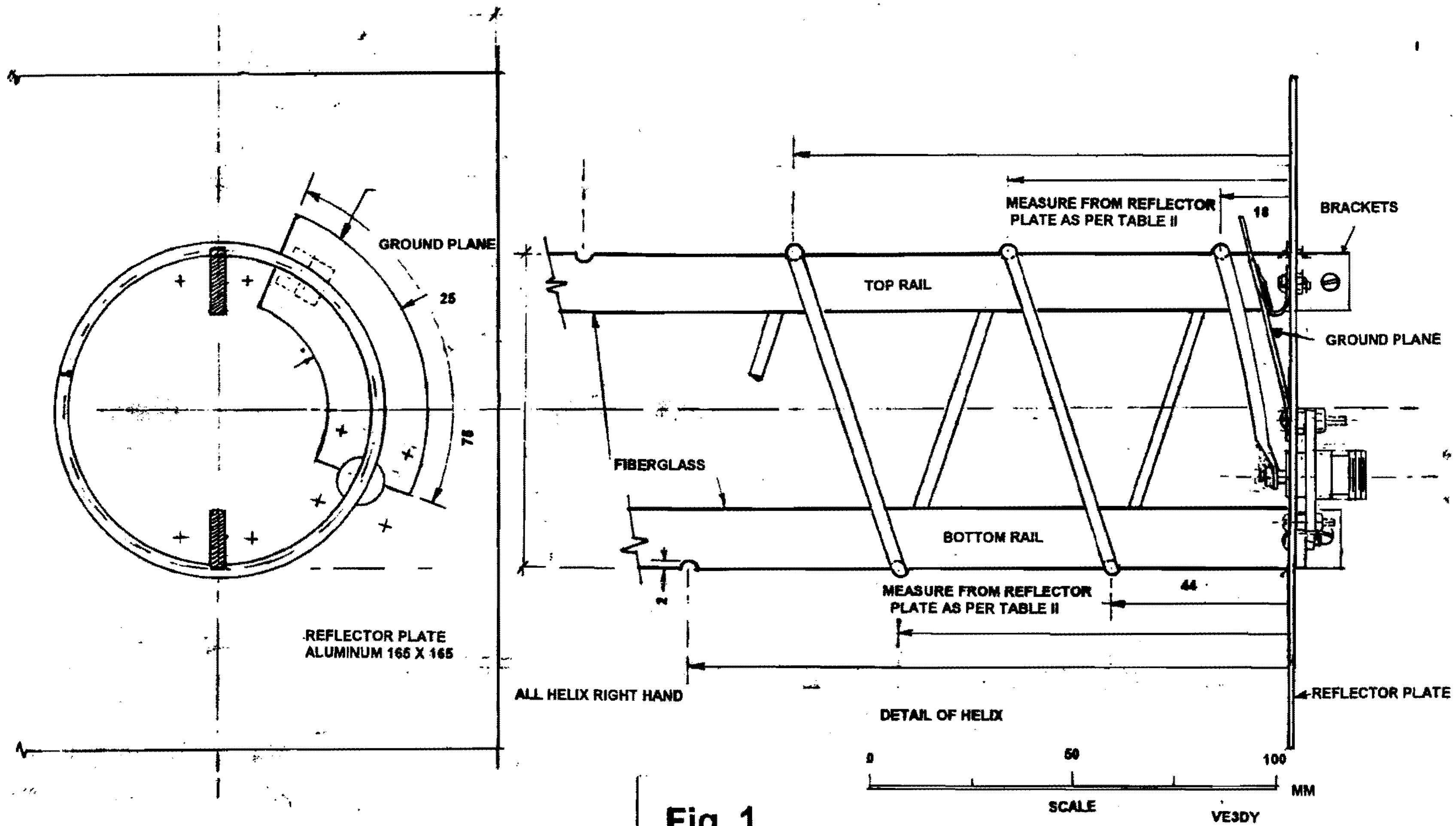
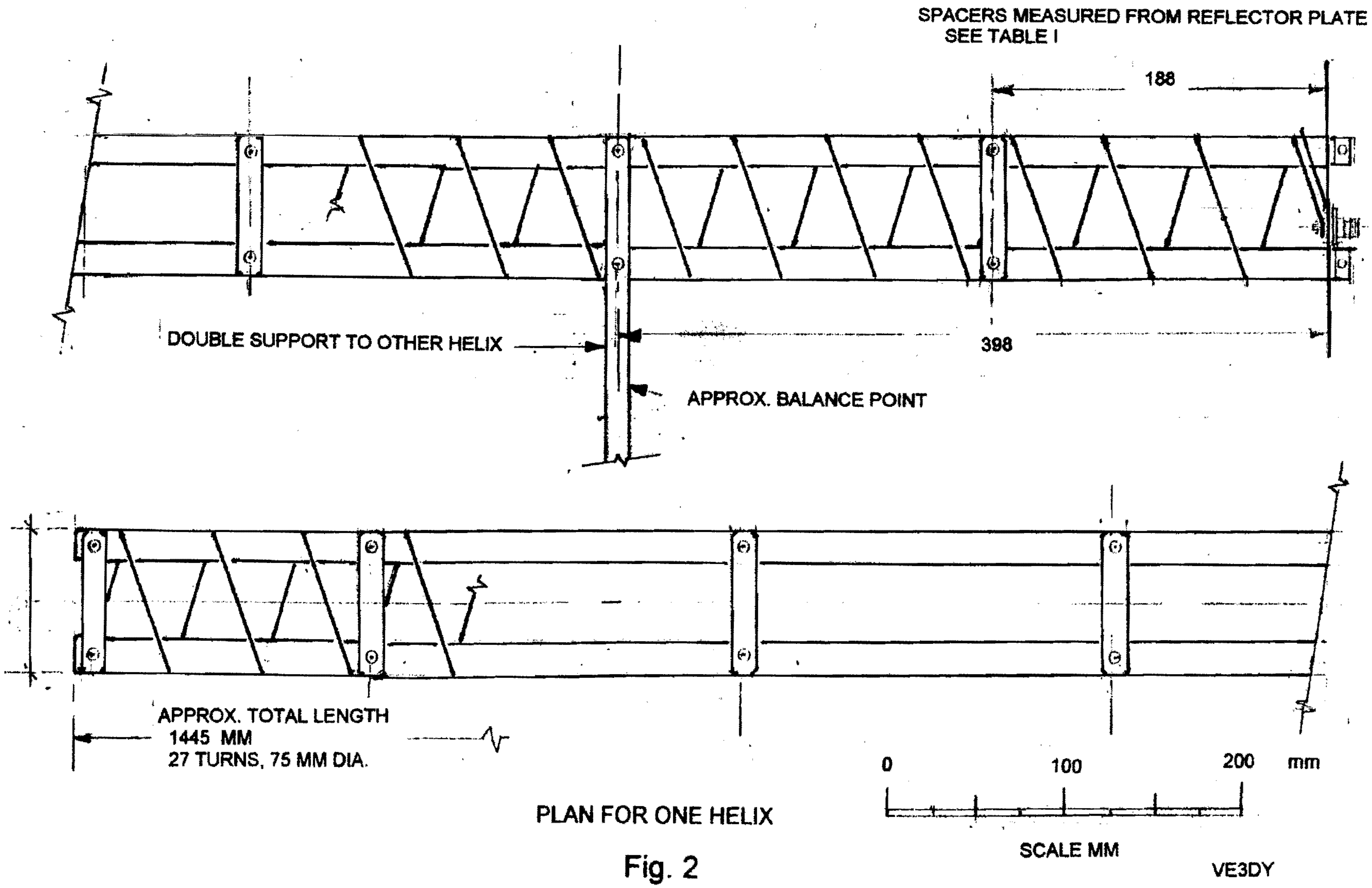

GROUND PLANE
25
78
REFLECTOR PLATE
ALUMINUM 165 X 165
MEASURE FROM REFLECTOR
PLATE AS PER TABLE II
18
BRACKETS
TOP RAIL
GROUND PLANE
FIBERGLASS
BOTTOM RAIL
2
MEASURE FROM REFLECTOR
PLATE AS PER TABLE II
44
ALL HELIX RIGHT HAND
REFLECTOR PLATE
DETAIL OF HELIX
0
50
100
MM
SCALE
VE3DY

Fig. 1



PLAN FOR ONE HELIX

Fig. 2

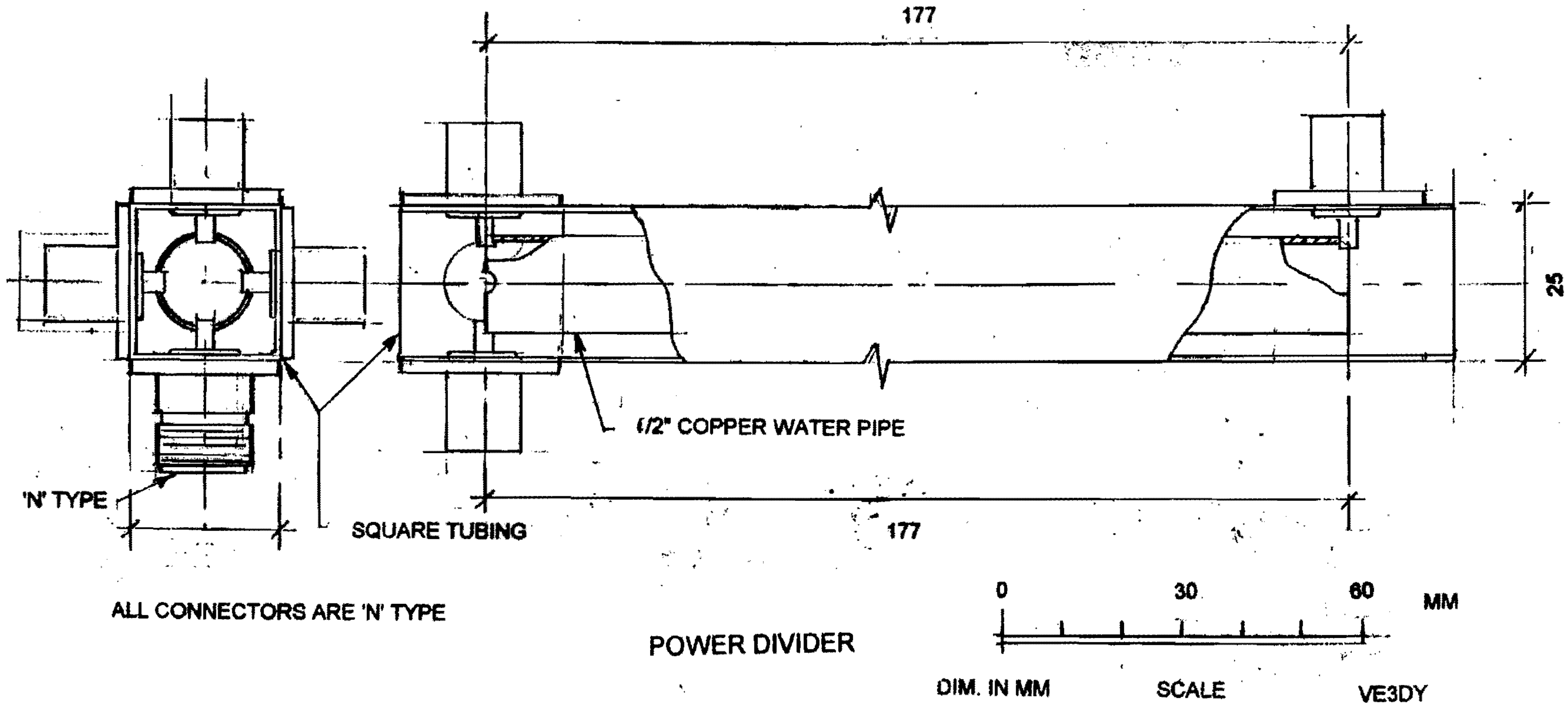

177
25
'N' TYPE
SQUARE TUBING
1/2" COPPER WATER PIPE
177
ALL CONNECTORS ARE 'N' TYPE
POWER DIVIDER
0
30
60
MM
DIM. IN MM
SCALE
VE3DY

Fig.3

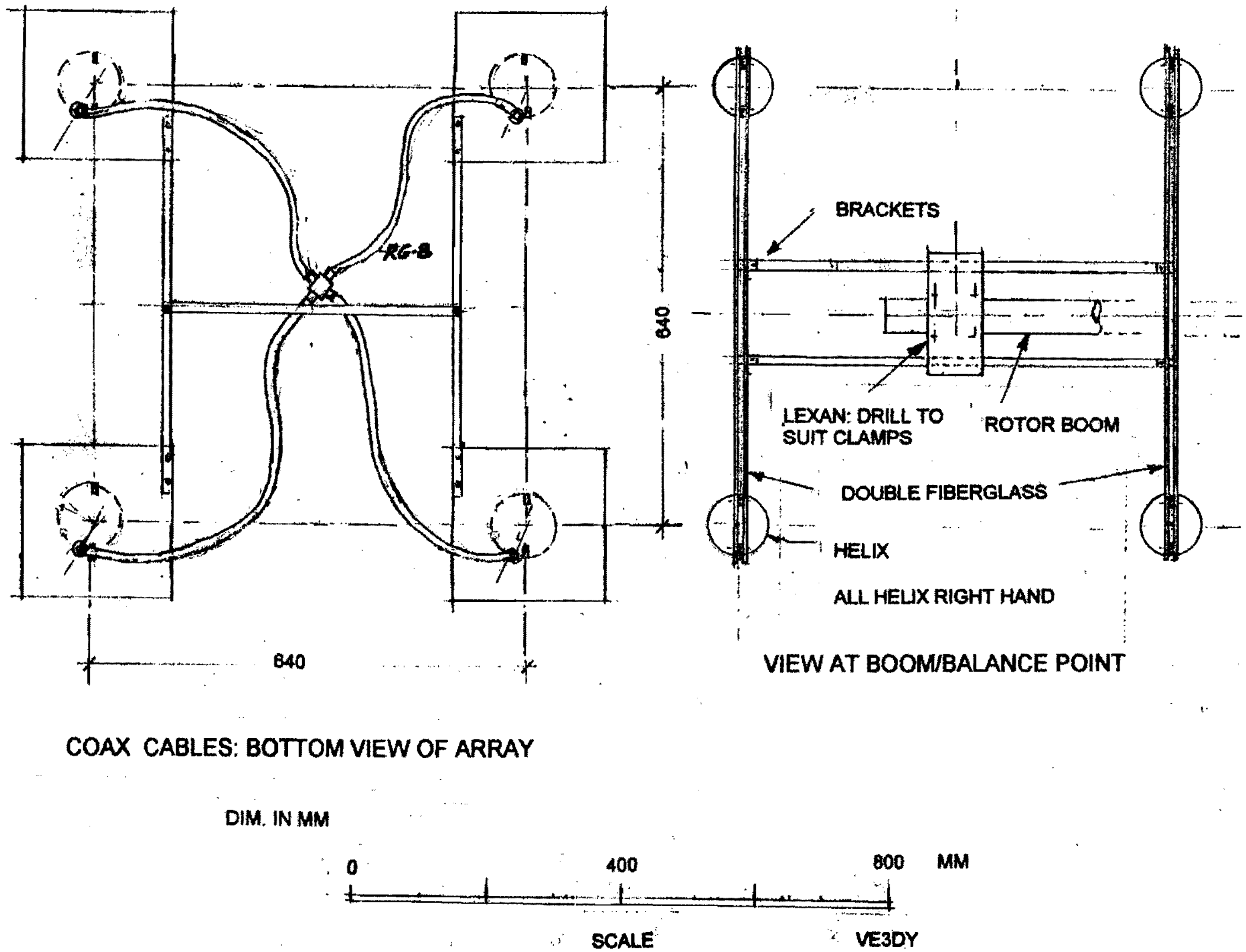

RG-8
640
640
BRACKETS
LEXAN: DRILL TO
SUIT CLAMPS
ROTOR BOOM
DOUBLE FIBERGLASS
HELIX
ALL HELIX RIGHT HAND
VIEW AT BOOM/BALANCE POINT
COAX CABLES: BOTTOM VIEW OF ARRAY
DIM. IN MM
0
400
800
MM
SCALE
VE3DY
7/'03

Fig. 4

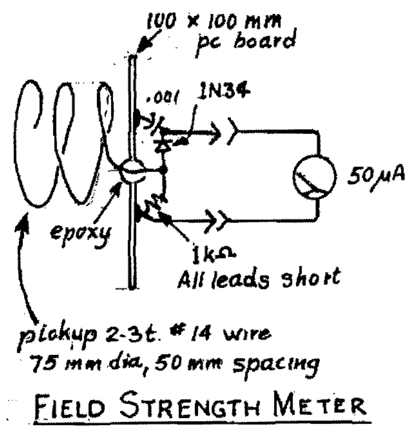


Fig. 5

TABLE I

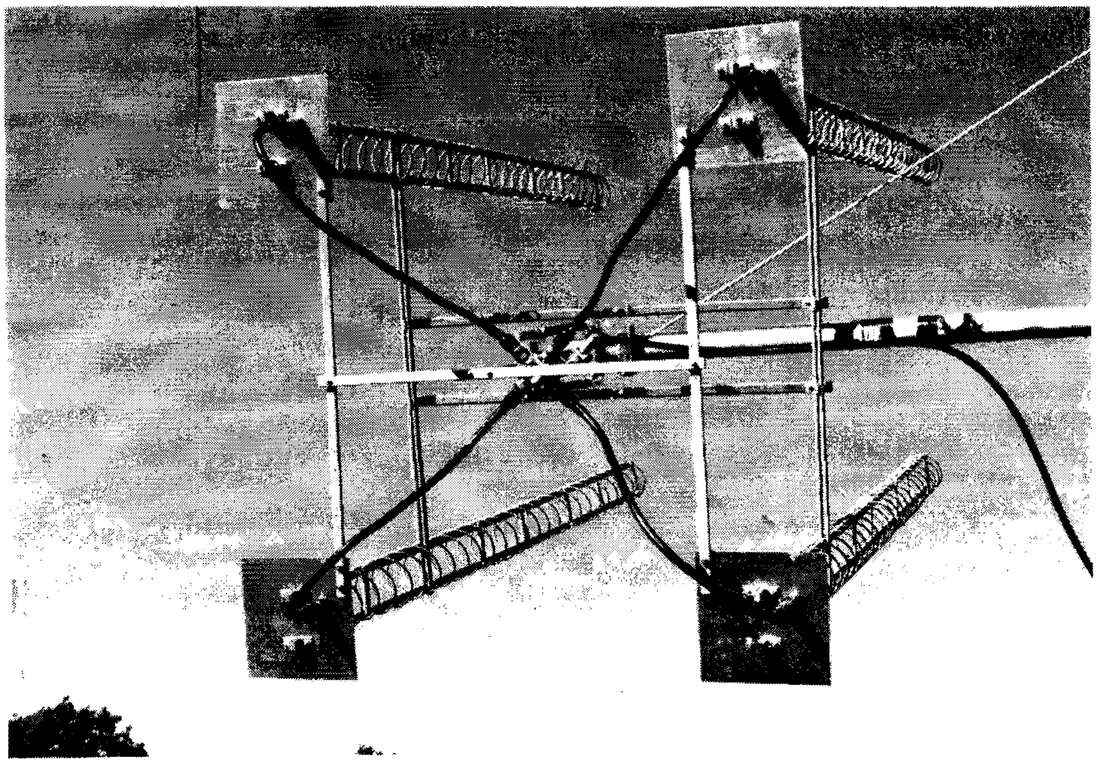
Cross brace spacing from reflector

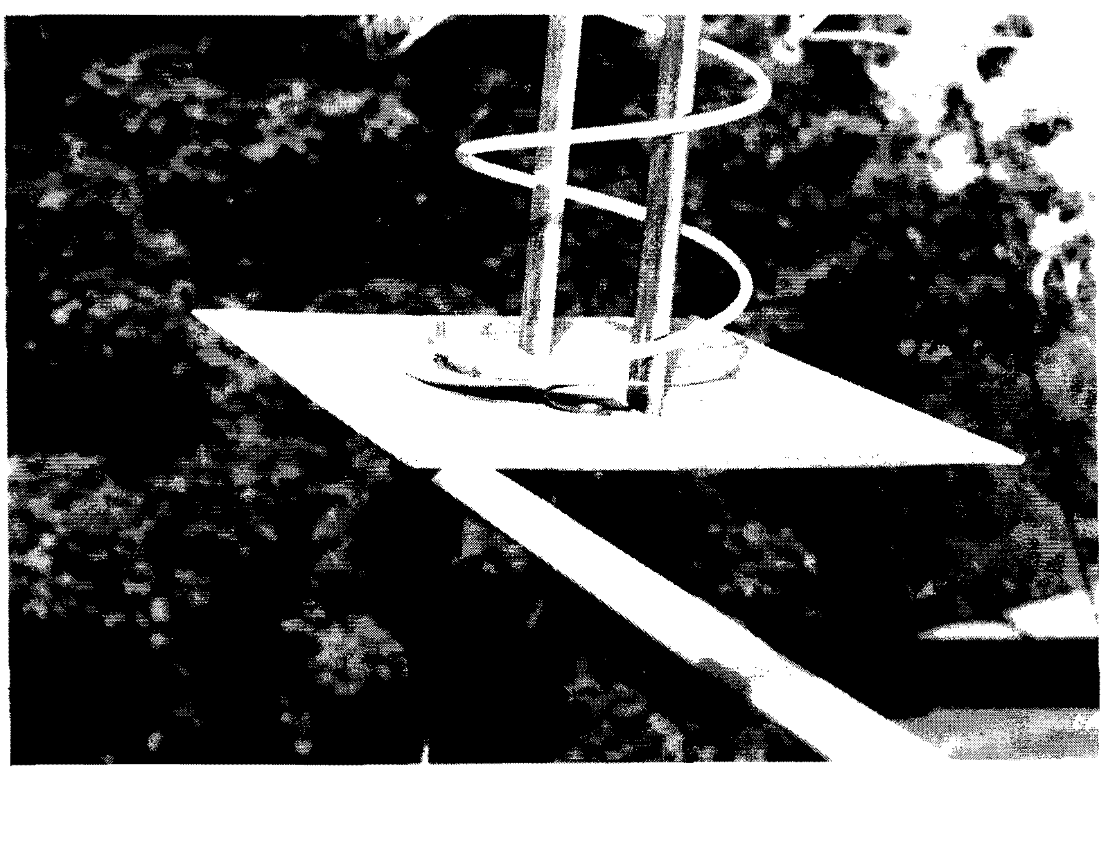
	Both Rails
1	18.8 cm
2	39.8
3	60.7
4	81.7
5	102.7
6	123.6
7	144.6

TABLE II

Notch spacing from reflector.

	Bottom Rail	Top Rail
1	4.4 cm	1.8 cm
2	9.7	7.0
3	14.9	12.3
4	20.1	17.5
5	25.4	22.8
6	30.6	28.0
7	35.9	33.2
8	41.1	38.5
9	46.3	43.7
10	51.6	49.0
11	56.8	54.2
12	62.1	59.4
13	67.3	64.7
14	72.5	69.9
15	77.8	75.2
16	83.0	80.4
17	88.3	85.6
18	93.5	90.9
19	98.7	96.1
20	104.0	101.4
21	109.2	107.0
22	114.5	111.8
23	119.7	117.1
24	124.9	122.3
25	130.2	127.6
26	135.4	132.8
27	140.7	143.3





Exploring the Mysteries of the Cosmos on the MOST Microsatellite Mission

Dr. Simon C. O. Grocott
Manager, Attitude Control Systems
Dynacon Incorporated
3565 Nashua Drive, 2nd Floor, Mississauga, Ontario, Canada, L4V 1R1
E-mail: scog@dynacon.ca, Tel: (905) 672-8828 x 223, Fax: (905) 672-8829

Dr. Robert E. Zee
Director, Space Flight Laboratory
University of Toronto Institute for Aerospace Studies
4925 Dufferin Street, Toronto, Ontario, Canada, M3H 5T6
E-mail: rzee@utias-sfl.net, Tel: (416) 667-7864, Fax: (416) 667-7799

Dr. Jaymie M. Matthews
Associate Professor
Department of Physics and Astronomy, University of British Columbia
6224 Agricultural Road, Vancouver, B.C., Canada, V6T1Z1
E-mail: matthews@astro.ubc.ca, Tel: (604) 822-2696, Fax: (604) 822-6047

Abstract. The MOST (Microvariability and Oscillations of STars) astronomy mission under the Canadian Space Agency's Small Payloads Program is Canada's first space science microsatellite and is scheduled to launch in June 2003. The MOST science team will use the satellite to conduct long-duration stellar photometry observations in space. The primary science objectives include: measuring light intensity oscillations in solar type stars; determining the age of nearby "metal-poor sub-dwarf" stars, which will in turn allow a lower limit to be set on the age of the Universe; and detecting the first reflected light from orbiting exoplanets and using it to determine the composition of their atmospheres. To make these measurements, MOST incorporates into a microsatellite design a small (15 cm aperture), high-photometric-precision optical telescope and a high performance attitude control system that is revolutionary in its pointing accuracy for a microsatellite. A key hurdle that the MOST mission had to overcome was that of access to space. MOST as initially conceived was designed to launch as a secondary payload aboard a Delta II rocket carrying Canada's Radarsat-2 mission. However, subsequent delays in the Radarsat-2 program have pushed its launch to the end of 2004 or beyond. Access to space was extremely important to the MOST mission because of the revolutionary science that is being done. Consequently, the Canadian Space Agency contracted with Eurockot to provide launch services using a "Rockot" launch vehicle launching from Plesetsk, Russia. As we prepare for the launch in June 2003, the paper will present a summary of the science goals of the mission, will highlight the progress of the integration team in preparing the satellite for launch, and will reflect on the impact that changing launch vehicles has had on the satellite in our quest for access to space.

Introduction

The MOST (Microvariability and Oscillations of STars) astronomy mission under the Canadian Space Agency's Small Payloads Program is Canada's first space science microsatellite and is scheduled to launch in June 2003. The MOST science team will use the satellite to conduct long-duration stellar photometry observations in space. The primary science objectives include: measuring light intensity oscillations in solar type stars; determining the age of nearby "metal-poor sub-dwarf" stars, which will in turn allow a lower limit to be set on the age of the Universe; and detecting the first reflected light from orbiting exoplanets and using it to determine the composition of their atmospheres. To make these measurements, MOST incorporates into a microsatellite design a small (15 cm aperture), high-photometric-precision optical telescope and a high performance attitude control system that is revolutionary in its pointing accuracy for a microsatellite (see Figure 1).

One of the key challenges for the MOST microsatellite team has been access to space. MOST was initially to launch as a secondary payload accompanying the Radarsat-2 satellite. Delays in the Radarsat-2 program have pushed its launch into 2005. In order to gain quicker access to space, the Canadian Space Agency contracted with Eurockot Launch Services to provide a launch scheduled for 30 June 2003 from the Plesetsk Cosmodrome in Russia.

The paper begins with a description of the science goals of the MOST satellite. These will be shown to have led to a particular choice of orbit and launch vehicle to make space accessible for this microsatellite. This is followed by a description of the satellite design, and the impact that changing launch vehicles to obtain faster access to space had

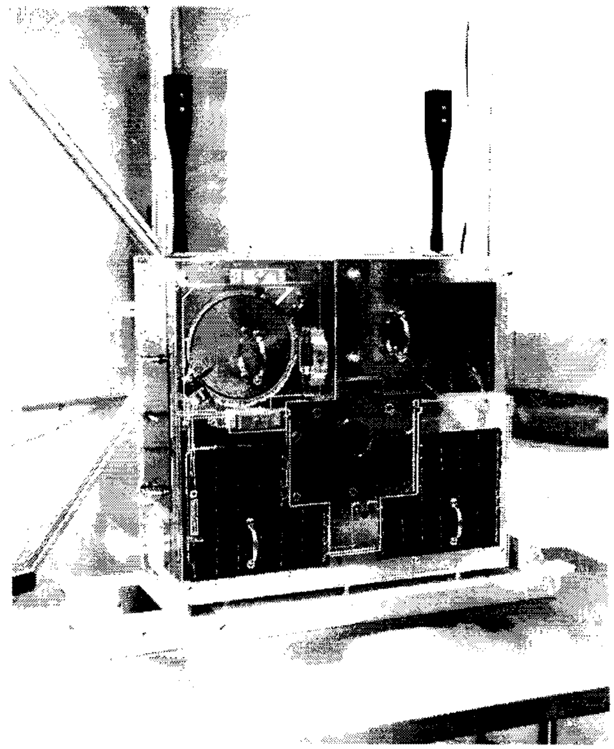


Figure 1: The MOST Microsatellite (with protective covers)

on the MOST program. Finally, the present status of the MOST program is discussed with launch scheduled for 30 June 2003.

Scientific Goals

Size doesn't always matter. Stellar seismologists exploit extremely tiny surface vibrations of stars, detected through brightness oscillations with amplitudes of a few parts per million, to probe stars' hidden interiors and ages and address big questions such as "What is the age of the Universe?") We don't need a big telescope to study many of the Sun's nearer neighbours in the Galaxy, which are bright enough to provide large photon fluxes and high signal-to-noise. However, atmospheric turbulence plus the day/night cycles inherent to single-site ground-based observing mean that a telescope must be in space. Even there, we don't necessarily need a big budget, if we take advantage of proven optical and detector technology and recent advances in microsatellite attitude control.

Until recently, performing optical astronomy experiments from a low-cost microsatellite (mass < 100 kg) was considered unfeasible because of the poor pointing possible from a platform with such small inertia (approx. ± 2°). In 1997, anticipating new microsat attitude control technology being developed by Dynacon Inc., a team of astronomers and aerospace engineers first proposed to the Canadian Space Agency (CSA) a project to obtain astronomical photometry of unprecedented precision from a microsatellite. In the next year, MOST (Microvariablity and Oscillations of STars / Microvariabilité et Oscillations STellaire) was selected to be Canada's first science microsat, as part of the CSA Small Payloads Program. Additional funding was provided by the Ontario Research and Development Challenge Fund, the Natural Sciences and Engineering Reseach Council (NSERC), the Ontario Centre for Research in Earth and Space Technology and the Universities of Toronto, British Columbia and Vienna.

MOST features a small optical telescope (aperture = 15 cm) equipped with a CCD photometer designed to return unprecedented

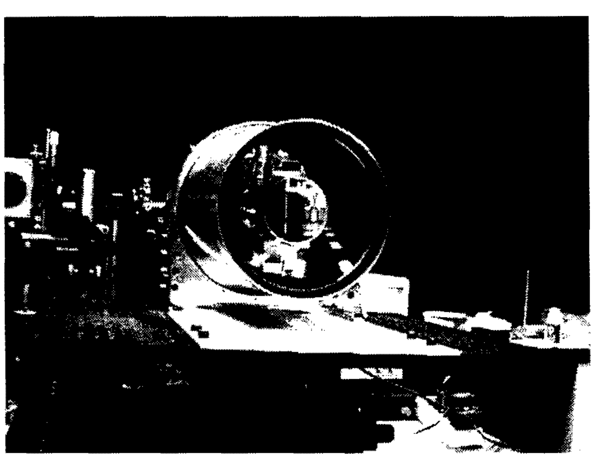


Figure 2: The MOST Telescope (15-cm Aperture)

photometric precision ($\Delta L / L \sim 10^{-6}$) and frequency resolution ($\Delta\nu \sim 0.1$ μHz) on stars other than the Sun. Given the fact that this instrument (see Figure 2) will be carried aboard a microsat bus about the size and mass of a suitcase, the Canadian public has come to know the MOST mission as the "Humble Space Telescope."

Probing Mysterious Planets: Following in Galileo's Footsteps

MOST was originally designed to detect rapid brightness oscillations in Sun-like stars, to seismically probe their interiors. However, once the project had passed the critical design

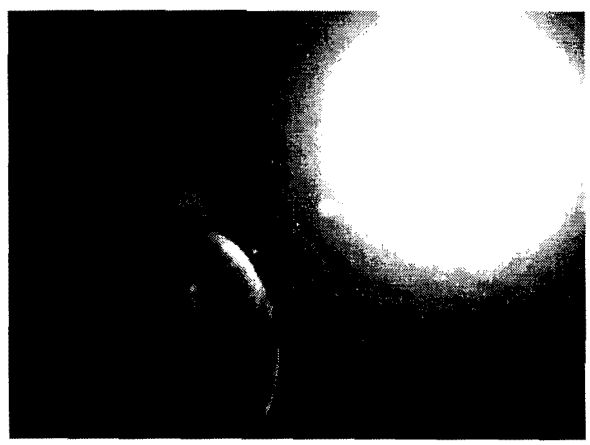


Figure 3: An Artistic Rendering of an Exoplanet

phase, it was realised the MOST instrument was more sensitive and versatile than originally expected in Phase A. It also had the potential to detect reflected light from some of the giant planets recently discovered to be orbiting other nearby stars. The amount of light reflected and scattered back to Earth by such an exoplanet (Figure 3) would vary during the planet's orbit, as it goes through illumination phases like those of the Moon or of Venus, as first observed telescopically by Galileo in the early 1600's.

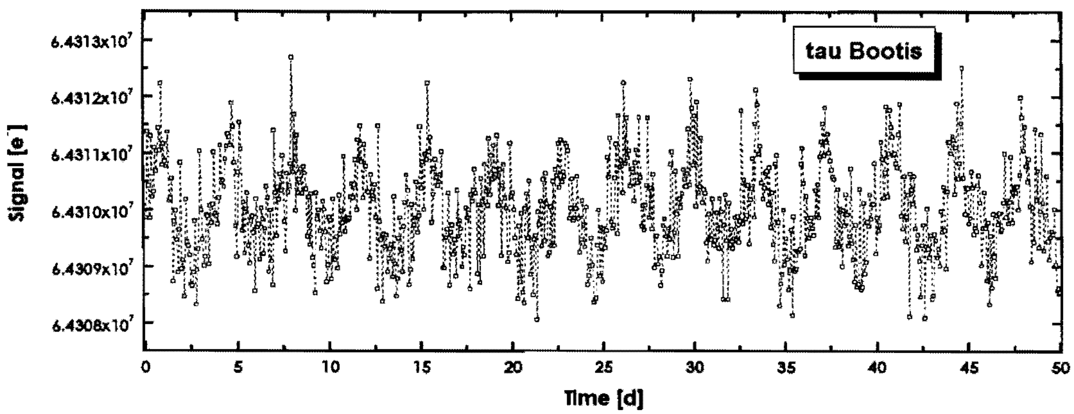


Figure 4: Simulated MOST "observations" of a star with an exoplanet orbiting every 3.3 days

Therefore, in Phase C of the project, the MOST team added an exciting new science application, without changing the hardware or software design, or the selected orbit, and at no added cost.

The amplitude and shape of the reflected light curve of an exoplanet depends on the planet's size, its orbital inclination and eccentricity, and most importantly, its atmospheric composition (which determines its albedo). However, the exoplanet signal is very subtle – about a part in 105 relative to the brightness of its parent star – with orbital periods of a few days for the exoplanets with the smallest orbits. Simulations by Green et al. (2003) indicate that MOST should be able to detect this signal for exoplanet systems like 51 Pegasi (the first solar-type planetary system to be discovered) and tau Bootis (Figure 4).

MOST would be the first instrument in history capable of detecting these signals and giving direct information about the atmospheres of these mysterious worlds. At the same time, data on the oscillations of the parent stars would specify the ages of these stellar/planetary systems – an important test of models of how these planets formed and evolved.

Why go to space?

It is not currently possible to perform photometry at the precision of 1-10 ppm required for solar-type seismology or exoplanet light curves. For example, if the Sun were observed as a point source (like a distant star), then the net amplitude of its integrated oscillations would be only a few cm/s in velocity and a few micromagnitudes in brightness. Such levels lie about two orders of magnitude below present detection limits for ground-based measurements (although efforts to improve the spectroscopic limits are underway). In fact, even the solar oscillations have been detected in brightness only from space, by the ACRIM bolometer aboard the Solar Maximum Mission, the IPHIR experiment aboard the Phobos probe, and the VIRGO irradiance instrument on the SOHO satellite.

To be able to perform seismology of Sun-like stars and the detection of reflected light from exoplanets requires both:

1. Very precise detections of photometric signals as low as a few ppm; and

2. Long, nearly uninterrupted monitoring of each star for weeks at a time.

Neither is easy to achieve but getting both simultaneously is virtually impossible from the surface of the Earth.

Scintillation noise

Turbulent cells of air at altitudes of about 10 km in the Earth's atmosphere have slightly different temperatures that change their refractive indices. As these cells, of order 10 cm across, are carried over the beam of a telescope, they modulate the intensity of starlight randomly and rapidly. This is the cause of star "twinkling"; i.e., atmospheric scintillation. Scintillation is the dominant source of photometric noise in measurements of oscillation amplitudes below about 0.1% (1000 ppm) and at timescales of only a few minutes. This noise term depends on the position of the star relative to the horizon, the exposure time, and the altitude and aperture of the telescope. Scintillation noise decreases with increasing aperture. As the light collecting area becomes larger, the incoming stellar signal is integrated over a larger number of turbulent cells and their effects begin to average out more effectively.

Consider a set of 60-second photometric measurements from the summit of Mauna Kea, Hawaii (altitude = 4200 m) of a bright star (apparent visual magnitude V = 3, about the brightness of the North Star) at the zenith. To reduce the scintillation noise to order 10^{-5} in a single reading, you'd need a telescope almost 100 metres across!

Continuous monitoring

From the Earth, an astronomer has only limited options if she wants to monitor a star continuously for times much longer than half a day:

1. Observe from a site near one of the poles during prolonged night.

2. Operate a network of telescopes spread in longitude around the globe so that at least one of the sites can observe the star in darkness at all times.

(Both these options require the astronomer to be somewhat religious, since she has to pray for clear weather everywhere for weeks at a time.)

The first approach is frustrated by the less-than-ideal conditions for stellar photometry in the Arctic and Antarctic, although there are plans for a South Pole stellar observatory which may experience photometric conditions in the near-infrared. The latter approach has been used successfully by the Global Oscillation Network Group (GONG) to study the low-amplitude velocity oscillations of a very bright source (the Sun), and by the Whole Earth Telescope (WET) to study the relatively high-amplitude (10%) oscillations of faint sources (pulsating white dwarfs). Both approaches are expensive of money, facilities, and human resources.

However, neither of these approaches can avoid the scintillation limit. Even if five of the world's existing 4-metre-class telescopes in Hawaii, the continental U.S., Chile, Spain, and Australia were dedicated to searching for solar-type oscillations in a bright star (V = 3) for over 6 weeks, they would still fail to detect the 4-ppm signal represented by the Sun's oscillations, or even a signal 10 times larger associated with the reflected light of a close-in giant exoplanet.

The "Humble Space Telescope"

The MOST instrument is a Maksutov telescope fed by a flat "periscope" mirror which allows it to sit in the allowed volume of the instrument bay. The Maksutov optics gives MOST a wide field (about 2° in diameter) so that it can serve as a guiding star sensor for the microsat attitude control as well as a science instrument. The telescope feeds starlight to a pair of frame-transfer CCDs: one for guiding, one for science. Through frame transfer, the integrations can be stopped without the need for a mechanical shutter. In fact, the MOST instrument is designed to have **no** moving parts (to reduce cost and increase reliability). The structure is athermal, so that the optics maintain focus across the wide temperature range between alignment on the ground and the orbital environment.

Light from a given target star is directed onto a Fabry lens, which will project an image of the telescope's pupil onto the CCD: a doughnut with an outer diameter of about 40 pixels. The reasons for the Fabry imaging are three-fold: (1) Spreading the starlight over many pixels reduces the sensitivity of the photometry to pixel-to-pixel sensitivity variations across the CCD, and to damaged pixels and columns. (2) For bright stars, the extended image avoids saturation of the individual pixels. (3) As the microsat wobbles in space by up to ± 10 arcsec rms, the pupil image will remain fixed on the same pixels, moving by no more than 0.1 pixel. This will make it possible to obtain ultraprecise photometry down to amplitudes of a few ppm for stars as faint as V ~ 6 (the limit of visibility for the naked eye).

The Right Orbit for the Science

To achieve the photometric sensitivity and Fourier frequency resolution required to meet the MOST science objectives, the ideal MOST orbit would maximize the size of the Continuous Viewing Zone (CVZ) and minimize the stray Earthlight that could enter the telescope aperture. However, the choice of orbit must also be tempered by practical considerations of the radiation environment, up/downlink capability, and of course, cost.

The ideal orbit for such a stellar seismology / exoplanet mission would be far from Earth, with a very large CVZ and little stray Earthlight interfering with the photometry. However, for a low-budget microsat mission, geostationary or L2 orbits are not affordable. So the MOST team was forced to consider Low Earth Orbit (LEO). The most common equatorial LEOs for space astronomy missions, like the Hubble Space Telescope, have inclinations which result in fairly small CVZs at the celestial poles, severely restricting target selection. Therefore, a polar orbit was selected which would provide a large equatorial CVZ.

To fully profit from staring continuously at a target for weeks, the science requirement was >80% duty cycle for observations, with a goal of >90%. This means that solar eclipses by the Earth's limb and passage through the South Atlantic Anomaly (SAA) must inhibit <10% of observations within the CVZ. Solar eclipses lead to loss of solar sensing and power as well as thermal shock to MOST. In operation, the normal to the rear solar panels must lie within 30° of the direction to the Sun if the satellite is not to lose too much power for science operations. Radiation damage to the electronics and detectors is also a consideration, as well as periods when high fluxes of cosmic ray strikes could confuse star tracker readings. The SAA expands with altitude, increasing the potential "black-out" time (when observations may be inhibited) for higher orbits. On the other hand, the higher the orbit the less the limb of the Earth cuts into the CVZ to introduce parasitic light and the shorter Earth eclipses will be at one or other of the solstices.

Careful estimates were made of the expected MOST radiation environment with SPACE RADIATION 4.0 (available from Space Radiation Associates, www.spacerad.com) and they indicated a significant but not serious degradation of CCD performance (dark current increase, hot pixels, reduced charge transfer efficiency etc.) during the first year in orbit for altitudes from 700 to 900 km. Most degradation is inflicted by passage through the high radiation concentrations of the SAA. A 5 mm thickness of aluminum shielding would largely prevent any degradation except by the most energetic particles. The Invar used in the main tube of the telescope structure and aluminum in the camera housing provides an effective 8 mm of shielding. In fact, much more shielding than this would induce a flux of secondaries more damaging than the primaries themselves.

As a compromise, an altitude of ~820 km has been chosen. This gives MOST a CVZ about 54° wide, spanning a range in declination from +36° to -18°. This region of the sky encompasses many bright solar-type stars, including several known to have large exoplanets in orbit around them. The maximum dwell time of a star in the middle of this CVZ is ~60 days. Such a long series of photometry with high duty cycle would resolve frequency spacings as small as about 0.1 μHz, needed to accurately estimate stellar ages from the oscillation spectrum.

Another important factor in a stellar photometry mission in LEO is scattered Earthlight. The secondary payload accomodation envelope baselined for MOST would not permit a large external baffle. Although the internal baffles have been designed to reduce parasitic light by a factor of 10^{-12}, light from the bright limb of the Earth would severely affect the photometry. Therefore, one of the most critical specifications for the MOST orbit was that it be Sun-synchronous and dawn-dusk, so the telescope could always look out over the shadowed limb of the Earth. (An orbit with a Local Time of Ascending Node (LTAN) crossing of 18:00 was eventually selected because the associated CVZ contained more targets of primary science interest.) The added bonuses of this orbit are thermal stability (no thermal snaps crossing the terminator except during brief eclipse seasons) and efficient use of the solar arrays on the rear face of the satellite (which would always be directed towards the Sun).

A three-stage Russian Rockot will inject MOST into a near-polar orbit (period ~100 min) inclined at approx. 98.7° to the equator, from the Plesetsk Cosmodrome in northern Russia. Launch is scheduled for 30 June 2003. The elements of the proposed orbit are given in Table 1.

Table 1: MOST Orbital Elements (Planned)

Altitude of Apogee	844.392 km
Altitude of Perigee	827.528 km
Semi-Major Axis	7206.960 km
Inclination	98.696°
Orbital Period	6088.9 sec
Local Time of Ascending Node (LTAN)	18 h 00 min 0.00 sec

Orbit and launch vehicle selection

The Radarsat-2 orbit, a dawn-dusk sun synchronous orbit, presented an excellent opportunity for the MOST mission. Subsequently the satellite was designed with this orbit in mind. This launch was initially scheduled for November 2001. However, it was plainly obvious early in the design of the MOST spacecraft that Radarsat-2 would not launch on schedule. Early in the Radarsat-2 program, the decision was made to change the spacecraft bus. The planned bus was dropped in favour of a new satellite bus that would be built by Alenia. This introduced a delay of at least 18 months to the scheduled launch date while the design and build of the MOST spacecraft proceeded. Further delays have resulted due to both payload and satellite bus developments. The Radarsat-2 launch is now scheduled no sooner than early 2005; a delay of more than 3 years.

This experience highlights one of the major issues regarding access to space for small satellites. Small satellites (i.e. low cost satellites) do not dictate launch schedule. For the most part, inexpensive satellites such as MOST can only afford to launch as secondary payloads. The launch schedule, however, is determined by the primary payload. In our case this could have resulted in a delay of more than 3 years in a program that was anticipated to be only 3 years (excepting operations). This would have been disastrous in terms of both cost and scientific return for the mission.

The strategy for designing the MOST spacecraft has been to use a small team of dedicated professionals. The primary reasons for this are to maintain a flexible team that can rapidly adapt to changing situations, and to keep the overall labour costs low. The larger the workforce, the less flexible it is. However, a small team in which every member is critical can be a double-edged sword. If a delay in the program occurs, every member is still critical and needed for the success of the program. Therefore the cost of the program will tend to increase by a greater percentage for a small team that must be maintained than for a large team that can be trimmed to a minimum number of members during delays. Considered as a whole, it is still cheaper to use the small team than to use the large team, but the longer a program is stretched out, the less benefit is provided in terms of cost.

In terms of scientific value, a delay of 3 years would have a significant impact. MOST is the first astronomical photometry mission of its kind. It is the first, but not the only mission. The French COROT mission and the ESA Eddington mission have similar goals only with larger satellites. Therefore there is a certain urgency in getting the MOST satellite into space to perform its ground breaking science.

As a result of the expected and continuing delays in the Radarsat-2 mission, the Canadian Space Agency in 2000 began to search for alternative launch opportunities. Fortunately for small satellites, there are presently a large number of launch opportunities on small Russian launch vehicles. The CSA consulted with the Dnepr, Cosmos and Rockot launch providers amongst others, and entered negotiations with Eurockot Launch Services of Bremen, Germany to launch on the converted Russian SS-19 "Rockot" launch vehicle. It is on the Rockot launch vehicle that MOST is scheduled for launch on 30 June, 2003. This may be 18 months behind as originally scheduled with Radarsat-2, but it is still more than 18 months ahead of the presently expected Radarsat-2 launch.

It is at this point that a small, integrated team was particularly useful, because in order to launch on the "Rockot" some key design changes had to be made. The small team was able to adapt well to these changes

Satellite Design Overview

The MOST satellite design originates from trying to fit as large a telescope as possible, all the electronics to interface with the telescope, the satellite bus equipment that allows the storage and transmission of the science data to the ground, the ACS hardware that is required to maintain better than 25 arcsecond pointing accuracy for the telescope, and a power system to provide enough power to the satellite, all into a package that can meet the requirements for launch as a secondary payload on a Delta II launch vehicle (with Radarsat-2 as the primary payload). It probably bears little resemblance to the satellite design that would have resulted had a launch on the Rockot been planned from Day 1. However, that is the nature of microsatellite design.

The telescope is a 15cm diameter aperture Maksutov telescope that is described in detail in Walker et. al [2]. A periscope mirror allows the long axis of the telescope to lie perpendicular to the aperture of the telscope and therefore fit into the Delta II secondary payload physical constraints. Attached to the telescope, separate from the satellite bus structure, is a two stage passive cryocooler that is capable of maintaining the focal plane of the telescope at a temperature of –40°C. Covering the aperture of the telescope is a door that is designed to actively close to protect the instrument focal plane from direct sunlight.

The satellite structure is based on a tray stack design. The structure consists of aluminum trays that house the satellite's electronics, battery, radios, and attitude actuators. These trays are stacked (see Figure 5) forming the structural backbone of the satellite. To this backbone, the science instrument, a 15 cm aperture Maksutov telescope is mounted with its barrel parallel to the axis of the stack. Six aluminum honeycomb panels, acting as substrates for solar cells and carriers for attitude sensors, enclose the tray stack/telescope assembly, forming the box seen in Figure 1. An actuated telescope door mounted on the star facing side of the satellite protects the telescope focal plane from direct stares at the Sun should the satellite tumble or lose attitude lock.

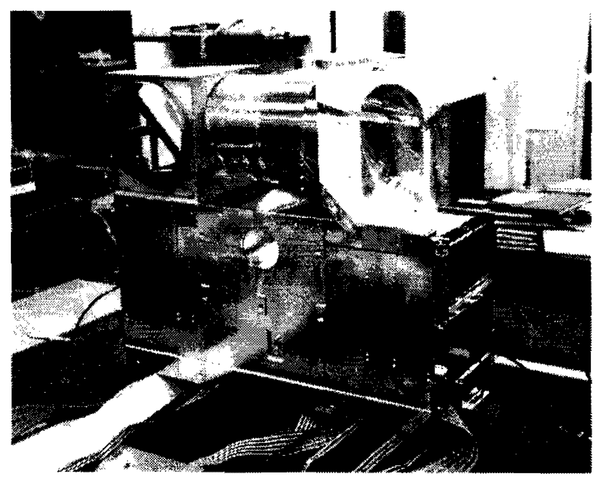


Figure 5: The MOST Tray Stack and Telescope

Satellite Electronic Architecture

The satellite electronic architecture is shown in Figure 6. The housekeeping computer, which is central to the design and the figure, is an off-the-shelf product that has been modified to meet MOST requirements. Based on a V53 processor, the computer's crystal frequency has been increased from 9 MHz to 29 MHz to accommodate the processing demands of the mission. It interfaces with the rest of the satellite through a custom interface card that provides power, serial and digital I/O connections. The housekeeping computer's main tasks include receiving, executing, and distributing commands and/or files uploaded

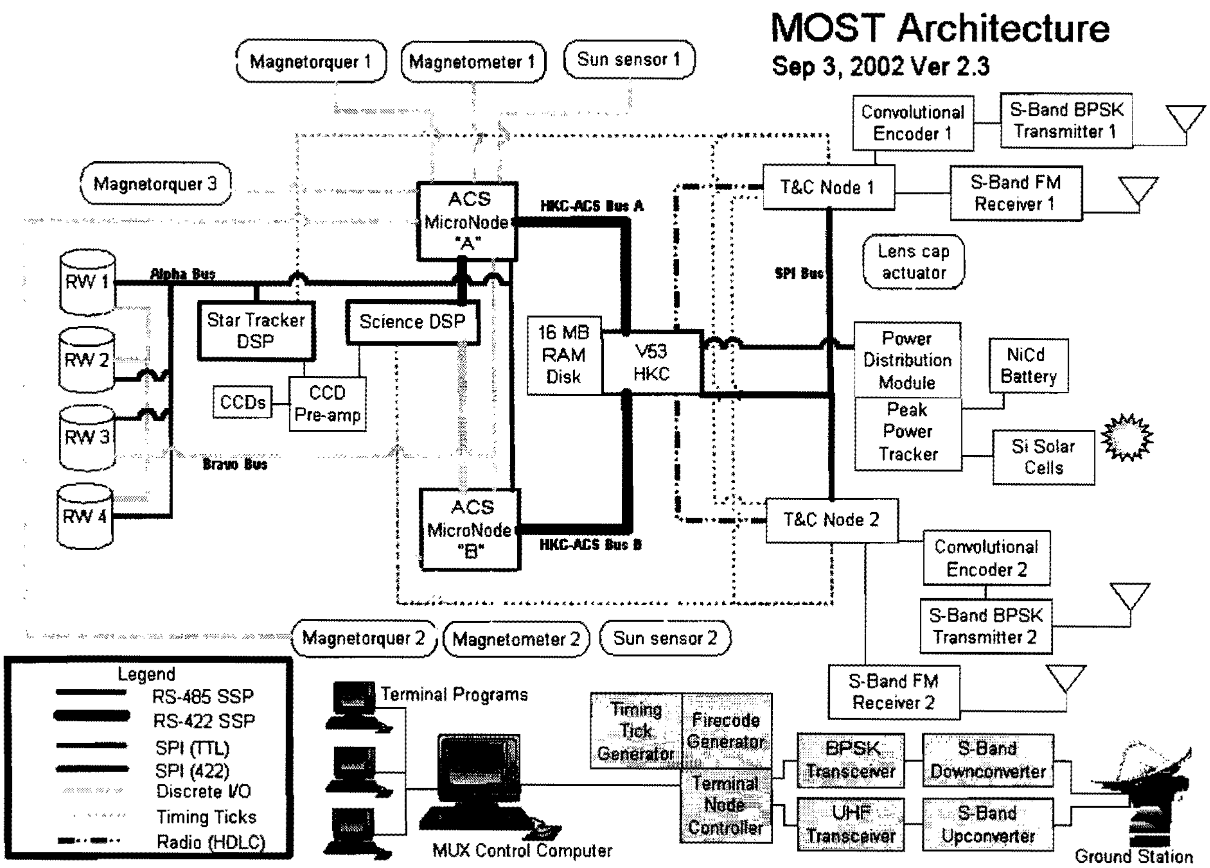


Figure 6: The MOST Architecture

from the ground, and collecting and transmitting engineering and science data to the ground.

In the figure, roughly from the V53 to the right, the satellite design is typical of AMSAT based designs. It consists of the main housekeeping computer (V53), radio transmitters and receivers including support electronics, and the power system for the satellite.

MOST employs two 0.5W RF output BPSK transmitters and two 2W FM receivers. All radios operate at S-band frequencies. Sufficient downlink margin is maintained by using a 0.5 rate convolutional code, implemented on a custom board. On the uplink, FM receivers provide a simple, robust, and low-cost means to talk to the satellite. Both receivers and transmitters connect to custom telemetry and command nodes that serve as modems and telemetry collection devices. To maintain omni-directional coverage, one receiver/transmitter pair is located on either side of the satellite, connected to quadrifilar antennas. Each radio operates on its own frequency. Thus, the appropriate transmitter is selected based on which receiver is being used.

The power subsystem is based on a centralized switching, decentralized regulation topology. Power regulation occurs through switching power supplies to maximize conversion efficiency (power is very limited in a satellite of this size - 35W in fine pointing operations and only 9W in safe-hold or tumbling operations). While this poses EMC/EMI challenges for the Science DSP computer that must read its CCD Array with almost zero noise, these challenges have been met.

The power system switches are controlled via the housekeeping computer. Two levels of load shed protect the satellite from unrecoverable battery drainage, allowing contingency operations to resume in safe-hold mode. All power lines have overcurrent protection.

In terms of energy storage, a NiCd battery provides power during eclipses and supports peak power draws from equipment such as the transmitters. High-efficiency silicon solar cells on all sides of the satellite generate energy to recharge the battery and provide power for fine pointing and safe-hold operations. Peak power tracking hardware and software (run by the housekeeping computer) maximize the available power to the satellite subsystems.

To the left of the V53 computer is the equipment that makes the MOST satellite unique for a microsatellite in the scientific contribution that it can make. These are the electronics to support the telescope, and the ACS hardware and electronics. The ACS equipment consists of magnetometers, sun sensors, and a star tracker for sensing, and magnetorquers and reaction wheels for actuation. The key developments here have been the use of reaction wheels for three-axis attitude control, and the development of a star tracker that is a fundamental part of the science telescope. Combined these enable the satellite bus to maintain pointing accuracy of less than 25 arcseconds.

Science and star tracker images are taken on dual 1024x1024 CCD arrays that share the focal plane of the telescope. Each CCD is connected to a pre-amplifier, and to analog and digital electronics boards (Figure 7). These boards are based around a Motorola 56303 DSP, and provide digital control and Analog to Digital conversion of the signals from the CCDs. The instrument computers are designed to provide nearly noiseless CCD readings while tolerating disturbances from switching power supplies.

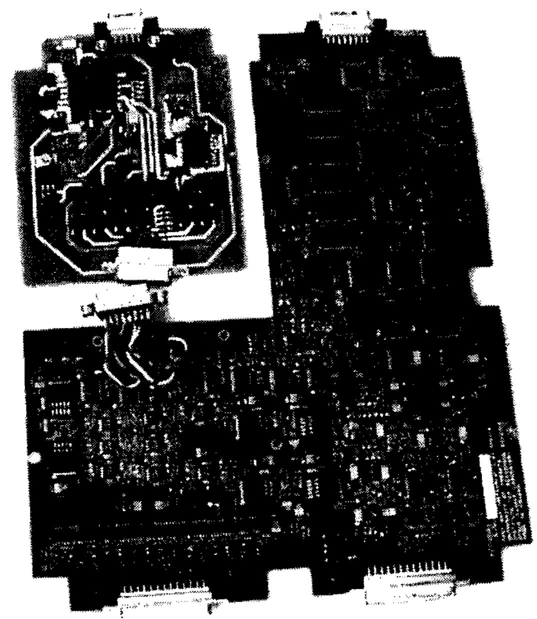


Figure 7: MOST Instrument Computer

There are four attitude control modes for the satellite:

Safe-Hold: . The satellite is essentially power positive in all practical orientations. Therefore, this is an uncontrolled state in which there is no active attitude control. In this mode, the focus is nominally on commissioning or recovery operations.

Detumbling: This mode involves using the magnetometers and magnetorquers to implement B-dot control to slow the tumble rate of the satellite so that coarse pointing control can be executed. Normally this is used after kick-off from the launch vehicle.

Coarse Pointing: After the satellite is detumbled, the ACS uses sun sensors and magnetometers to determine the spacecraft attitude, while using reaction wheels to control the attitude to orient the main solar array towards the Sun and to roughly point in the direction of science interest. The magnetorquers are used to desaturate the reaction wheels.

Fine Pointing: The ACS the star tracker to determine spacecraft attitude to an accuracy of three arcseconds. The reaction wheels are used to control the attitude. The magnetorquers are used to desaturate the reaction wheels.

The attitude control computers (ACS nodes) are also based on the Motorola 56303 DSP. The DSP acts as the fundamental processing unit that runs the ACS software. The computers provide analog control of the magnetorquers, power and analog to digital conversion of the magnetometer and sun sensor signals, as well as RS-485 connections to the main housekeeping computer, the reaction wheels (which contain their own microcontroller) the star tracker and science DSP boards. Nominally, only one ACS node is operational. The second is designed as a cold spare to add redundancy where it was practical.

All computers have Error Detection and Correction (EDAC) hardware and software to correct for bit errors induced by radiation. Single event latch-ups are corrected by power cycling the affected device.

To ensure that components within the satellite operate at suitable temperatures, a combination of passive surface treatments are used including aluminum, gold, and silver teflon tapes. In the event that the satellite enters a cold state due to a disadvantageous attitude relative to the Sun, resistive heaters are used to keep the battery and trays sufficiently warm. During fine pointing operations, a passive radiator cools the telescope focal plane so as to minimize thermal noise in the CCD readout

Ground Stations

Three ground stations in Toronto, Vancouver and Vienna will be used to download data from MOST. The primary control station will be in Toronto (Figures 8 and 9), while the secondary stations (Vancouver and Vienna)

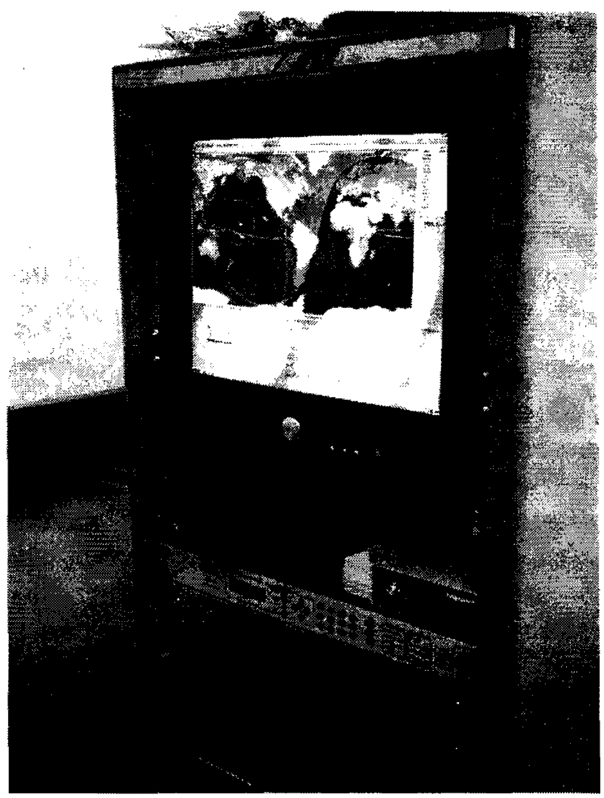


Figure 8: MOST Ground Station

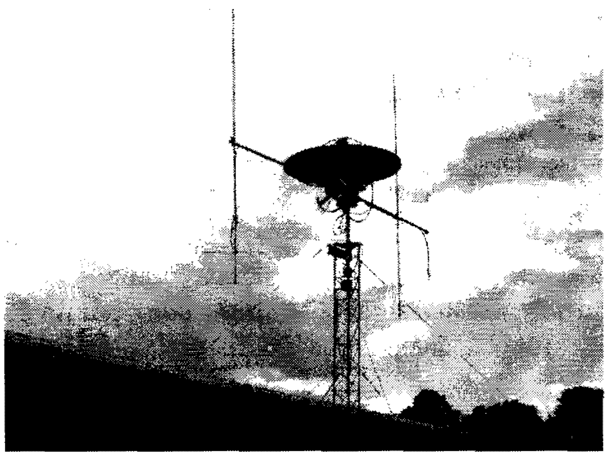


Figure 9: Antenna System at UTIAS/SFL

will be controlled and coordinated over the Internet. Although the basic mission can be accomplished with just one ground station, additional science data can be acquired using the secondary stations.

The stations used for MOST communications are based on an amateur radio core station operating at VHF and UHF frequencies. They are upgraded with S-band transverters and BPSK transceivers connected to a 2-m parabolic antenna (downlink) and a 45 element loop yagi (uplink). The antennas are mounted on a heavy-duty, precisely controlled rotator located atop a 20-foot tower (Figure 9).

The ground station radios are connected to a custom terminal node controller (combination modem and serial communications controller) which is in turn connected to a computer that coordinates multiple terminals each running interface software for specific components on the satellite (see Figure 6). Through this system, terminal users have a virtual link to their satellite hardware of interest. The terminal node controller also generates "firecodes" or emergency commands to reset satellite hardware. A "timing tick" generator is used to maintain knowledge of clock drift in the instrument computers so as to accurately time tag science observations.

Impact on Design as a result of change of launch vehicle

The change from Delta II to Rockot launch vehicle had no significant changes on the electrical design of the satellite. However, there were important changes that were needed in the structural design, and these had an important effect on cost and schedule of the

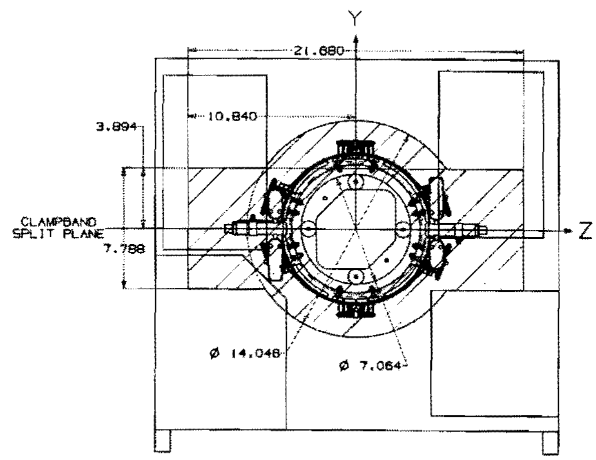


Figure 10: Delta II Marmon Clamp Attached to MOST

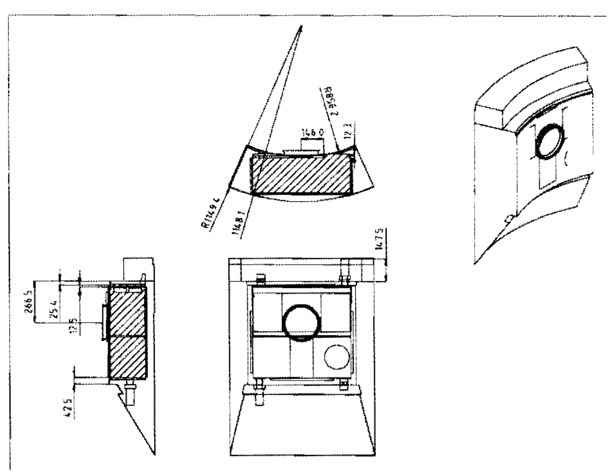


Figure 11: MOST in Delta II Secondary Envelope

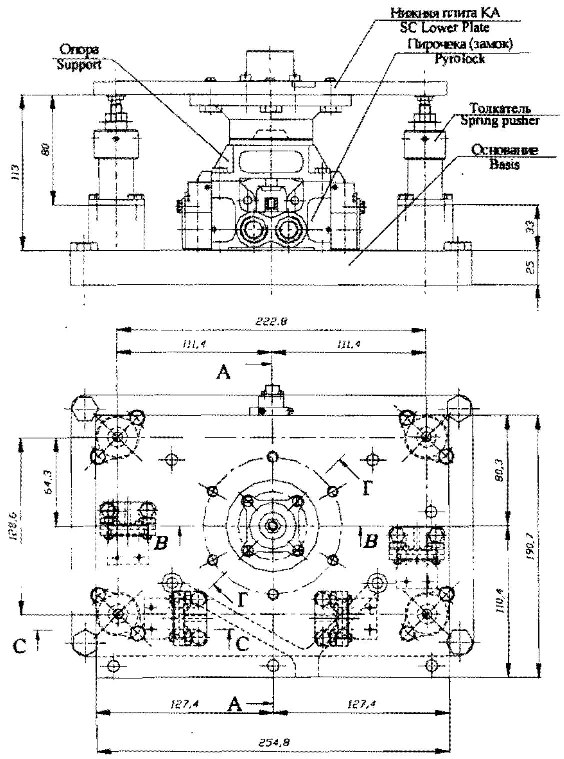


Figure 12: Rockot Pyrolock System

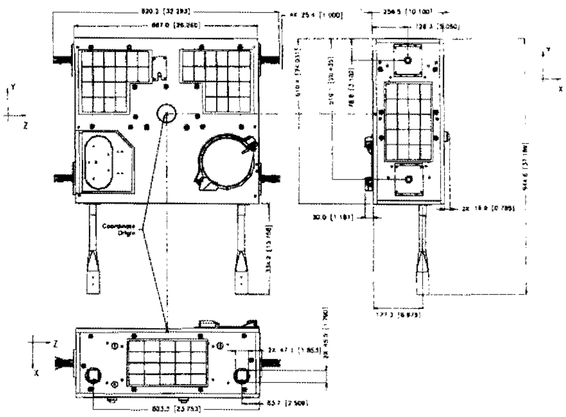


Figure 13: MOST Modified to Accommodate Rockot Pyrolock

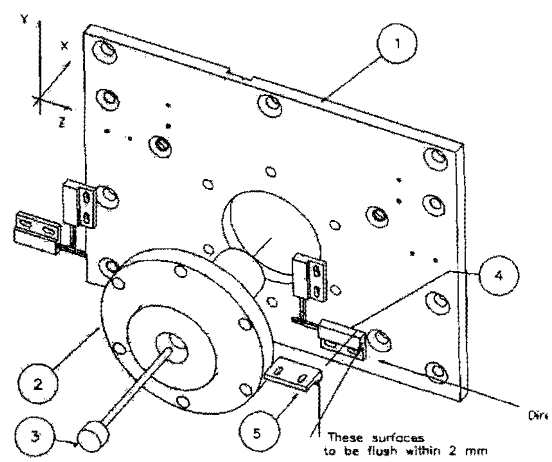


Figure 14: Payload Attach Fitting to Accommodate Pyrolock System

program. For our purposes, the primary difference between accommodation on the Delta II and the Rockot launch vehicles is the payload adapter interface. The Delta II uses a 9-inch Marmon clamp (see Figures 10 and 11), while the Rockot uses a pyrolock mechanism (Figure 12). The pyrolock mechanism has as very different interface to the satellite. It consists of a central rod that pulls the spacecraft towards the launch vehicle. There are 3-4 hardpoints that contact the satellite to oppose the preload that is provided by the central rod. At these hardpoints, there are spring pushers to provide separation forces once the central rod is released by the pyro-mechanism.

While negotiations were in progress with Eurockot on the launch contract, work was frozen on the central five trays of the tray structure, and the –X panel of the spacecraft that interface with either the Marmon clamp or the pyrolock mechanism. This resulted in approximately 6 months of delay in the program and the costs that are associated with the delay. (See Figures 13 and 14 for the resulting MOST and payload attach fitting designs.)

Program Status

The MOST spacecraft began environmental test on October 15, 2002 at the CSA's David Florida Laboratory in Ottawa, Canada and completed environmental testing on January 18, 2002. Environmental testing consisted of spacecraft vibration testing, EMI testing, and TVAC testing.

The spacecraft was put through a series of low-level sine, high-level sine, sine burst and random vibration tests to qualify the satellite for launch on the Rockot vehicle. For the random vibration tests, a force-limited vibration technique was used to avoid overtesting of the satellite (See Scharton [3]).

The spacecraft is nominally unpowered on the launch vehicle. However there is a small circuit that monitors the state of non-contacting separation sensors that is active during launch. The spacecraft was tested to ensure that the launch vehicle RF environment would not result in EMI pickup on the separation sensor lines. This is to ensure that the satellite does not mistakenly engage prior to actual separation from the launch vehicle.

The Thermal Vacuum testing was performed to verify that functionality of all of the satellite equipment over the expected thermal range in a vacuum environment. TVAC tests were performed at the each of the extremes of the thermal range that are expected on orbit. At each of these extremes all of the equipment that is required at these temperatures was functionally tested. In addition, operational scenarios were tested. These included testing during changing thermal enviroments that result from the satellite entering and exiting eclipse once per orbit.

Following environmental testing, the

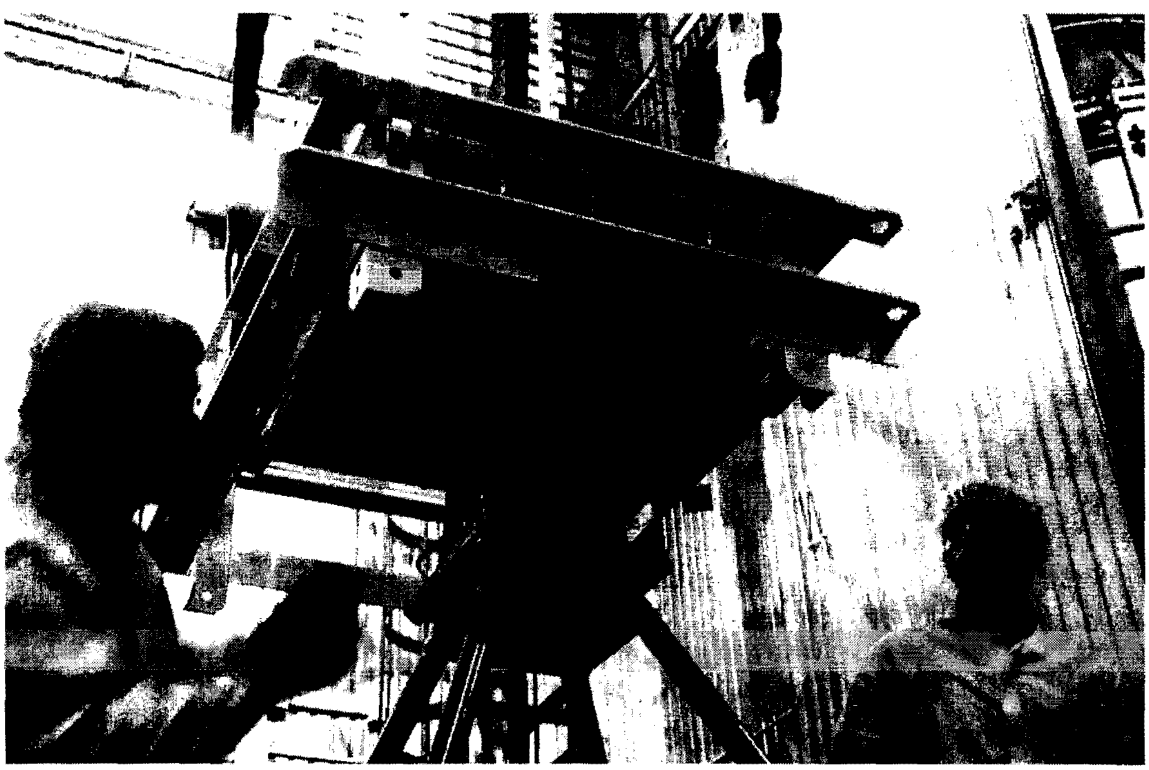


Figure 15: MOST at the Plesetsk Cosmodrome. Shown here is a mating check.

spacecraft completed its functional testing. The functional test plan covers all aspects of unit functionality within the context of spacecraft-level operation. This included testing of the attitude control system which could not be tested during TVAC. The ACS is functionally tested using a series of tests performed with the spacecraft on a single axis air bearing. On the single-axis air bearing, the detumble, coarse pointing and fine pointing modes of the satellite were checked out and shown to work functionally. Performance testing was not possible in a 1-g environment.

The MOST satellite program passed its flight readiness review on 7 May 2003.

On 13 May 2003 the MOST satellite and GSE was shipped from Toronto, Canada to begin its long journey to the Plesetsk Cosmodrome in Russia. The launch campaign began on 26 May 2003 at the Plesetsk Cosmodrome where the satellite was given a final checkout. The satellite was mated with the separation system designed and built by the Khrunichev State Research and Production Space Center (a 49% partner in the Eurockot consortium). Figure 15 illustrates the activities in the Integration Hall of the Plesetsk Cosmodrome.

Integration with the launch vehicle is scheduled to take place on 14 June 2003, with the launch scheduled for 30 June 2003.

Figure 16 shows our team at the Plesetsk Cosmodrome. The sign says Russian Space Forces, Plesetsk Cosmodrome.

Figure 16: The MOST Team at the Plesetsk Cosmodrome. From left to right, Jaymie Matthews, Simon Grocott, Daniel Foisy, Rainer Kuschnig, Hugh Chesser, Alexander Beattie, Anatoly Borshchov (our friendly Russian Security official)

Conclusion

When all is said and done, there are both positive and negative aspects that we have experienced concerning accessibility to space. One the one hand, there has been a negative impact on the cost and schedule or our program. Our launch is approximately 18 months later than was expected, and significant redesign and rework was required that resulted affected the cost of our program.

However, there is a very positive outlook as well. A wide selection of Russian launch vehicles from which we have used the Rockot provided by Eurockot Launch Services, have greatly increased access to space. Without the Russian launch opportunities, our program would have been further delayed as we would be tied to the Radarsat-2 launch. Because our satellite once designed required a dawn-dusk sun synchronous orbit, the only other alternative would have been to find another primary going to such an orbit and hitchhike with it. However, this orbit is used little enough that there were few other opportunities. Without the accessibility provided by the Russian launch vehicles, our program would have suffered further delays and cost significantly more as a result.

Acknowledgments

Dynacon Incorporated would like to thank the program manager for MOST, Mr. Glen Campbell and the Space Science Branch of the Canadian Space Agency for their support and encouragement throughout the MOST project. The University of British Columbia acknowledges the contributions of the Natural Sciences and Engineering Research Council (NSERC) and the Canadian Foundation for Innovation (CFI). The University of Toronto Institute for Aerospace Studies would like to thank the Ontario Research and Development Challenge Fund (ORDCF) and the Center for Research in Earth and Space Technology (CRESTech) for their financial support.

The Space Flight Laboratory gratefully acknowledges the donations and contributions of the following organizations to its microsatellite program:

- Agilent Technologies
- Altera
- Altium
- Analytical Graphics
- ATI
- Autodesk
- ARC International
- Cadence
- CMC Electronics
- E. Jordan Brookes
- EDS
- Emcore Photovoltaics
- Encad
- Honeywell
- Integrated Systems
- MDRobotics
- Micrografx
- National Instruments
- Raymond EMC
- Rogers Microwave Materials
- SDRC
- Stanford University, Space Systems Development Laboratory

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AMSAT OSCAR-E Project
Fall 2003 Status Report
by
Richard M. Hambly W2GPS

This status report about AMSAT-OSCAR-E ("Echo") is an update to the presentation given at the Dayton Hamvention in May 2003 and the to the previous articles published in the AMSAT Journal and CQ/VHF.

INTRODUCTION

Progress on the Echo satellite has been significant since the articles published this past summer. On August 5, 2003 the AMSAT project team of Dick Daniels W4PUJ, Tom Clark W3IWI and Rick Hambly W2GPS met with the SpaceQuest team Dino Lorenzini, KC4YMG, Mark Kanawati N4TPY and Bob Bruhns WA3WDR. At this meeting it was resolved that spacecraft integration would take place in December 2003 and Launch is now scheduled for March 31, 2004.

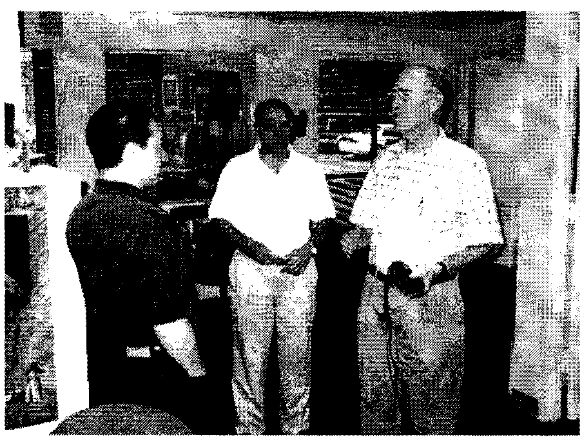

Figure 1: AMSAT Echo project leader Dick Daniels W4PUJ (right) discussing the project with SpaceQuest's Dino Lorenzini, KC4YMG (middle) and Mark Kanawati N4TPY (left)

Following the formal meeting the AMSAT team was treated to a demonstration of Echo features including data communications, command and control, and the attitude control subsystem. The modules were laid out in the "flat-sat" configuration with a special wiring harness designed for this purpose.

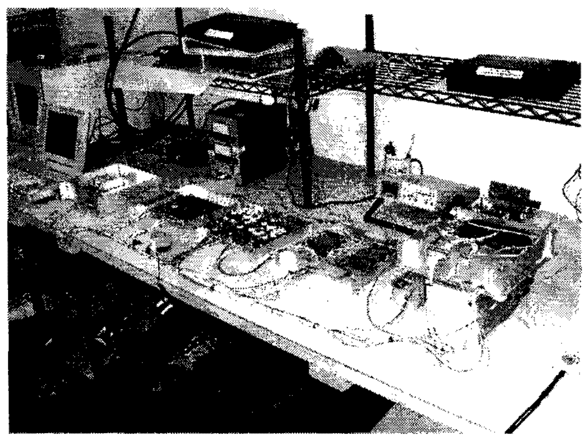

Figure 3: Echo flight hardware powered up for testing in "flat-sat" configuration

BACKGROUND:

The AMSAT OSCAR-E satellite, also known as "Echo", was conceived by the AMSAT Board of Directors when on October 8, 2001 they initiated review of "a new small satellite

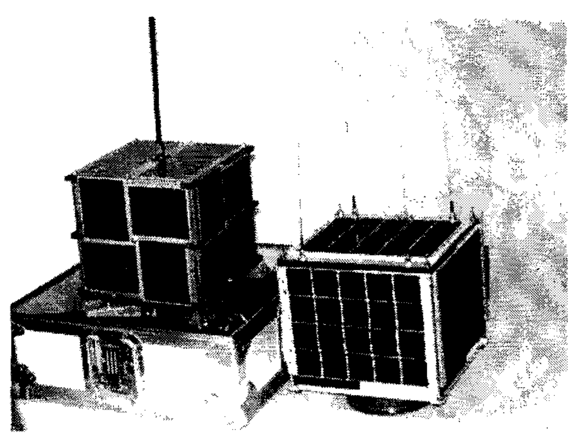

Figure 2: Original Microsat model (left) and Echo mechanical model (right)

project." Since that time an expanding team of AMSAT volunteers have been working in cooperation with our contractor SpaceQuest on the design, construction and launch preparations for this new satellite.

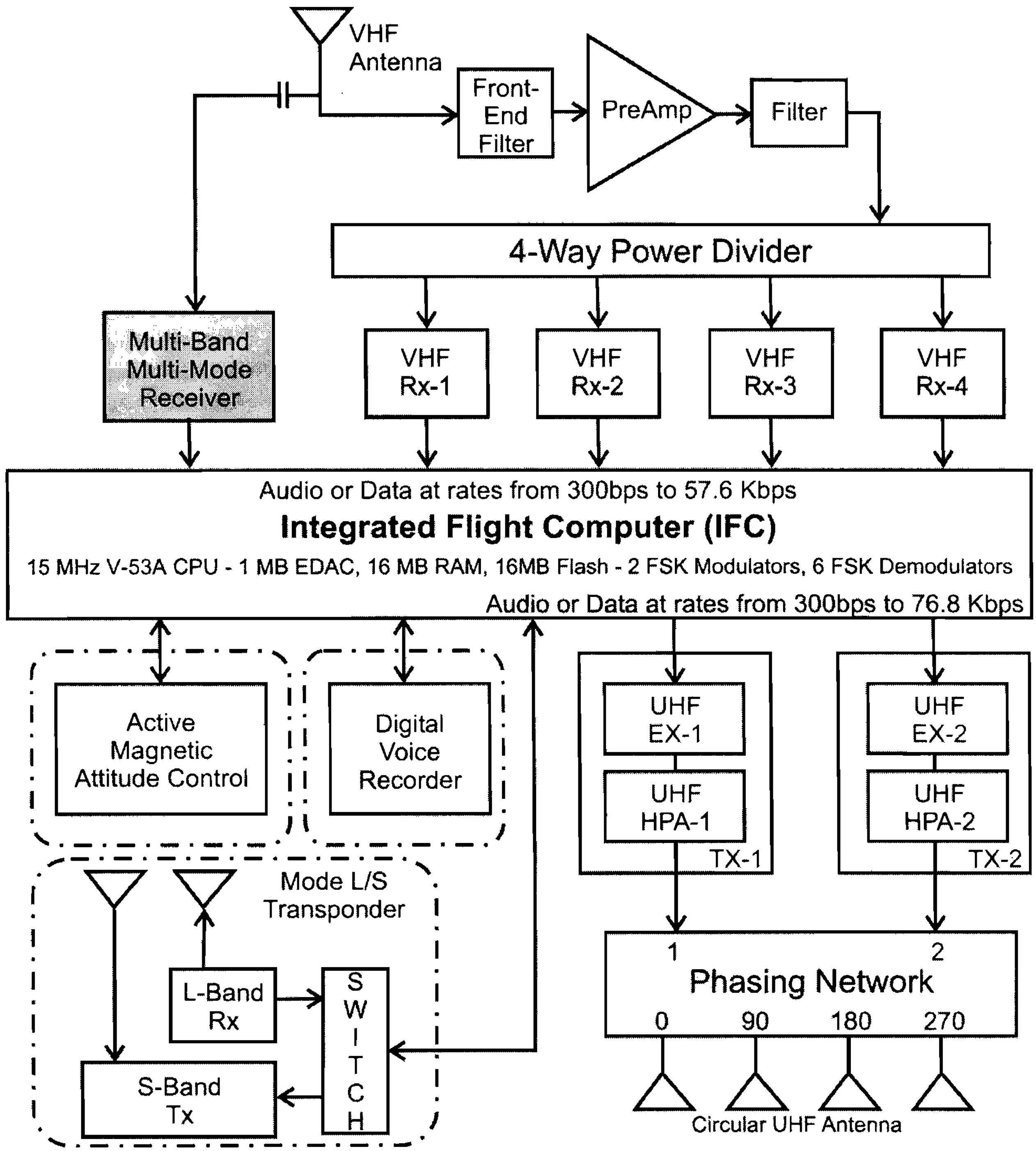

Figure 4: Block Diagram of the Echo Spacecraft

Echo is a Microsat class satellite that owes a great deal to the heritage of the original AMSAT Microsats AO-16, DO-17, WO-18, and LO-19 that were launched in 1990 and to the AMRAD-sponsored Microsat AO-27 that was launched in 1993. As shown in Figure 3 Echo is a small cube about 9.5" (25 cm) on a side, like those first Microsats. It is made up from a stacked set of aluminum trays and covered on all sides by solar panels.

SUMMARY OF FEATURES

Echo will offer capabilities that will appeal to users with a wide range of interests from "EasySat" operations to scientific experiments. Here are the highlights:

- Mode V/U, L/S and HF/U Operation. Modes V/S, L/U and HF/S are also possible.
- Analog operation including FM voice.
- Digital modes. Store and forward operation is planned. Many speeds are possible but 9.6, 38.4, 57.6K and 76.8Kbps are the most likely.
- PSK31 repeater mode using 10-meter SSB uplink and UHF FM downlink.
- Four VHF receivers and two UHF high power 8-Watt transmitters.
- Can be configured for simultaneous voice and data.
- Has a multi-band, multi-mode receiver.
- Can be configured with geographical personalities.
- Advanced power management system.
- Digital Voice Recorder (DVR).
- Active magnetic attitude control.

TECHNICAL OVERVIEW

Echo's internal subsystems have been refined and modified since they were described in the previous articles. As you will see in the following figures significant progress has been made and Echo's hardware is taking shape.

As shown in Figure 4, Echo is made up of a number of modules and subsystems including:

- Four VHF receivers.
- A Multi-Band Multi-Mode Receiver.
- Two UHF transmitters.
- Six demodulators and 2 modulators.
- Integrated Flight computer.
- Batteries, BCR, Regulators (not shown).
- Wiring harness, RF cabling.
- RF switching and phasing networks.
- 56 channels of telemetry.
- Magnetic attitude control.

STRUCTURE

As shown in Figure 5 Echo is made up from six trays each made from solid blocks of 6061-T6 aluminum and stacked with stainless steel sheer pins and four 4-40 tie-down rods. The tray dimensions are:

- Receiver tray: 58mm with 2mm base.
- CPU tray: 24.8mm with 2mm base.
- Charger tray: 24.8mm with 2mm base.
- Battery tray: 38mm with 2mm base.
- Payload tray: 58mm with 2mm base.
- Transmitter tray: 39mm with 9mm base.

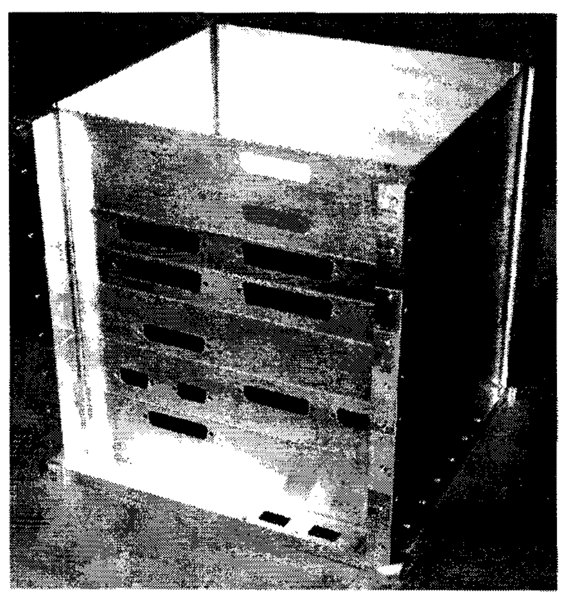

Figure 5: Echo's Trays

Thus Echo has overall dimensions of approximately 9.5" x 9.5" x 9.5".

RECEIVERS

Echo has four miniature VHF FM receivers each consuming less than 40 mW of power and weighing less than 40 gm each. Each receiver has 2-channel capability although the second channel is not planned to be used. The sensitivity of each receiver is -121dbm for 12db SINAD.

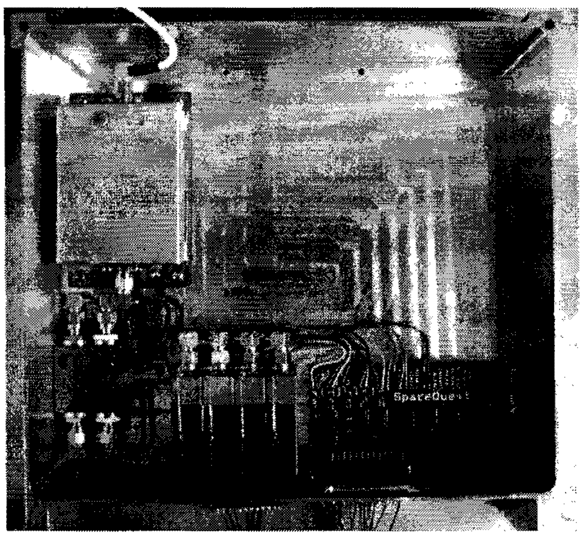

Figure 6: VHF PreAmp/Filters, 4-Way Power Splitter, Four VHF Receivers and Interface Board. The open space is for the DVR.

TRANSMITTERS

Echo has two UHF FM transmitters that can be operated simultaneously. Each transmitter can be operated at any power level from 1 to 8 watts output. The transmitters are frequency agile in 2.5KHz steps and are tunable over about 20 MHz.

MULTI-BAND RECEIVER

Echo has a single all-mode receiver capable of receiving signals on the 10m, 2m, 70cm and 23cm Ham bands and possibly on other frequencies. Its performance is limited primarily by the performance of the broadband antenna, which will probably be shared with the 2-meter whip antenna.

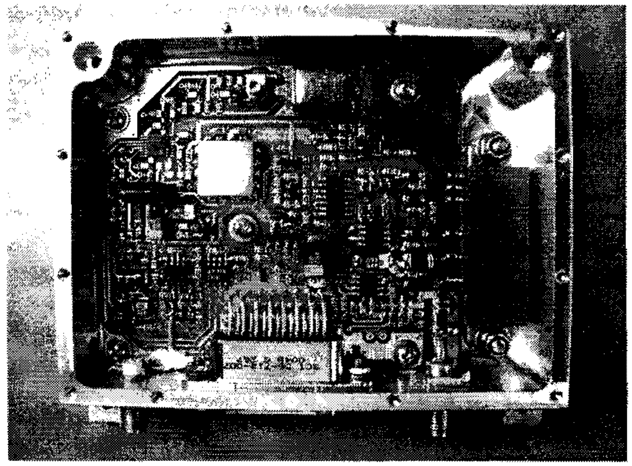

Figure 7: One of Echo's UHF Transmitters

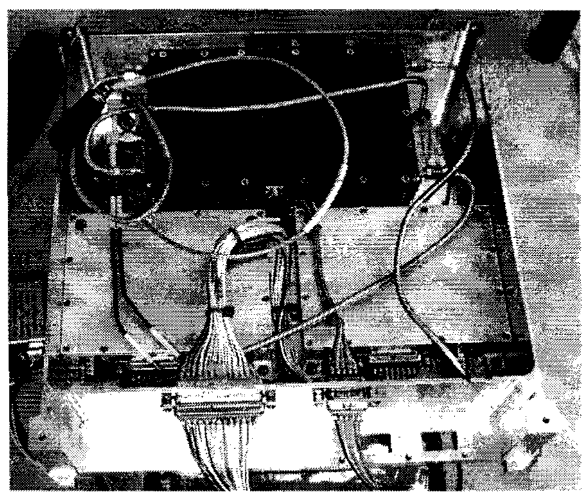

Figure 8: UHF Hybrid Combiner (rear) on top of the Multi Mode Receiver and two UHF Transmitters (front).

ANTENNAS

Echo's antenna design has undergone a number of revisions and is still in a state of flux. At present there are three antennas:

- A VHF 18" whip on top.
- A UHF "Mary" Turnstile on bottom.
- An L+S band "open sleeve" antenna on the bottom.

The Multi-band Multi-Mode receiver shares the VHF whip.

The two UHF transmitters are fed through a phasing network to the "Mary" UHF antenna, resulting in one UHF transmitter having right hand circular polarization and the other UHF transmitter having left hand circular polarization.

LINK BUDGET DATA

Echo's UHF transmitters are adjustable from 1 to 8 Watts. Maximum efficiency is achieved at 8 Watts and that is the expected operating power level.

Antenna gain on the UHF is +2 dBic at +/- 45 degrees to -6 dBic at the backside of the spacecraft.

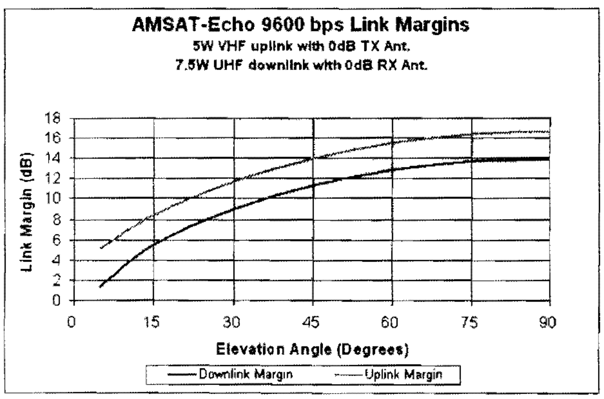

Figure 9: Mode V/U Link Margin Graph

The VHF antenna feeds a low noise amplifier (LNA) with 0.7db noise figure and 20db of gain. The LNA is followed by a band pass filter with 1.5db of loss. The overall receiver performance is -125 dbm for 12db SINAD.

DATA MODES

The modulation is either narrow band FM voice or data using baseband shaped raised-cosine-in-time FSK. Many data rates are possible but 9.6, 38.4, 57.6K and 76.8Kbps are the most likely rates to see operational use. To be more specific, it is expected that 9.6K and 57.6Kbps will be used on uplinks and 9.6, 38.4, and 76.8Kbps on downlinks.

The 57.6K waveform is about 100 KHz wide so it can't be used on the VHF uplink. The L-band uplink utilizes the multiband receiver that has both narrow and wide band filters. Unfortunately, the 57.6K L-band uplink will be less than optimal because the receiver's wideband FM mode bandwidth is 150KHz; it will take extra uplink power to overcome the additional noise from the mismatched filter bandwidth.

Downlinks will be 9.6Kbps on UHF (57.6Kbps is possible but not likely). Downlinks on S-band will be 9.6Kbps initially with 38.4Kbps and 76.8Kbps in use later. I expect we will run S-band at 9.6Kbps to test and get folks with AO-40 stations interested, then move to 38.4Kbps and 76.8Kbps to get users excited about those faster speeds and gain experience on how they work with regard to Doppler.

We are looking forward to using 57.6Kbps, however no ground equipment currently exists to support it so operation of uplink or downlink at this speed will have to wait until some equipment becomes available.

INTEGRATED FLIGHT COMPUTER

The Integrated Flight Computer (IFC) was developed by Lyle Johnson KK7P. It is a flight proven board with a power consumption of less than 300 mW. The IFC includes advanced features including six receive and six transmit serial communication channels, 1 MB of error-detecting and correcting (EDAC) memory, 16 MB RAM, and 16MB flash memory for mass storage.

The IDC also has six agile demodulators and two agile modulators to support data communications.

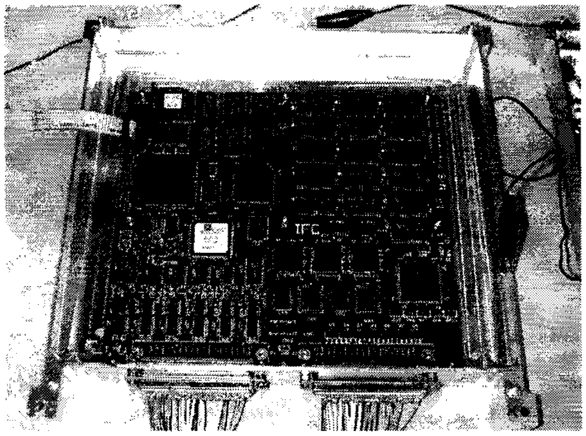

Figure 10: Integrated Flight Computer

SPACECRAFT FLIGHT SOFTWARE

Echo's software consists of a boot loader, kernel, operating system and applications. Echo will use the Spacecraft Operating System (SCOS), which has been used on all of the Amateur Radio Microsat projects to date. Harold Price NK6K should be thanked for allowing AMSAT to use SCOS.

The software development team consists of Bob Diersing N5AHD, Jim White WD0E, Harold Price NK6K, Lyle Johnson KK7P, and Skip Hansen WB6YMH.

Bob Diersing N5AHD has agreed to update the boot loader. A test version of boot loader is now complete. This is the first step to enable the rest of the software effort.

The SCOS kernel port has started. Enhancements are planned to be made to the SCOS drivers and supporting software.

A Windows command and telemetry program for the ground station is about 50% complete at the time this is being written. A Windows based boot loader prototype for the ground station is done. The housekeeping task has been created and will soon be tested.

The communication protocol for the Digital Voice Recorder interface is documented.

SOLAR PANELS

Echo will have six high efficiency Solar Panels The panels will use triple junction MCORE GaAs cells that are nearly 27% efficient. This results in about 20 Watts of power generation capacity when not in eclipse (12-14 Watts per side).

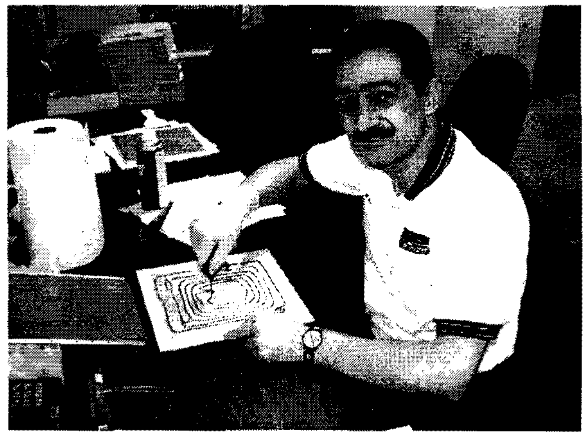

Figure 11: Mark Kanawati N4TPY Preparing to Bond Solar Cells to the Panels.

POWER DISTRIBUTION

Echo is equipped with a matched set of six NiCd cells that have a capacity of 4.4 Amp-Hours each. The output of the battery subsystem is nominally 8 Volts DC.

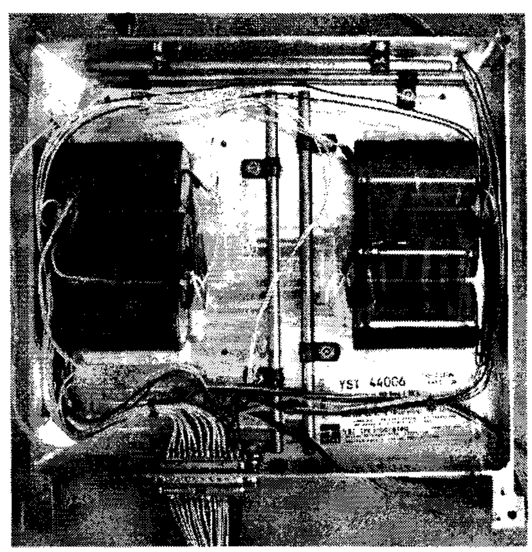

Figure 12: Battery Tray

The interface between the solar panels and the batteries is through the Battery Control Regulator (BCR). This critical subsystem is designed to be autonomous and fail-safe so that the batteries are protected above all else.

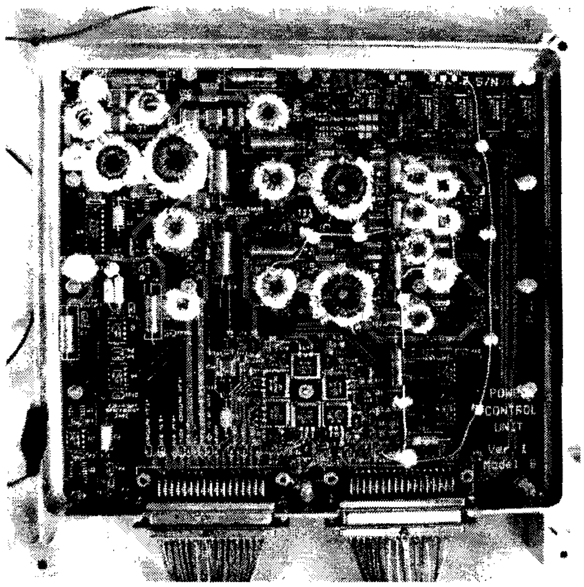

Figure 13: Battery Control Regulator

The BCR operates at 50KHz with 89% efficiency. It charges the battery using only solar panel power, so is capable of charging a dead battery. The BCR prevents the battery from overcharging or depleting completely at any temperature and provides the necessary voltages and telemetry.

ATTITUDE CONTROL

A new experimental active magnetic attitude control has replaced the passive system used on previous Microsats. This design by Doug Sinclair VA3DNS consists of a torquer rod and a charging module.

The torquer rod is a semi-permanent magnetic rod whose strength and polarity are adjustable by applying a charging current over a period of up to 15 seconds, where 15 seconds imparts a maximum charge. This allows some control over the satellite's attitude relative to the Earth's magnetic field. It also permits us to turn the satellite upside down.

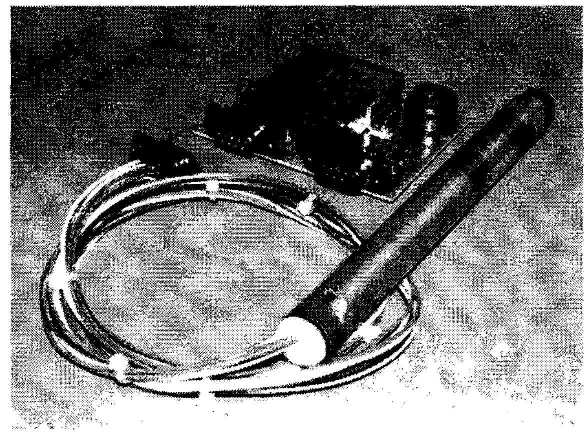

Figure 14: Active Magnetic Attitude Control

DIGITAL VOICE RECORDER (DVR)

Echo will be equipped with a multi-channel digital recorder. This recorder can sample audio from a selected receiver output with 16 bits resolution at a rate of 48K samples/second. Recordings can be played back on any of Echo's downlink channels.

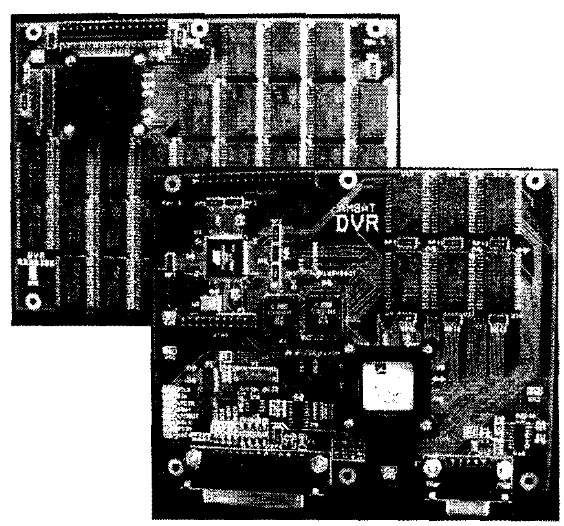

Figure 15: DVR CPU board in front of the DVR RAMDISK Board

The DVR is based on the same ARM7 processor planned for use in the IHU3 for upcoming high-orbit missions. It has up to

64MB of RAMdisk storage, providing almost 12 minutes recording time.

INTEGRATION LAB

Thanks to the efforts of Ron Parise WA4SIR, NASA Goddard Space Flight Center has returned the AMSAT Integration Lab to us. This building was constructed in the Spring of 1978 on the grounds of what is now the NASA Visitor's Center by NASA and a group of Hams led by Jan King W3GEY and Tom Clark W3IWI.

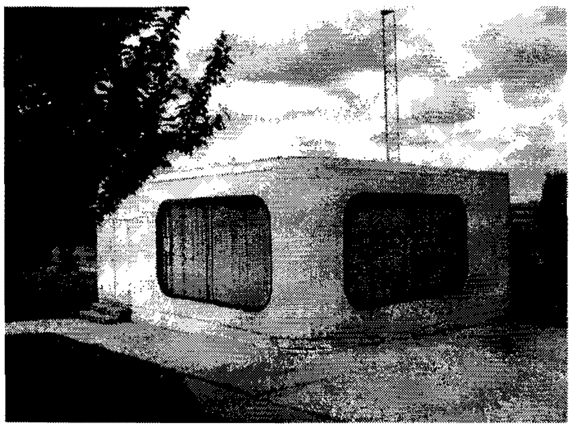

Figure 16: AMSAT Integration Lab at NASA

The Integration Lab was used between 1978 and 1988. It was instrumental in the construction of the Phase 3A satellite and Oscar-10.

The Goddard Amateur Radio Club has helped to clear the building of the materials stored there by the Visitor's Center. We are now waiting for NASA's facility department to repair the roof and floor. Once that is done we will bring in furniture and test equipment, much of which will be provided by NASA and the Goddard Amateur Radio Club.

Unfortunately, the repairs to the building have been delayed in red tape so the integration of Echo will have to take place at SpaceQuest. We are still working on this and hope to have the building ready for Eagle and ARISS projects.

We are also assembling a satellite command and test station for this facility. Fortunately our satellite antenna tower is still standing and is in good condition.

LAUNCH

Echo's launch is planned for May 2004. The launch will be on a Dnepr LV (SS-18) rocket from the Baikonur Cosmodrome in Kazakhstan.

By this time next year the Echo satellite should be in orbit providing communications services to the Ham community for many years to come.

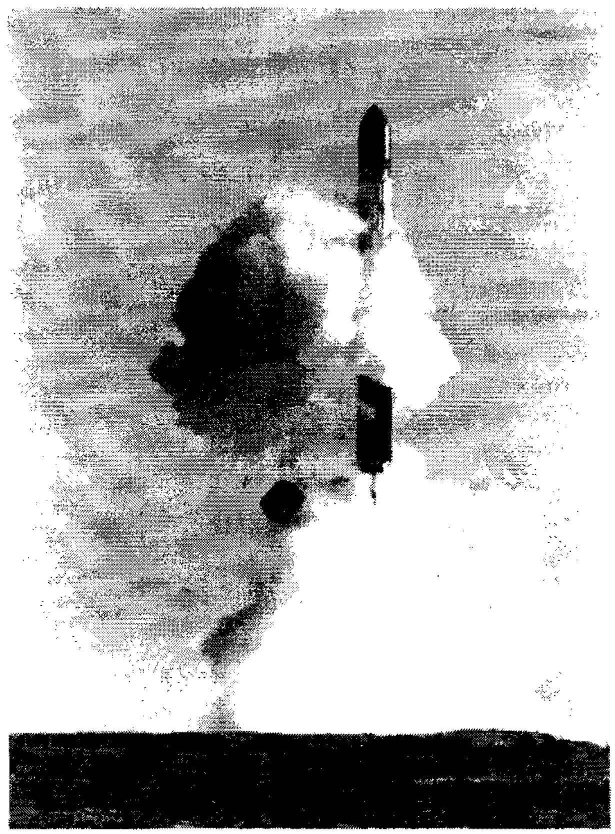

Figure 17: Dnepr LV (SS-18) Launch from Baikonur Cosmodrome in Kazakhstan, Dec 2002

CONCLUSION

AMSAT OSCAR-E ("Echo") has evolved and matured since its inception in late 2001. Many of its modules are now built and undergoing preliminary testing. Software is beginning to come together. Soon we will begin the system integration where the various subsystems will be tested in functional groupings. Then we will proceed with full satellite integration and testing.

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A Panel-Reflector Antenna for Transmitting to AO-40

Anthony Monteiro, AA2TX
aa2tx@amsat.org

Abstract: *This article introduces a Panel-Reflector Antenna for accessing the OSCAR-40 satellite uplink. The antenna operates on the 70cm (UHF) band and provides right-hand circular polarization. Its compact size and its ability to be mounted directly to a metal cross-boom make it a convenient alternative to the usual cross-polarized Yagi array.*

Introduction

The article describes the design and construction of a Panel-Reflector Antenna intended to be used for accessing the OSCAR-40 satellite on its 70 cm (UHF) band uplink. There are two major features of this antenna that make it appealing as an alternative to the usual cross-polarized Yagi array. First, it is a compact package that is small and nearly-flat. Among other things, this can reduce the load on your elevation rotator and is especially helpful if the rotator is of the light-duty type. Second, it can be mounted directly to a metal cross-boom, eliminating the need to use fiber-glass or other non-conducting materials which can be expensive and less reliable than a simple aluminum or steel cross-boom.

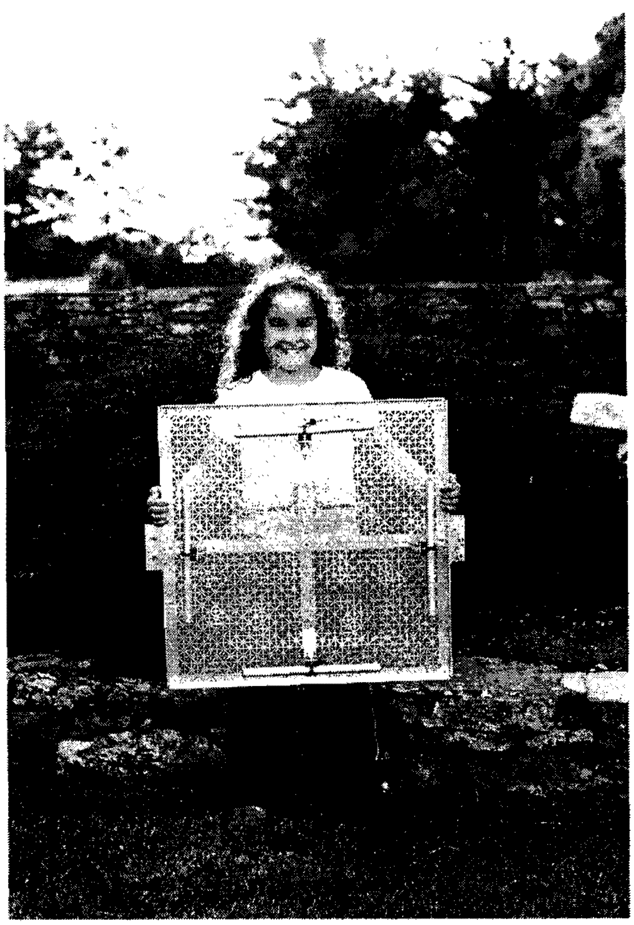

Figure 1. Veronica Monteiro, age 8, demonstrates the compact size of the Panel-Reflector Antenna.

The Panel-Reflector Antenna is designed to provide right-hand, circular polarization (RHCP) and over 10 dBi gain. Since the current generation of commercially available satellite radios provide 50 to 75 watts output on the 70 cm (UHF) band, the combination can provide more than enough power to allow a reliable OSCAR-40 uplink under even difficult conditions without requiring additional power amplification.

Theory of Operation

The Panel-Reflector Antenna consists of four radiating dipole elements over a flat reflector; please see Figure 2. The two horizontal dipoles are fed in-phase so that they operate as a two-element, phased array. Similarly, the two vertical dipoles are also fed in-phase and operate as a two-element, phased array. However, the horizontal and vertical pairs are fed 90° out-of-phase to produce right-hand, circular polarization as is needed for OSCAR-40.

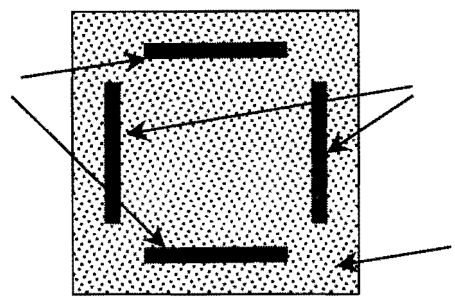

Figure 2. Panel-Reflector Antenna showing dipole radiators over the flat reflector surface

The flat panel reflector under the dipoles reflects the radiation from the back side of the dipoles to the forward direction and increases the overall gain. The size of the reflector is 24-inches by 24-inches which is less than 1-wavelength. This small size reduces the gain over the maximum possible but represents a reasonable compromise between gain and a nice, compact package.

In order to make up for some of the gain lost through the small size reflector, the dipole pairs are spaced beyond the canonical ½-wavelength found in textbook descriptions of phased-arrays, to about .72 wavelengths. This increases the gain by about .75 dB although it also decreases the front to side ratio. Please see the radiation pattern plot, calculated with EZNEC, shown in Figure 3. For transmitting to OSCAR-40 the increased side-lobes are not an important consideration and the additional gain is helpful when conditions are difficult. With the increased spacing, the calculated gain of this antenna is 10.88 dB over an isotropic radiator. Since there are some losses in the feed cables, connectors and power splitter, the actual gain will be a little less than this calculated value.

Unlike a Yagi, the location of the phase-center of the radiating elements has only a minor affect on the overall gain of the Panel-Reflector Antenna. This is due to the fact that flat reflectors do not have a focal point. As a result, there is no need to use balanced-to-unbalanced (BALUN) transformers to feed the dipoles which significantly simplifies the construction and reduces the cost and complexity of the antenna.

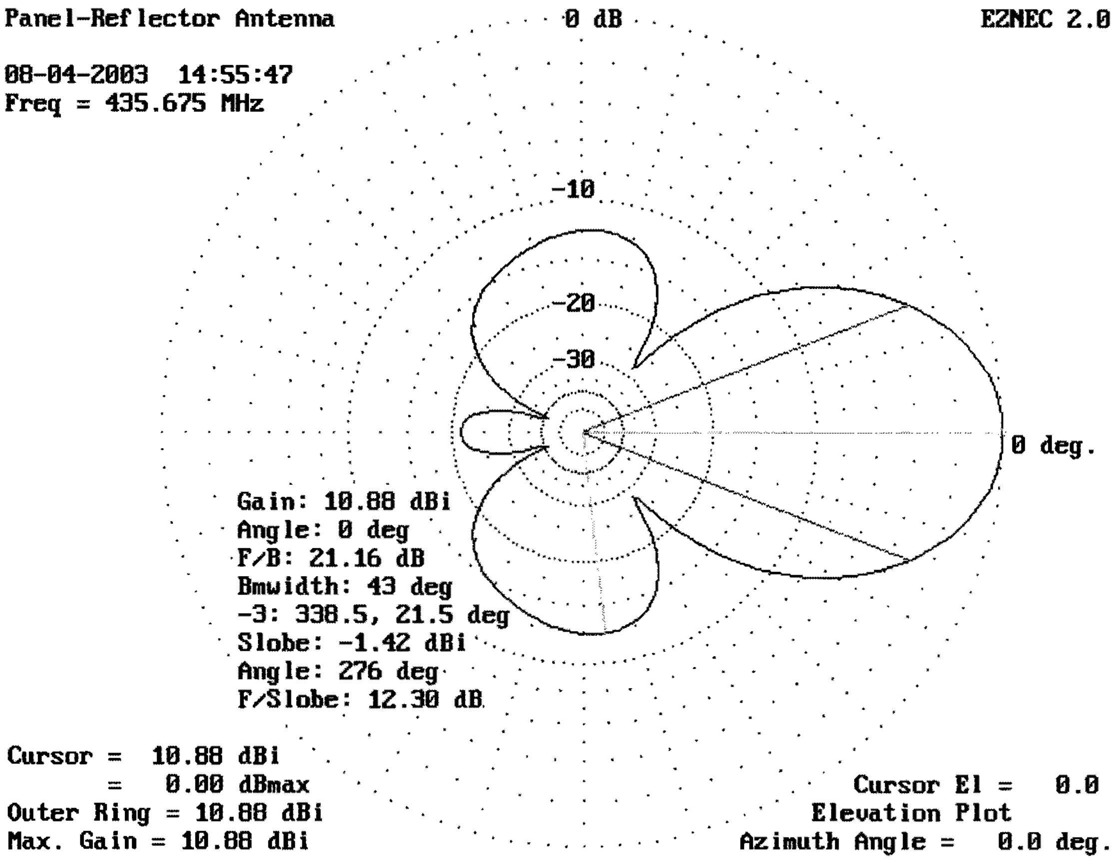

Figure 3. Calculated Radiation Pattern

The height of the dipoles from the reflector surface affects the radiation resistance and this spacing was designed so that the dipoles each present a 50-ohm load. Along with the fact that no BALUN is needed, this allows the dipoles to be fed directly with ordinary 50-ohm coaxial cable. Note that the dipoles will not individually measure 50 ohms (i.e. you cannot measure each dipole's impedance separately) as only when both are fed in-phase do they present 50-ohm loads.

The phasing of the dipole elements is accomplished by using specific lengths of the coaxial feed cables. Although it is common to feed pairs of a phased-array using same-length cables, this approach was not used as it would require an untidy cable arrangement. Instead, pairs of dipoles are fed with cables that differ by 180° of electrical length and then the wires are reversed at the dipoles to restore the required in-phase feed. Since the horizontal and vertical pairs are fed 90° out-of-phase, this means that each feed cable is a different length. This is a bit more complex but results in a much nicer wiring arrangement.

The feed cables are each connected to one port of a four-way, 0° power-splitter. The power-splitter is very simple and easy to construct as it is assembled from ordinary 50-ohm coaxial cable and standard N-type, coaxial connectors. Please see Figure 4 for a schematic of the power splitter.

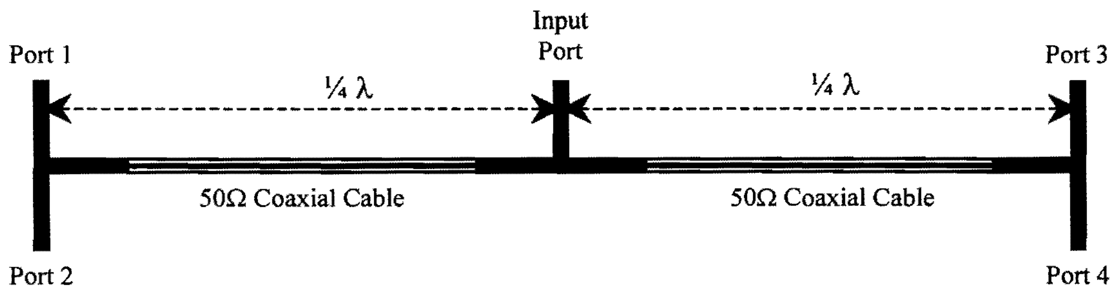

Figure 4. Four-way, 0° Power Splitter

The operation of the power-splitter is as follows: Each dipole presents a 50-ohm load and is connected to one of the feed ports (numbered 1 - 4) of the power-splitter using 50-ohm coaxial cable. Each feed port is thus terminated in a 50-ohm load. Each of these ports is a leg of a standard, N-Type, T-connector. At the center of the T-connector that joins ports 1 and 2, the impedance is 25 ohms, the result of the two, 50-ohm loads in parallel. This 25-ohm load is transformed into 100 ohms via an electrical quarter-wavelength, section of 50-ohm coaxial cable. The same thing occurs with ports 3 and 4. At the center of the T-connector at the Input port, the two 100-ohm loads are joined in parallel resulting in a 50-ohm antenna input impedance.

This antenna design employs thick dipoles and with its feed method and power splitter has a wide bandwidth so that no tuning is required. This simplifies the construction and eliminates the need for any special UHF test equipment.

Construction

The Panel-Reflector Antenna, while not exactly a beginner's project, is relatively straightforward to construct. Except for the coaxial cable and connectors, all of the materials were obtained from a local hardware store and the prototype was built using only ordinary hand tools. Experienced builders should feel free to substitute their own favorite construction techniques. The antenna was designed to be insensitive to small deviations in the dimensions. The complete list of materials used to construct the prototype is shown in Table 1 below.

This list of materials is generally not critical with only a few exceptions; the reflector panel must be at least 2' x 2' in size and the tubing, used to construct the dipoles, must be 3/4" outer diameter. The other materials were selected because they were readily available at a local hardware store.

Quantity	Description
4'	1" x 1" x 1/8" aluminum angle stock
2' x 2'	perforated aluminum sheet
8'	1" x 1/8" aluminum rectangular bar stock
2'	1-1/2" x 1-1/2" x 1/8" aluminum angle stock
4'	3/4" (outer diameter) aluminum tubing
(4)	1/2" "Black" PVC insert coupling (for lawn sprinkler systems)
(4)	1/4" (inner diameter) rubber grommet
(8)	1/2" nylon spacer
(8)	1/16" nylon bushing
(8)	mylar washer
(8)	#8-32 x 2" stainless steel screw
(8)	#8 stainless steel flat washer
(8)	#8 stainless steel lock washer
(8)	#8-32 stainless steel nut
(8)	1/4" aluminum screw post fastener
-	1/8" and 3/16" aluminum "pop" rivets
(2)	1-1/4" stainless steel U-bolt assembly
(8)	Type N, male connector for LMR-240 cable
(2)	Type N, female/female/female T-connector,
(1)	Type N, female/male/female T-connector,
(1)	Type N, female/female bulkhead connector
10'	LMR-240, 50-Ohm, coaxial cable

Table 1. Bill of Materials

The LMR-240 cable was selected because it is thin and yet has a very low loss and can handle over 300 watts of power at 436 MHz. Other thin 50-Ohm cables, such as RG-58, could be used instead but the maximum power rating and gain of the antenna will be less due to increased losses. Also, the matching section lengths used in the four-way power splitter would need to be re-calculated to match the velocity factor of the cable. In any case, make sure the Type-N male connectors match the cable type.

To build the antenna, start by constructing a frame for the reflector, please see figure 5. The outside of the frame was made from 1" x 1" x 1/8" angle stock. The interior cross supports are made sections of 1" x 1/8" rectangular bar stock. The assembly is held together with aluminum pop rivets. Note that the corners are not mitered, the top and bottom supports are mounted beneath the side supports. The center supports are offset to be at the same height as the side sections so that the reflector can be mounted flat. The techniques used here are not critical, the idea is only to provide a rigid, flat support structure for the 2' x 2' reflector panel. When the frame is complete, attach the reflector panel with pop rivets as shown in figure 6.

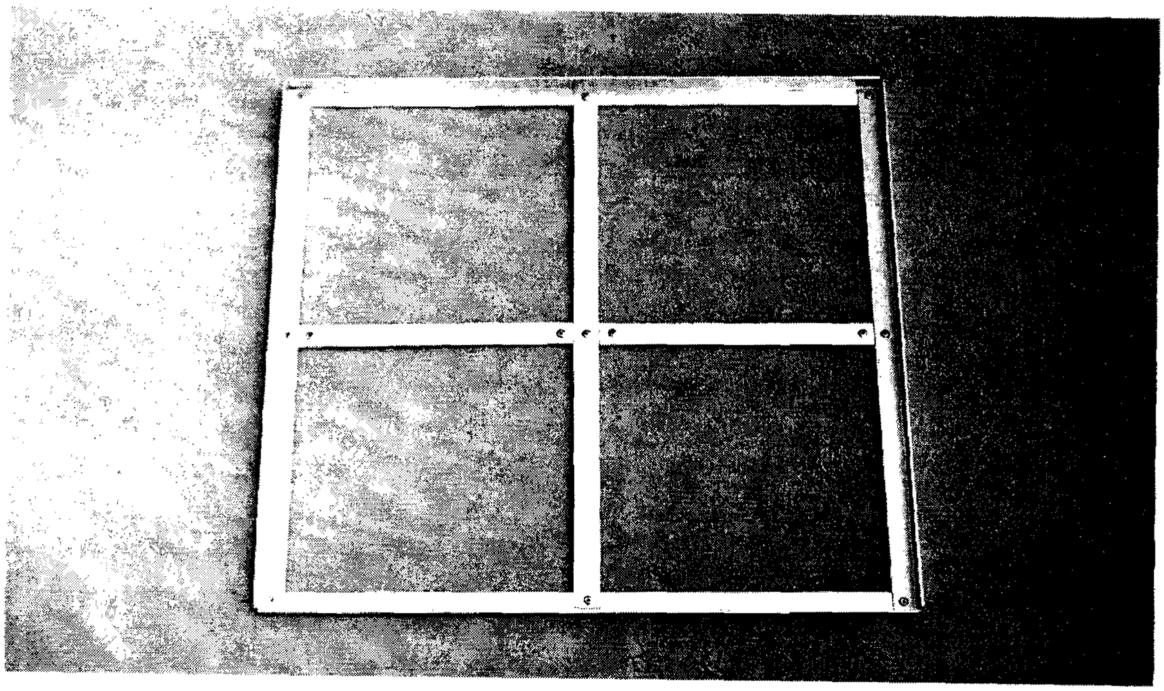

Figure 5. Reflector Frame

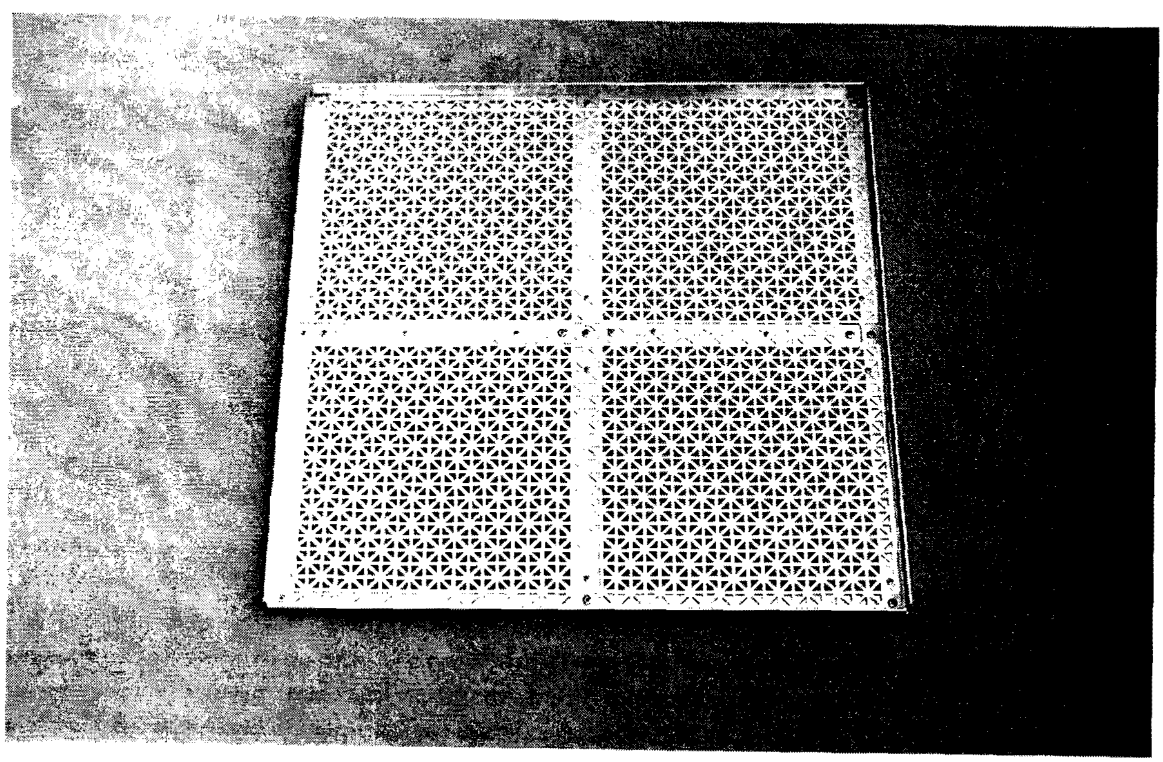

Figure 6. Completed Reflector Panel

Construct the four dipoles using the 3/4-inch aluminum tubing and the PVC insert couplings. Please see figure 7 for the dipole dimension details. The tubing pieces are each 5-1/2 inches long and they are spaced 1/4 inch apart at the center giving an overall length of 11-3/4 inches. The PVC insert couplings, used as the center insulators, will need to be filed or sanded to fit inside the tubing. The fit should be snug. After assembling the tubing sections over the insulator, drill two holes, each 11/64 inches, all the way through the tubing and the center insulator. These holes will be used to mount the dipoles and provide the electrical connections.

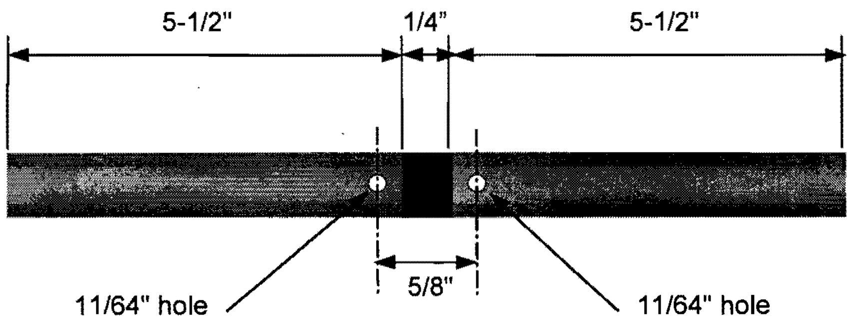

Figure 7. Dipole Dimensions

The dipoles are held in place by the dipole support brackets. These were fabricated from a 1-inch wide section of the 1-1/2 inch x 1-1/2 inch x 1/8 inch angle stock and a length of 1 inch x 1/8 inch bar stock fastened together with pop-rivets as shown in figure 8 below. The centers of the dipoles need to be mounted at 5-5/16 inches from the reflector surface and 9-3/4 inches from the center of the reflector (i.e. dipole pairs are spaced 19-1/2 inches apart.) The dipole mounting holes are 5/8" apart to mate with the holes on the dipoles. The brackets are fastened to the reflector panel using aluminum "screw-posts" allowing them to be easily removed if required for transporting the antenna.

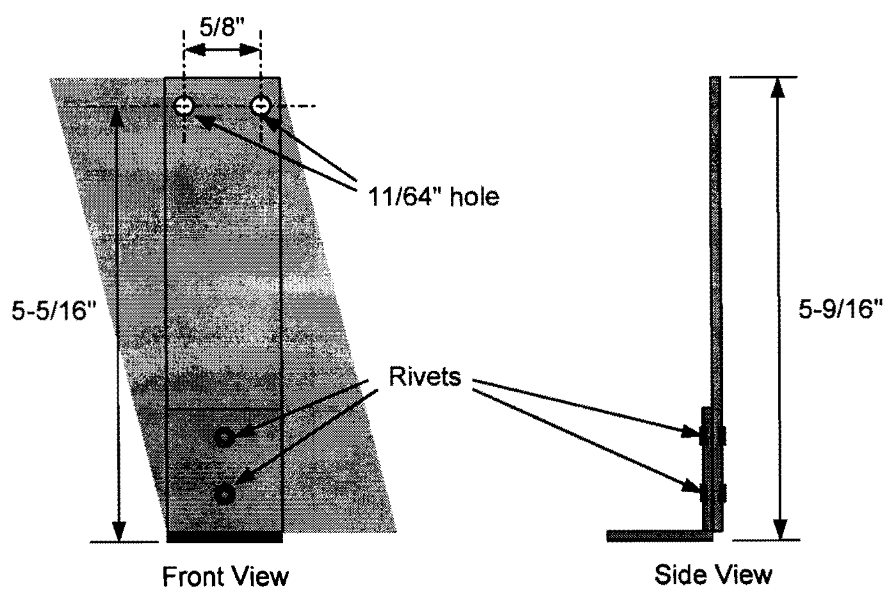

Figure 8. Dipole Support Bracket Dimensions

The dipoles are fastened to the support brackets with the #8-32 x 2 inch screws and associated #8-32 hardware. The nylon bushings and mylar washers are used to insulate the screws from the dipole brackets. The nylon spacers hold the dipole assembly 1/2-inch away from the support bracket. All of the nylon and mylar hardware was painted black to mitigate the effects of the ultra-violet radiation from the sun. The completed dipole and mounting bracket assembly is shown in Figure 9.

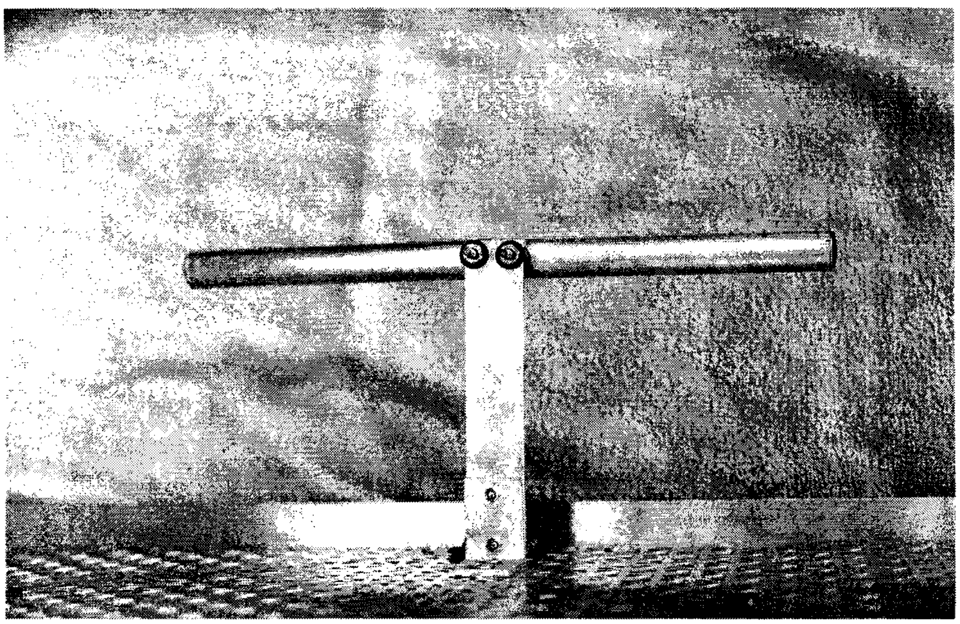

Figure 9. Dipole mounted to dipole support bracket

The coaxial feed cables were cut to the lengths shown in Table 2 below and then 1" of insulation was removed from one end of each cable leaving the shield and center conductors exposed. Heat-shrink tubing was used to protect the cable ends. It is important to keep the lengths of the shields and center conductors the same to the extent possible. A male, N-connector was attached to the other end of each cable.

Feed for Dipole#	Cable Length (inches)
1	17
2	22.7
3	28.4
4	34.1

Table 2. Coaxial Feed Cables

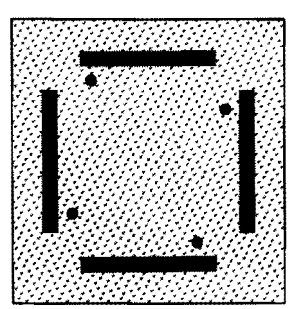

Figure 10. Front of Antenna showing dipole numbering

The coaxial feed cables are connected directly to the dipoles using #8 flat washers to compress the conductors against the aluminum tubing sections. The dipole numbering is shown in Figure 10. The black dots indicate the side of the dipole that is connected to the center conductor of the coaxial cable. OX-GARD™ grease is recommended to assure a good electrical connection between the aluminum tubing and the copper coaxial cable conductors. Rubber grommets are used to protect the coaxial cable as it passes through the reflector. A view of the coaxial cable connection to the dipole is shown in Figure 11 below.

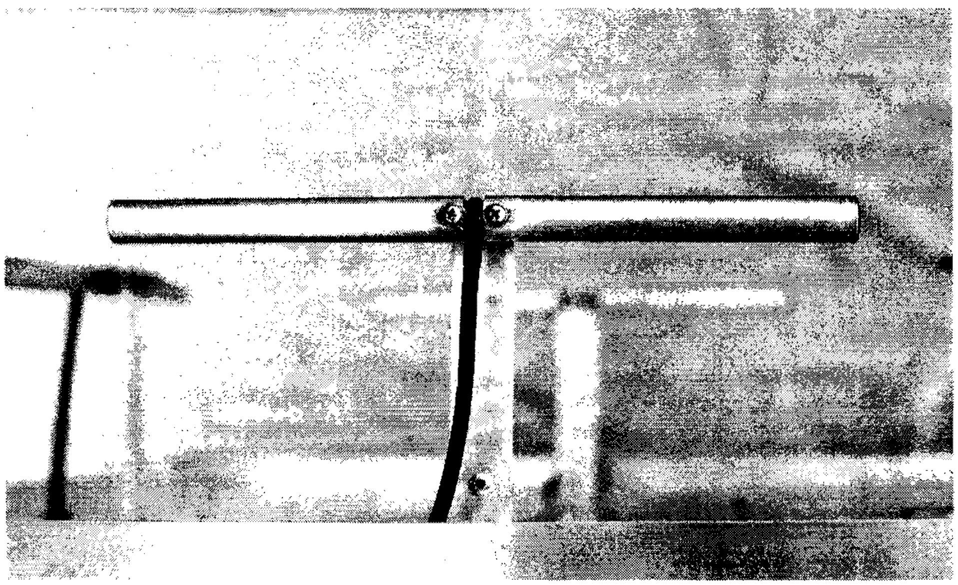

Figure 11. Dipole and feed cable connection

The dipole feed cables are connected to the four-way, 0° power splitter. This is made from standard N-connectors and a short length of LMR-240 cable. The two female/female/female tees are used at the output ports. The female/male/female tee is used at the input port. Each output tee is connected to one leg of the input tee with a short male to male jumper cable made with enough cable so that the distance from the center of the output tee to the center of the input tee is 1/4 wavelength. LMR-240 cable has a velocity factor of .84 and the tees were assumed to also have a .84 velocity factor so this requires a total length of 5.7 inches. With common, crimp, male N-connectors, there will be 3.1 inches of the coax jacket showing between the two connectors on the jumper. You can substitute other types of cable or connectors but make sure to recalculate the 1/4 wavelength section.

A bulkhead connector is mounted on a bracket made from a 1-inch wide section of 1-1/2 inch x 1-1/2 inch x 1/8 inch angle stock. The male part of the input tee is connected to the bulkhead connector. A close-up photograph of the power splitter is shown in Figure 12. A photograph of the back of the antenna showing all of the cable connections is shown in Figure 13.

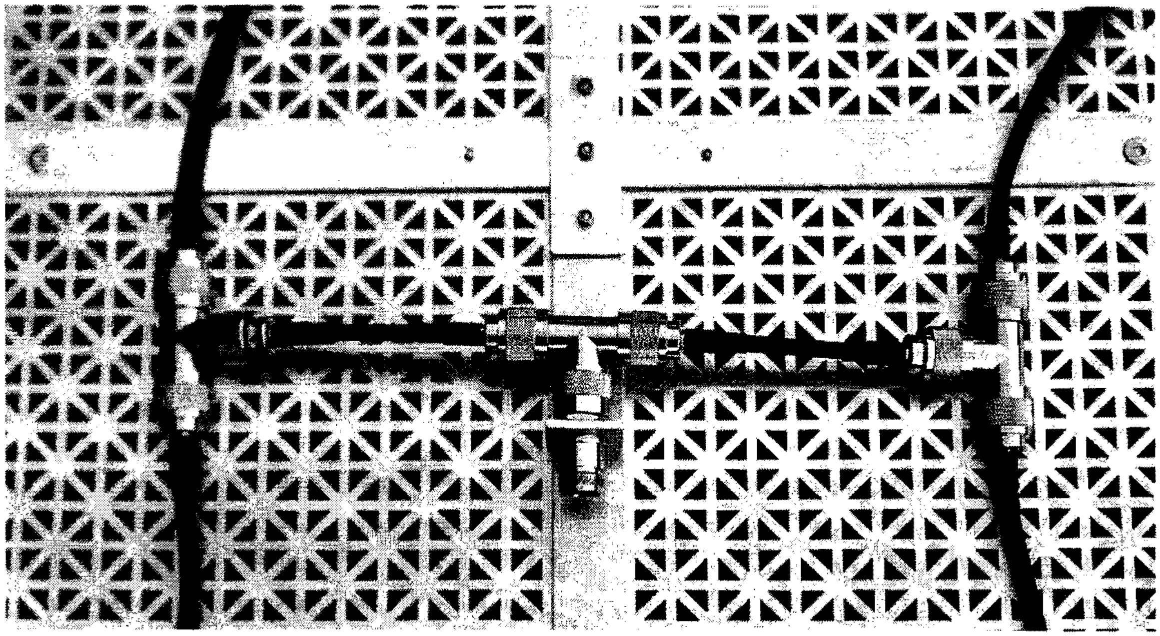

Figure 12. Close-up of power-splitter

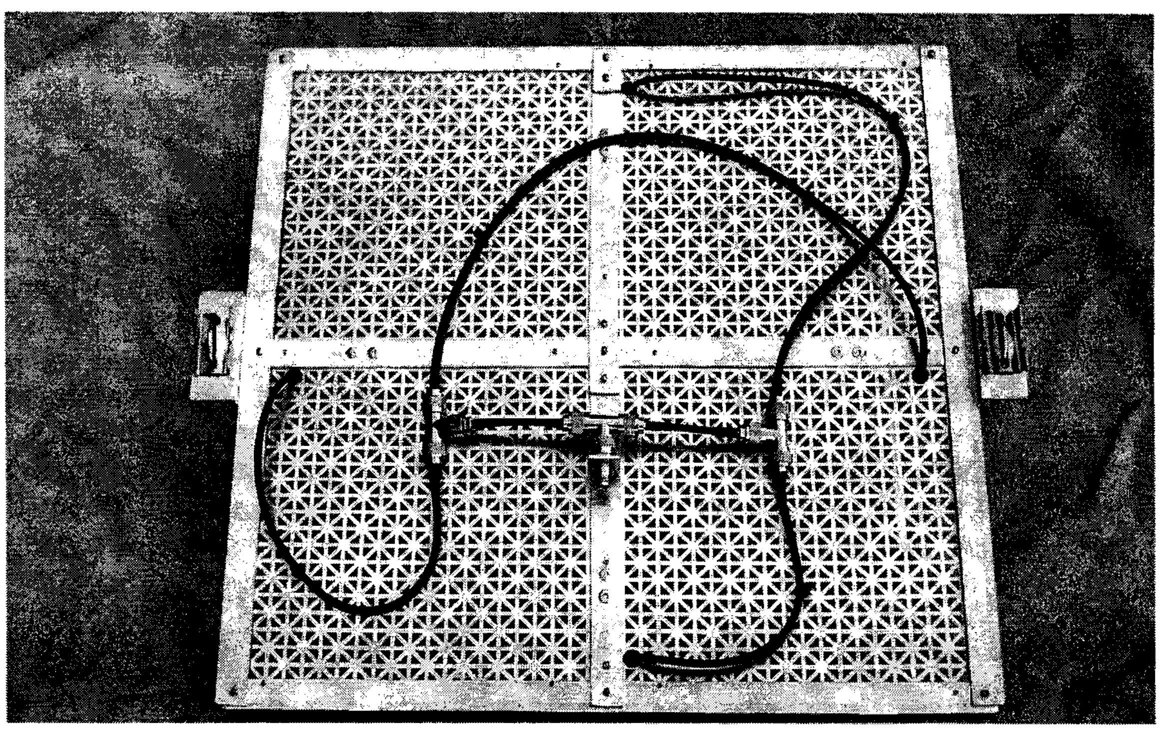

Figure 13. Back of antenna showing feed cables and power-splitter.

The front view of the completed Panel-Reflector Antenna is shown in Figure 14. Note that mounting brackets, made from 1-1/2 inch x 1-1/2 inch x 1/8 inch angle stock, have been riveted to the sides of the reflector frame and fitted with U-bolts.

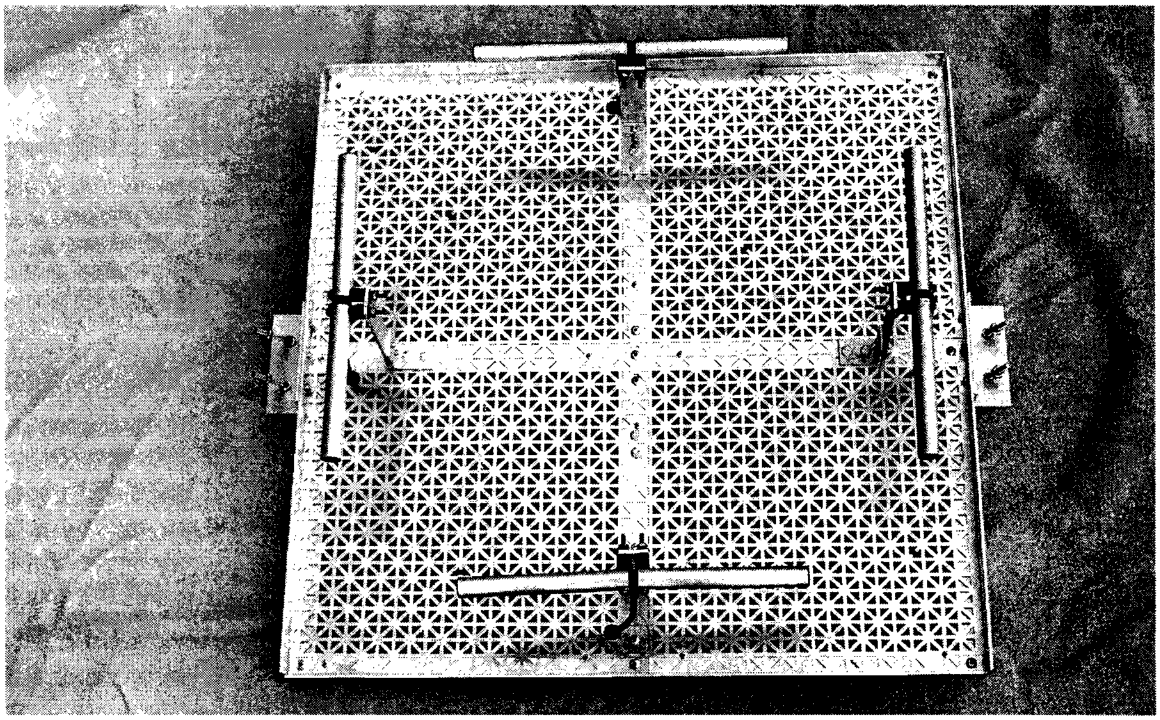

Figure 14. Front view of completed Panel-Reflector Antenna

Performance

The Panel-Reflector Antenna was designed to provide a reliable, single-sideband (SSB) uplink to OSCAR-40 under all but the most severe conditions using a typical satellite transceiver with no external amplifier (*i.e. "barefoot"*)

Using the "ao40eval.xls" spreadsheet developed by Gene Markus, W3PM, Table 3 was created to show the required power at the antenna input under a variety of operating conditions as well as the resulting EIRPc. The power level shown provides a downlink signal that is at the recommended level of 10 dB below the beacon. The table shows that under good conditions, a power input of less than 20 watts (EIRPc < 200 watts) provides the required uplink signal level.

At the maximum satellite range (~65Km) and at high squint angles, a power input in the range of 23 to 44 watts will be required. This is well within the 50 to 75 watts available from the current generation of satellite transceivers. Of course, if there are excessive losses in the feed lines up to the antenna, these would need to be accounted for in the total power required. In general, this table shows that under most conditions, even with several dB loss in the feed line, the Panel-Reflector Antenna should provide a reliable SSB uplink signal without additional power amplification.

AO-40 Range (Km)	Squint Angle (degrees)	Input Power (watts)	EIRPc (watts)
50,000	0	11	127
60,000	5	17	196
60,000	10	20	231
65,000	10	23	265
65,000	20	44	508

Table 3. Required Antenna Input Power at various satellite ranges and squint angles

Design Verification Testing

A variety of tests were performed on the antenna to verify the design.

First, the four-way power splitter was checked by putting a 50 ohm load on each output port and checking the input SWR. This measured about 1.2:1 across 420-440 MHz on an MFJ-219 UHF SWR Analyzer. Note that since this is not a precision instrument the exact value of SWR may differ somewhat from the measurement. However, the fact that the SWR was low and constant across the 70cm band was taken as an indication that the power splitter was working correctly.

Second, the return loss of the assembled antenna was tested by running 50 watts of forward power into the antenna and measuring the reflected power using a Bird Model 43 Wattmeter with a 50D sensor. With the forward power set to indicate full scale, the reflected measurement just barely moved the meter indicating less than one watt reflected power and a return loss of better than 20 dB. While the exact value of return loss is hard to discern with such a low meter reading, a reading such as this indicates that a typical transmitter would have no difficulty operating into this antenna. In point of fact, the several tests were run using the popular Yaesu FT-847 radio and it operated normally throughout this testing.

Third, the antenna circularity was checked. The author did not attempt to directly measure the antenna circularity but a variety of on-the-air tests were performed. In one test, the antenna circularity was checked by listening to the carrier of a distant FM repeater using a transceiver set to SSB mode. The antenna was rotated through 0, 45, and 90 degrees while both observing the S-meter and listening to the received signal. It was not possible to discern any difference in the received signal strength as the angle was changed. Another check was made by keying up a weak (S-3,) distant, FM repeater using just 0.5 watts of power into the antenna. As before, the antenna was rotated through 0, 45, and 90 degrees to see if any differences could be found in either the ability to trigger the repeater or in the received signal strength. There were no cases where any differences could be found indicating a reasonably good circularity.

As an additional circularity test, the polarization was briefly changed to left-hand circular by reversing the leads to one pair of dipole radiators. This test resulted in a dramatic demonstration that OSCAR-40 is right-hand polarized as it was difficult to hear the uplink signal in this configuration.

Finally, the antenna gain was checked. The antenna gain was also not directly measured but was verified through on-the-air tests using OSCAR-40. The input power at the antenna was measured using a Bird Model 43 Wattmeter and a 50D sensor. The received signal was subjectively set to 10 dB below the beacon and the input power noted. The power input corresponded well with the expected receive levels. In one test, performed while OSCAR-40 was lightly occupied, with the satellite range at over 60,000 Km and a squint angle of around 18 degrees, the input power was run up to 50 watts with the result that LEILA was immediately triggered. This corresponded well with the expected point at which LEILA would just be triggered so this and the other tests seemed to indicate that the antenna gain was as expected.

Field Day 2003

The ultimate uplink antenna test was performed by using the Panel-Reflector Antenna for the ARRL Field Day exercise in June of 2003. Due to the contest nature of this event, the unusually high number of stations operating, and the corresponding OSCAR-40 receiver's automatic gain control (AGC) action, Field Day presents an unusually difficult set of conditions for generating a reliable uplink signal.

The author set up a "bonus" OSCAR-40 satellite station for the North Shore Radio Association (NS1RA.) The intent of the station was to generate exposure to satellite operating and to give other club members a chance to try out OSCAR-40. None of the other participants had ever operated through OSCAR-40.

The station equipment was very basic. A Yaesu FT-847 transceiver was used and no external power amplifiers were employed. The maximum output power used was 50 watts as measured on a Bird Wattmeter. To complement the Panel-Reflector transmitting antenna, a pyramidal-horn, receiving antenna was made from some cardboard boxes and aluminum-foil[1], as shown in Figure 15. As can be seen in the photo, the Panel-Reflector Antenna, on the right, easily fits on a small folding chair.

A laptop computer was set-up to provide satellite tracking information using *Instant*Track[2]. The antennas were manually pointed using a compass and a protractor. *Instant*Tune[3] was used to auto-tune the FT-847 to ease the Doppler-tuning effort and a loudspeaker was connected in parallel with the operators headphones so that the crowd of observers could listen-in on the action.

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[1] "Work OSCAR-40 with Cardboard Box Antennas!" by Anthony Monteiro, AA2TX. QST Magazine, March 2003.

[2] *Instant*Track is available from AMSAT, see www.amsat.org

[3] *Instant*Tune is available for download at www.amsat.org

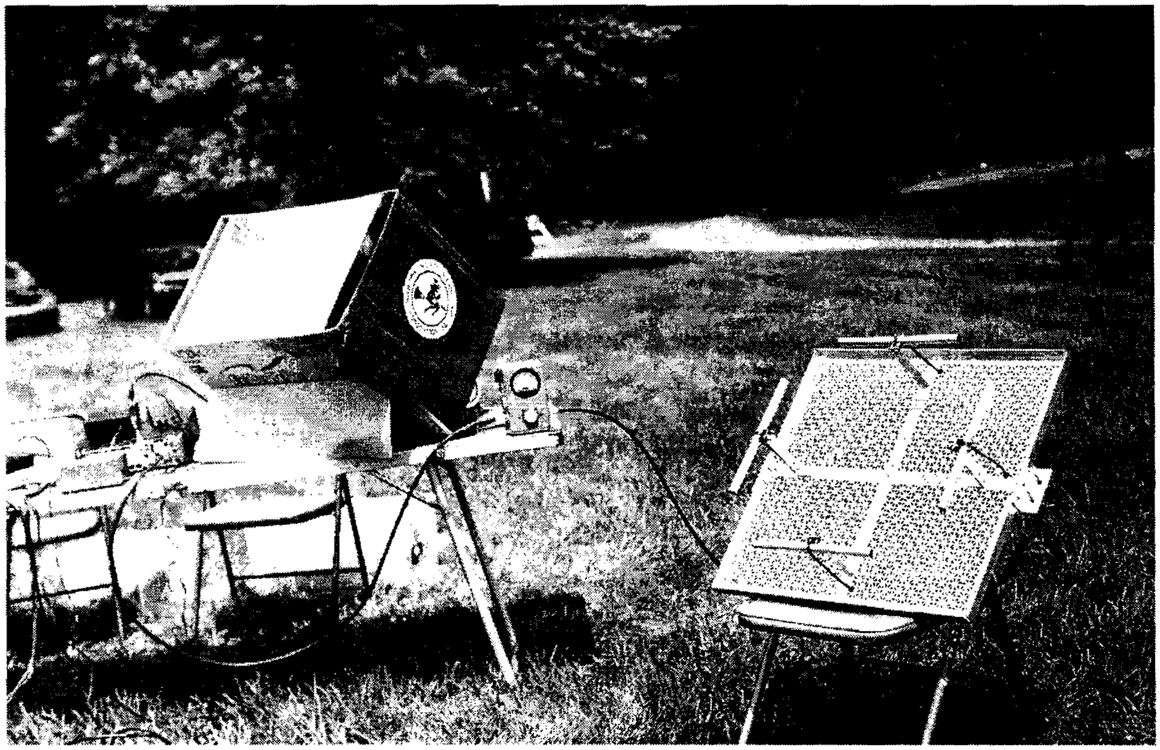

Figure 15. The NS1RA Field Day 2003 Satellite Station using the Panel-Reflector Antenna and a cardboard Pyramidal Horn.

The author set up the station and made the first few contacts to verify proper operation and to assure the 100 bonus points. The station was then made available to anyone who wanted to try out OSCAR-40. In spite of the lack of satellite experience among club members, the effort yielded about two-dozen contacts in a few hours of operation. Many operators and observers seemed excited just to hear OSCAR-40 for the first time. One of participants, who had just taken a break from operating an HF station, expressed amazement at how clearly he could hear the satellite and how easy it seemed to make contacts compared to how difficult things were on HF. Although this was one of the most challenging situations for operating on OSCAR-40, we had no difficulty generating a reliable uplink signal with the FT-847 and the Panel-Reflector Antenna.

Summary

This article has described a Panel-Reflector Antenna that was designed for accessing the OSCAR-40 satellite on its UHF uplink. This antenna's small size and ability to be directly mounted to a metal cross-boom provide a convenient alternative to the conventional cross-polarized Yagi array. In spite of its small size, this antenna provides a reliable uplink to OSCAR-40, even under difficult conditions, with less than 50 watts of transmitter power.

A Proposed Microsat Open Experimental Platform for Amateur Space Communications Research

Timothy J. Salo, ABØDO
salo@saloits.com

Abstract. An on-orbit, open experimental platform (OEP) that includes a flight computer, a real-time operating system, and other supporting systems will enable new, innovative, space communications, spacecraft software, and flight computer research and experimentation. Access to the proposed OEP will be made available to a variety of investigators to support a range of experiments. An experiments board will identify the proposed projects with the greatest scientific merit and relevance to amateur satellites and amateur radio. The OEP could provide great benefits by stimulating radio amateurs and others to undertake technical investigations that will advance amateur satellites and amateur radio. Most importantly, it will inspire and develop the next generation of scientists, engineers and satellite designers.

Introduction

An on-orbit, open, experimental platform that permits, supports and motivates space communications, spacecraft software, and flight computer research and experimentation by radio amateurs and others will provide a tremendous boost to amateur satellites and amateur radio. For brevity, this concept is referred to here as the Space Communications Research (SCR) Open Experimental Platform (OEP), or SCR-OEP. This proposed project has several objectives:

- Inspire and enable amateurs to "conduct technical investigations relevant to the development of radio technique"[8*] by providing an accessible, on-orbit, experimental platform;
- Foster the creation and maturation of technologies that will facilitate the development of future amateur satellites and amateur satellite missions;
- Expand the pool of radio amateurs capable of and motivated to support amateur satellite missions, whether as software developers, as computer designers, as part of a distributed, collaborative ground station, as financial contributors, or in other beneficial roles;
- Use scientifically meritorious space communications, spacecraft software, or flight computer research to subsidize the development and launch of amateur satellites.

The SCR-OEP Vision

The proposed SCR-OEP project will make a dedicated, on-orbit, flight computer available to a variety of investigators for space communications, spacecraft software, flight computers and similar research and experimentation. Access to the SCR-OEP will be granted based on factors such as the scientific merit and relevance to amateur radio and amateur satellites of the proposed work. The SCR-OEP will use amateur spectrum and all operations will conform to international and national amateur radio and amateur satellite regulations.

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[*] A restatement by the International Amateur Radio Union (IARU) of paragraphs 1.56 and 1.57 of the International Telecommunications Union (ITU) Radio Regulations[9].

Access to the SCR-OEP could be administered by an Experiments Board, which will prioritize proposed projects. Meritorious projects could be granted dedicated use of the SCR-OEP, as well as shared up-link and down-link bandwidth, for a period of time. A selected investigator will upload his or her software into the SCR-OEP and conduct experimentation that will typically involve communication with amateur radio ground stations. The investigator may use his own ground station, or may use a distributed ground station coordinated by the SCR-OEP project. Because the SCR-OEP will be an independent, largely isolated flight computer, experimental software and hardware cannot put the satellite or its mission at risk. As a result, it will support experimental software that may have a greater risk of failure than can be tolerated on a primary flight computer.

Potentially, the SCR-OEP project could subsidize the development and launch of amateur satellites. For example, the development of some or all of the SCR-OEP hardware and software might be funded as part of a Federally funded research project. Furthermore, this research project could potentially help qualify an amateur satellite for a no-cost launch as a government-sponsored payload.

The SCR-OEP project will include:

- A hardware platform, a dedicated, non-mission-critical, flight computer onboard an amateur satellite
- A software platform, based on an inexpensive, readily available, real-time operating system
- Experiments, performed using the SCR-OEP
- Investigators, who will design and conduct these experiments
- An Experiments Board, which will prioritize proposed experiments
- A distributed ground station, a system of coordinated amateur radio ground stations that will support SCR-OEP experiments
- The Project Team, responsible for funding, designing, developing, supporting, and maintaining the SCR-OEP
- External support, potentially justified, in part, by the scientific merit and relevance of some of the proposed research

SCR-OEP Hardware Platform

The SCR-OEP hardware platform will be a dedicated flight computer onboard an amateur satellite. The primary mission of this computer will be to support SCR-OEP experiments. As such, it will be connected to the spacecraft's communications receivers and sensors, permitting experiments to access these data. Likewise, the SCR-OEP flight computer will be able to access the spacecraft's transmitters and actuators, although it may be prudent to enable the primary flight computer to selectively inhibit this access. In a similar fashion, the primary flight computer should be able to reset the SCR-OEP flight computer. Figure 1 below outlines a possible configuration for an SCR-OEP flight computer.

The objective of this configuration is to enable the SCR-OEP to support a broad array of experiments, while simultaneously protecting the spacecraft from the effects of unproven software. Additionally, this configuration will provide an ideal environment in which to test new or experimental flight software by actually using it to control the operation of the satellite. As a precaution, the primary flight computer could monitor the behavior of experimental flight software running on the SCR-OEP and quickly reacquire control of the spacecraft in the event of undesirable results. Furthermore, the SCR-OEP hardware could provide a backup, in the event of the failure of the primary flight computer.

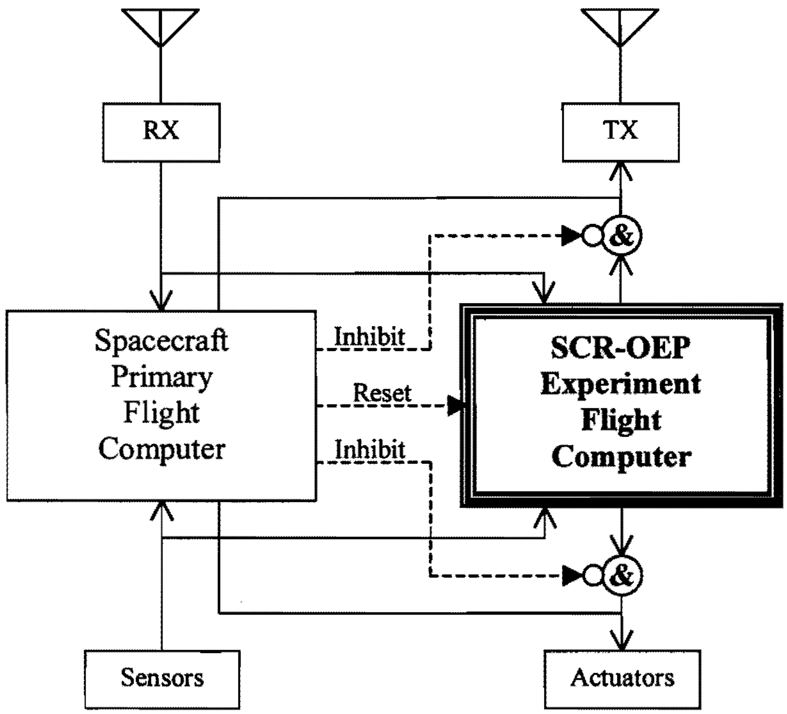

Figure 1. SCR-OEP Hardware Platform Configuration

Many different flight computers could potentially host the SCR-OEP. Of course, a 32-bit, multi-megabyte computer would support a much greater variety of experiments than would an 8-bit, 64-KB machine. A flash memory file system would extend the capabilities of the SCR-OEP by providing permanent storage for software and data, avoiding the repeated upload software or potential loss of experimental data if down-link bandwidth isn't immediately available. A hardware modem would ensure that the processor could communicate reliably after a reset, but digital signal processors (DSPs) would permit experimentation with advanced encoding techniques. The SCR-OEP could use a proven system, such as the SpaceQuest IFC-1000 Integrated Flight Computer[22] being used by the AMSAT OSCAR-E project[5,6,7]. An experimental flight computer, however, would be much more in keeping with the spirit of the SCR-OEP mission. For instance, the SCR-OEP could provide an opportunity for a new flight computer, such as the IHU-3 being considered for the AMSAT-DL P3E project[4], to gain on-orbit experience prior to being flown as a mission-critical component.

SCR-OEP Software Platform

The SCR-OEP will include an operating system and software library, which will permit investigators to focus on developing their own experiments, rather than on creating basic systems software. An embedded, real-time operating system (OS) is required. An embedded operating system is designed to operate in resource-constrained environments and is often tailored to the specific needs of its host system, while a real-time operating system ensures that interrupts and other time-critical tasks are processed when required. The choice of operating system should maximize the accessibility of the SCR-OEP by potential investigators – an inexpensive, readily available, operating system is needed. This requirement all but demands an open-source operating system, and the need for an embedded, real-time OS (RTOS) further restricts the potential candidates.

The selected RTOS should facilitate the development of experimental software. Investigators, particularly those with limited budgets, should be able to easily run the SCR-OEP RTOS on inexpensive or readily available development systems. Ideally, the RTOS will support Intel x86 processors, as well as the SCR-OEP architecture. This will permit an investigator to develop much of his or her software on a commodity PC, and minimize, perhaps eliminate, the need for access to flight hardware prior to using the on-orbit SCR-OEP. In a similar fashion, the OS should offer an effective software development environment, including compilers for the development system, cross-compilers for the SCR-OEP hardware, good debugging facilities, and other traditional software development tools.

The SCR-OEP systems software will include, beyond an open-source RTOS, a software library that will reduce the effort required to develop software for the SCR-OEP. This library should include:

- Drivers for the peripherals attached to the SCR-OEP flight computer, and stubs or emulators that can substitute for these drivers on a development system
- A flash memory file system
- File transfer software that will enable the up-loading and down-loading of software
- Support for space communications protocols, including the Internet protocols, perhaps the Consultative Committee for Space Data Systems (CCSDS) protocols[2] or the Space Communications Protocols Standards (SCPS) protocols[16], and perhaps even the amateur radio AX.25 protocol.

The operating system selected, enhanced, and used by the SCR-OEP project will provide a modern, mature, space-proven operating system for future amateur satellites. But, the use of this standard SCR-OEP operating system will not be mandatory. Some investigators may wish to use enhanced versions of the SCR-OEP operating system or even experiment with alternative system software. The SCR-OEP will provide a unique, on-orbit host for these projects.

RTEMS

RTEMS (Real-Time Executive for Multiprocessor Systems)[18], an open-source, real-time, operating system, is a strong candidate for the SCR-OEP. It was developed by On-Line Applications Research Corporation (OAR)[19] for the U.S. Army Missile Command in the late 1980s and early 1990s. Since that time, the RTEMS developer community has continued to add features and has ported the OS to numerous architectures and systems. Developers are generally using the freely available GNU toolset on either UNIX or Microsoft Windows. RTEMS includes:

- A subset of the POSIX 1003.1b (i.e., UNIX-like) applications program interface (API) including threads
- Multitasking support
- Powerful scheduling capabilities
- A port of the FreeBSD TCP/IP stack, including IP, UDP, TCP, ICMP, and DHCP
- Support for several file systems, including an in-memory file system, FAT32, FAT16 and FAT12

NASA Goddard Space Flight Center (GSFC) has ported RTEMS to the Mongoose V flight computer[13] with the intent that it will fly on NASA's Science Technology 5 (ST5) mission[17].

SCR-OEP Experiments

The SCR-OEP is ideally suited to hosting experiments in space communications, spacecraft software, flight computers, and other "technical investigations relevant to the development of radio technique". While a few illustrative examples are included below, investigators will undoubtedly develop a much longer, more creative list when offered a realistic chance to run their software on an Earth-orbiting satellite. Of course, because the SCR-OEP will use amateur radio spectrum, the experiments it hosts must conform to the international and national regulations governing amateur radio and amateur satellites, as is discussed below.

Space Communications. Amateurs have a long history of experimenting with space communications technologies, dating from the first artificial satellite. Examples of research that could be supported by the SCR-OEP include:

- **The use of the Internet Protocols in space communications.** NASA is exploring the use of the Internet Protocols to communicate with near-Earth spacecraft and to enable researchers to access on-orbit experimental data from Internet-attached computers[15]. Opportunities for hand-on experimentation with the Internet protocols in space, such as will be provided by the SCR-OEP, will undoubtedly attract additional members of the Internet generation to amateur satellites and amateur radio.
- **Integration of satellites with digital public safety communications.** Public safety agencies are deploying a new generation of digital radios that use the Project 25 protocols[1]. These protocols specify a 9,600 bps digital channel that includes a 4,800 bps digital voice data stream. SCR-OEP experiments that examine the use of satellite communications to interconnect clusters of digital public safety radios would combine traditional areas of amateur radio activity with cutting-edge satellite and digital voice technologies.
- **Foward Error Correction (FEC) Telemetry Protocols.** FEC techniques developed by Phil Karn have dramatically improved the reception of AO-40 telemetry[10,11]. Extensions of this work could further improve communications with amateur satellites.

Spacecraft Software. The extensive, on-orbit experience with RTEMS gained by the SCR-OEP project will provide future missions a space-qualified, open-source RTOS. Some SCR-OEP experiments might examine, based on real-world experience, the strengths and limitations of RTEMS as a spacecraft operating system.

Flight Computers. Spacecraft designers, by necessity, are very selective in the risks that they accept when developing a spacecraft or mission. Relying upon an unproven flight computer is a risk that most designers are unlikely to accept unnecessarily. The SCR-OEP, however, will offer a rare opportunity for innovative, and potentially risky, flight computer designs to gain flight experience.

SCR-OEP Investigators

Three classes of investigators will use the SCR-OEP for experiments.

- Outside Investigators, who will propose experiments and may be granted access to the SCR-OEP for a period of time by the Experiments Board
- The SCR-OEP Project Team, which will support the SCR-OEP and will undertake investigations that are intended, in part, to attract external support for the SCR-OEP project
- The sponsoring agency, which may be granted access to the SCR-OEP in return for support

The SCR-OEP will be an *open* experimental platform; it will be available to potentially any investigator with a meritorious proposal. Outside investigators do not need to be members of the Project Team or otherwise associated with the project. Presumably, most of the investigators will be radio amateurs. Some may be pursuing a personal interest in space technologies, some may be students, and conceivably some may be researchers in their professional lives.

SCR-OEP Experiments Board

An Experiments Board will administer the portion of the SCR-OEP time available to outside investigators. Potential investigators will submit proposals describing their desired use of the SCR-OEP. The Board will prioritize the proposed work, based on scientific merit, relevance to amateur satellites and amateur radio, and perhaps other factors. It may also provide guidance on the use of the amateur spectrum and perhaps provide coordination between proposed experiments. Ideally, the Board will include expertise in amateur satellites, small satellites, amateur radio and relevant technologies and research.

The Project Team and the sponsoring agency will be responsible for allocating the other two blocks of SCR-OEP time. The allocation of time between outside investigators, the Project Team and potentially a sponsoring agency is a topic for further study.

SCR-OEP Distributed Ground Station

A virtual ground station, composed of a system of coordinated, geographically distributed amateur radio ground stations, will support SCR-OEP experiments. This system will use the Internet to interconnect participating ground stations and to provide service to investigators. The distributed ground station will enhance access to the SCR-OEP, by permitting investigators without ground stations to conduct experiments on the SCR-OEP. It will also ensure that the

SCR-OEP is used more productively than if every investigator is responsible for communicating directly with the satellite. For example, the distributed ground station will minimize the time required to upload new software to the SCR-OEP by handing off upload responsibility between ground stations as the satellite orbits.

SCR-OEP Project Team

The Project Team will be responsible for the design, development and operation of the SCR-OEP. They will also assume much of the burden of obtaining funds for the project. The team will include a researcher whose mission is to obtain Federal support to subsidize the project. Like any satellite project, the SCR-OEP will require the talent and expertise of a large team. Other responsibilities of the Team will include:

- Support outside investigators in their use of the SCR-OEP hardware and software platforms by providing documentation, consultation and mentoring
- Coordinate the creation of the distributed ground station
- Sponsor Investigators' Meetings, where investigators, potential investigators, and others can share their experiences and learn from others
- Publicize the plans, status, successes and experiences of the SCR-OEP project to the amateur satellite community, radio amateurs, potential outside investigators, potential sponsors, and the general public

Opportunities for External Support

The development and launch of amateur satellites are *very* expensive undertakings. Finding new ways to support these activities is critical to the continued success, perhaps even existence, of our hobby. The SCR-OEP will provide an opportunity to further explore two long-standing, although perhaps not widely used, sources of external support for amateur satellites: Federally funded research projects and government-sponsored launch opportunities.

Federally Funded Research

The SCR-OEP on-orbit experimental platform will be fully capable of hosting "real science", scientifically meritorious research and experiments of the quality expected of professional researchers or Federally funded research projects. The following examples include research projects that could have used the SCR-OEP, if it had been available, or topics from recent Federal research solicitations that could easily benefit from the SCR-OEP.

- **Space Communications Research.** Some of NASA GSFC's IP-in-space experiments were conducted on a flight computer onboard UoSAT-12, known in amateur circles as UO-36[20,21]. These experiments could easily have been performed on the SCR-OEP, if it had been available. The latest NASA Small Business Innovative Research (SBIR) solicitation includes a request to create "Internet-based protocol modules and architectures that will provide seamless network continuity between terrestrial and aerospace-based platforms and environments"[12]. Not surprisingly, this topic is similar in concept to the SCR-OEP distributed ground station.

- **Spacecraft Software Research.** NASA has explored the use of open source, real-time operating systems, including the FlightLinux project, which examined the potential use of RTLinux, a real-time variant of Linux, as a flight operating system[14]. The SCR-OEP will provide an opportunity to gain flight experience with an open-source RTOS, perhaps RTEMS.

- **Education and Outreach.** NASA's mission is, in part, "to inspire the next generation of explorers ... as only NASA can". The Amateur Radio on the International Space Station (ARISS) project has been highly successful in inspiring countless school children – and apparently not a few adult radio amateurs as well. Earlier this year, the Air Force's top two space officials told a Senate subcommittee that the development of a "space cadre" was one of their top priorities[3]. It is hard to imagine anything more inspiring or educational for a student than to conceive, propose and conduct an experiment on an on-orbit flight computer hosted by an Earth-orbiting satellite. The SCR-OEP project would be an ideal candidate for providing these opportunities.

Conceivably, portions of the SCR-OEP project, such as the development of the flight software, the flight computer or the distributed ground station, have enough scientific merit to justify the award of Federal research funds. Of course, the only way to know for sure is to offer Federal agencies an opportunity to fund this work by submitting research proposals.

Government-Sponsored Launch Opportunities

The Department of Defense (DoD) Space Test Program (STP)[24] "provides spaceflight for qualified DOD sponsored experiments at no charge to the experimenter, via the DOD Space Experiments Review Board" (SERB)[23]. The SERB evaluates the "military relevance and technical merit" of the proposed experiments. The SERB Web site states that "DOD experiments normally originate in the Service (Army, Air Force, Navy, NASA) laboratories or research institutions (colleges, universities, think tanks, etc.) but are in no way limited to these institutions." Clearly, competition for free space launches is very intense. Nonetheless, the Naval Postgraduate School and the Air Force Academy have successfully used this process to launch their student satellites[25]. Certainly, the hurdles are very high and the competition is very fierce, but the potential rewards are so great that the amateur satellite community would be remiss if it didn't aggressively pursue this opportunity

SCR-OEP and Amateur Spectrum

The SCR-OEP will use amateur satellite spectrum and its operation will be consistent with the international and national regulations governing amateur radio and amateur satellites. Radio amateurs will be the primary users and beneficiaries of the SCR-OEP project. Many of the investigators will be licensed radio amateurs, as will be all of the satellite ground station operators. The SCR-OEP experimental platform is expected to be hosted by and help support an amateur satellite and the technologies developed by this project are likely to benefit future amateur satellites.

International Amateur Radio Union (IARU)

The International Amateur Radio Union (IARU) coordinates the use of amateur radio spectrum by amateur satellites. Their "Amateur Radio Satellites: Information for Developers of Satellites Planned to use Frequency Bands Allocated to the Amateur-Satellite Service" contains a wealth of useful information[8]. It contains the IARU's highly relevant interpretation of the phrase "technical investigations ... [of] radio technique" in the International Telecommunications Union (ITU) Radio Regulations[9]:

> *Development of "radio technique" means having a reasonable possibility of application to the development of radio communication systems.*
>
> *Examples of technical investigations relevant to development of radio technique include, but are not limited to:*
>
> - *operational analysis of protocols for digital voice and data communication ...*
> - *development of spacecraft computers, memory, operating systems, programs, and related items ...*

Clearly, the potential topics of SCR-OEP experiments listed above, space communications, spacecraft software, and flight computers, fall within the IARU's guidelines. Of course, proposed experiments that fall outside these areas should be evaluated against the IARU guidelines and ITU and national regulations.

The IARU also states that experiments using amateur spectrum should be open to all amateurs.

> *All telecommunication facilities, except space telecommand, operating in amateur-satellite service allocations should be open for use by amateur radio operators worldwide. All experiments utilising frequencies allocated to the amateur-satellite service should be freely available for use by radio amateurs worldwide and for reception by students and educators.*

The SCR-OEP gives new meaning to the term "open" by permitting investigators unaffiliated with the project to execute their own software on an on-orbit flight computer hosted by an amateur satellite.

The preliminary, informal, and undoubtedly incomplete analysis of the SCR-OEP's use of amateur spectrum presented here should be supplemented by a more detailed examination by experts with experience in this area.

Potential Benefits for Amateur Satellites

Attracting and inspiring the next generation, developing new amateur satellite technologies, and expanding sources of support for amateur satellites are just a few of the benefits that will result from a successful SCR-OEP project.

Attract, Inspire, and Develop the Next Generation

The SCR-OEP project will attract, inspire and develop the next generation of scientists and engineers, radio amateurs, and satellite designers, builders, and operators. It will enable future satellite designers and builders to gain hands-on experience developing software for amateur satellites, an opportunity previously available only to a small group of highly qualified individuals. This project will also enhance communications between the amateur satellite community and those building student and academic satellites.

Develop New Satellite Technologies

The SCR-OEP project will develop new technologies applicable to amateur satellites. It will develop and mature a modern RTOS for amateur and small satellites. This RTOS offers the promise of a de facto standard for small satellites, enabling flight software to more easily be reused between satellite projects and perhaps even terrestrial amateur radio projects. Direct Internet access to orbiting amateur satellites will offer new ways to publicize the accomplishments of amateur satellites.

Expand Sources of Support for Amateur Satellites

Perhaps the biggest contribution of this project will be to develop new sources of support for amateur satellites, specifically Federal research funds and government-sponsored launches.

Making Proposed SCR-OEP Fly

The proposed SCR-OEP concept is currently just that, a concept. Translating this concept in to a real, on-orbit, experimental platform is a major undertaking. The following small, first steps will provide a solid foundation for a highly successful SCR-OEP project.

- Review and discussion within the amateur satellite and amateur radio communities will help refine and strengthen the SCR-OEP concept.
- Evaluation, feedback, and particularly formal support by the AMSAT Board of Directors will considerably improve the likelihood of its success.
- Creation of one or more research proposals will potentially help obtain funding and even a government-sponsored launch.
- Further investigation of the use of amateur spectrum by licensed radio amateurs supported indirectly by Federal funds or government-sponsored launches will help ensure that this project operates consistent with international and national radio regulations.

The SCR-OEP concept proposed here, combined with a tremendous amount of hard work and not a small amount of luck, could offer a means to attract new participants to the amateur satellite community and support the construction and launch of additional amateur satellites.

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K BAND ON AO-40

Mike Seguin, N1JEZ
n1jez@amsat.org
2003 AMSAT Symposium
October 17th & 18th, 2003
Toronto, Ontario Canada

INTRODUCTION

One of the most significant challenges for satellite operators is K Band reception from Oscar 40. The center downlink frequency is 24.048035 GHz. The transponder is 50 kHz wide. What follows are my experiences as I went from conception to full operation on Oscar 40's highest operating downlink frequency. (We're all still waiting for laser!)

I will purposely include references to terrestrial 24 GHz microwave operation. One should consider building for this frequency as well. Not a lot of changes are necessary and 24 GHz is becoming more popular among the microwave community.

IN THE BEGINNING

I first became interested in K Band during the 2001 AMSAT Symposium in Georgia. At that time, I was just beginning my microwave experimentation using 10 GHz equipment. It all seemed like an immense uphill battle to first understand the equipment requirements and then to secure the necessary pieces to complete a working system. Unlike the relative simplicity of Mode S, K Band seemed very complex. I suppose the lack of "Elmers" made the task seem huge.

I came away from the "K Band Working Breakfast" presentation with lots of ideas. Over the next few weeks, I re-read the material and slowly began to formulate a plan. My microwave experience, using 10 GHz narrow band gear, was beginning to help shed light on the various obstacles to overcome.

The Oscar 40 K Band transponder transmits with only 800 mW into a 23 dBi linear horn. This was going to be a true weak signal mode.

THE EQUIPMENT

Over time, I developed a list of equipment that I would have to acquire to attempt to hear AO-40 on K Band. This included:

1. Dish and Feed
2. Receive Preamp
3. Waveguide Filter
4. Mixer
5. Local Oscillator (LO)
6. IF
7. Mount and Pointing System

Early on, I decided that I wanted to be able to operate both satellite and terrestrial on 24 GHz. The frequencies are different. Satellite is receive only on 24.048 GHz while terrestrial is on 24.192 GHz. This added more parts and pieces to my list of equipment. I now was in need of a second LO, waveguide filter, waveguide switch and power amp.

Please bear in mind that I was designing a high-end portable system and I was looking for very good performance. Two factors led to this decision. First, because of the 'incident' with AO-40, the minimum requirements for successful reception had been elevated somewhat. Most notably, we're looking at an additional 10,000 km of path loss. Range for me is typically 60,000 km+. Also, for terrestrial operation, I wanted more power than just a bare mixer could provide. This is also a totally portable system, which creates additional requirements that I'll discuss further.

One of the biggest decisions that I made was whether to try and build or buy most of the assemblies. My decision was to buy. The rational was really quite simple. Without at least some test gear at these frequencies, I would really have no way to test or optimize anything I built. I was slowly acquiring test gear for 10 GHz and knew I could extend that to 24 GHz in time, but for now I wanted to go with a known quantity.

At this frequency, we try and use waveguide when ever possible to minimize losses. The standard for 24 GHz is WR-42. You will see it mentioned numerous times in the text.

All of this led to the decisions I made on equipment:

1. Dish and Feed	Procom[1] – 0.5 meter – Linear Feed
2. Receive Preamp	DB6NT – Kuhne Electronic GmbH[2] < 2 dB NF
3. Waveguide Filters (2)	MikroMechanik[3] & SSB Electronic USA[4]
4. Mixer	DB6NT Subharmonic
5. LO – 2 units	DB6NT 11.880 GHz & 11.952 GHz
6. IF – 2 units	FT-290 & FT-790

The Dish and Feed were chosen because of previous experience with Procom at 10 GHz. While not the best performers, efficiency wise, they are a known quantity. The size of dish was a tradeoff between gain, beamwidth and portability. The decision to go with a linear feed was based primarily on terrestrial operation where we use horizontal polarization for narrow band operation. I was aware that AO-40 has a linear horn antenna and is spinning. I knew using a linear feed would cause deep fades due to polarity mismatch. In fact, I was told that I wouldn't be able to make a contact because of the QSB. This really surprised me! I looked at the spin rate and determined that it shouldn't be a huge problem. Yes, there would be fades, but it wouldn't be insurmountable. I predicted that I would see approximately 7 to 8 seconds of good signal, followed by 3 to 4 seconds of fade. I knew I could trade callsigns/grids/reports in that time. However, carrying on an extended QSO would be easier with circular polarization to minimize the fades.

A receive preamp was an absolute necessity. I chose a DB6NT preamp. They are state of the art. I chose a waveguide (WR-42) input and SMA output. Waveguide input was chosen to be able to attach directly to the feed on the dish. This was to minimize losses to maintain a good receive noise figure. SMA was used on the output to couple to an amplifier I use for terrestrial operation.

I needed two WR-42 waveguide filters; one for each segment of the band I planned to operate. Waveguide filters were chosen because of tight filter requirements due to the use of a 2M and 432 IF. It turned out that SSB Electronic had a terrestrial waveguide filter that was less expensive than MikroMechanik, so I ended up with one from each company.

The mixer was a subharmonic design by DB6NT. The input/output was WR-42 waveguide. SMA connectors are used for both LO input and IF.

The Local Oscillators (LO) are DB6NT. For AO-40, I chose 11.952 GHz. This results in a low side injected 2M IF frequency. The LO frequency is doubled in the mixer.

(11.952 GHz x 2) + 144 MHz = 24.048 GHz.

For terrestrial operation, I chose 11.880 GHz. This results in a low side injected 432 MHz IF frequency. The LO frequency is doubled in the mixer.

(11.880 GHz x 2) + 432 MHz = 24.192 GHz.

11.880 GHz turned out to be a good choice because it can also be used at 47.088 GHz with a high side injected 432 MHz IF frequency. This LO frequency is quadrupled in a DB6NT mixer I have for 47 GHz operation.

(11.880 GHz x 4) - 432 MHz = 47.088 GHz.

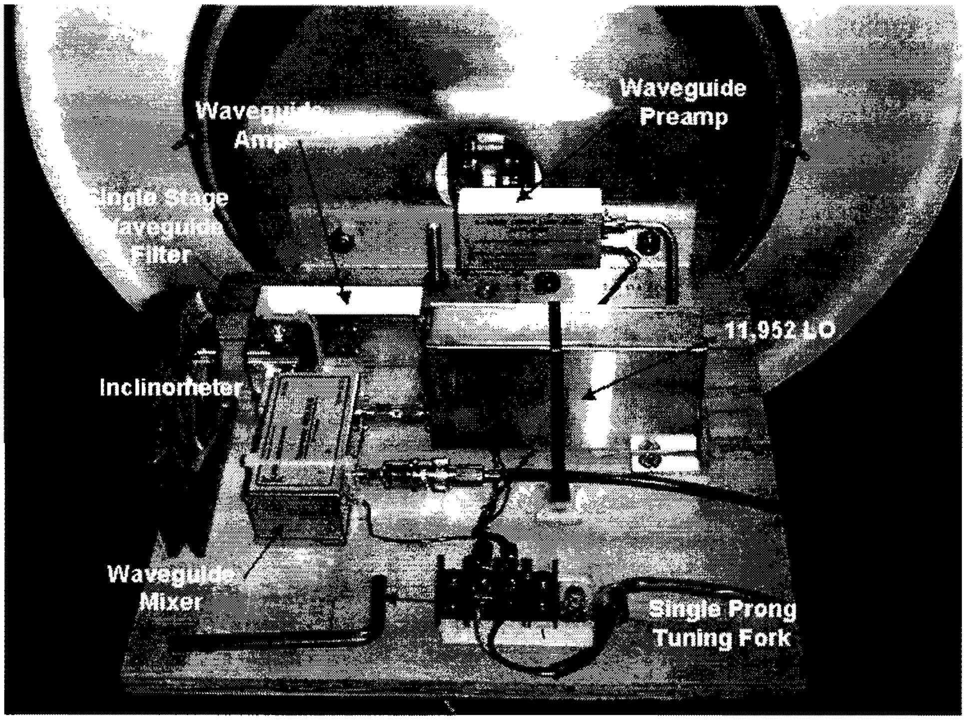
The IF rigs chosen were the Yaesu FT-290/790 portable series. I had the FT-290 2M IF and picked up the FT-790 432 IF surplus. The Yaesu FT-817 was not an option at the time. It would have been a good choice as well.

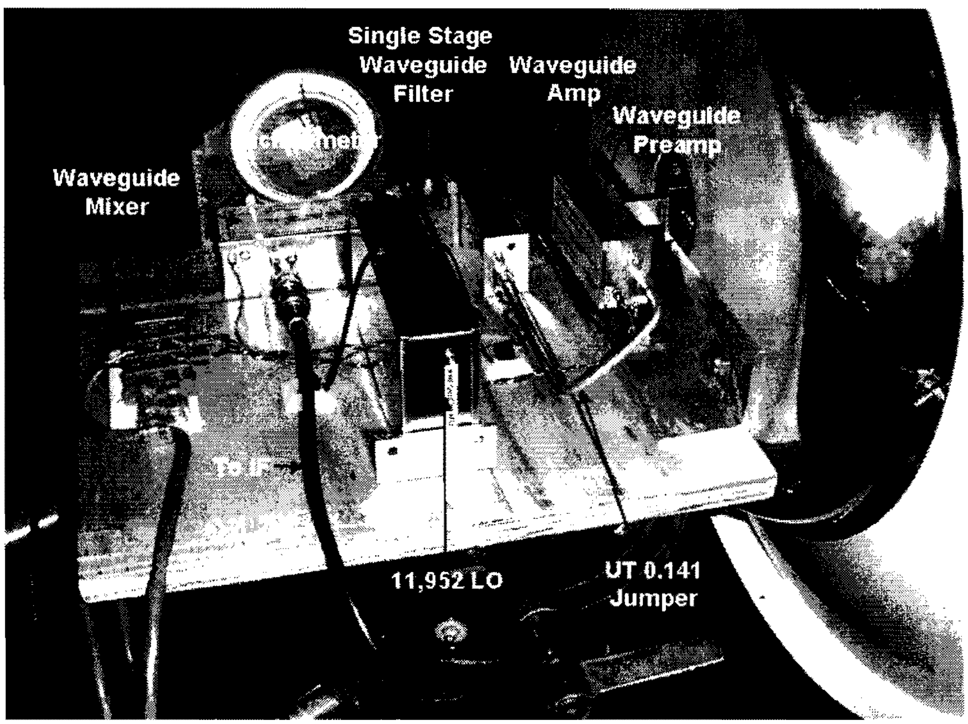
For mounting, I used my QuickSet[5] Hercules tripod. This is the same one I use for mountaintop microwave activity. It's extremely rugged, being designed for a large format camera. It will easily handle a 150 pound top load. I can attest that it is stable even in 50+ mph winds having operated with it on top of Mt. Washington in NH. With a dish that needs to be accurately aimed within a few degrees, stability is important.

For pointing, I use a combination of compass rose for azimuth and inclinometer to set elevation.

THE SYSTEM

The first receive only system I built is pictured below.

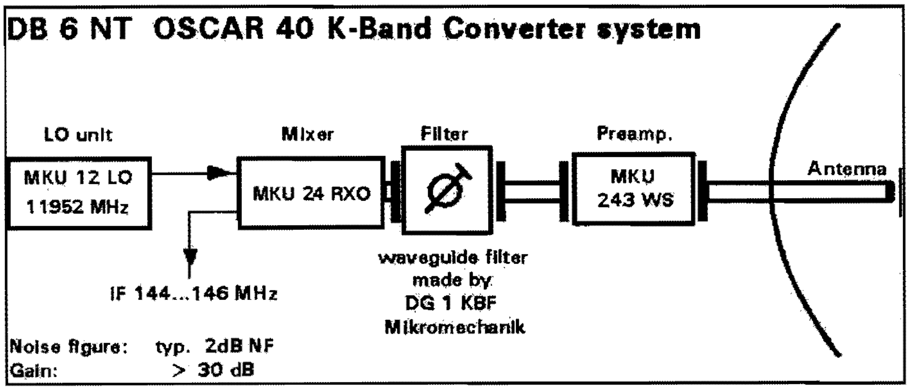




For dish mounting, I've adopted the use of frying pans. Mirro makes a series of frying pans that have a lip that makes them easy to drill and ideal for this purpose.

In the pictures above, you'll notice a second amplifier between the preamp and filter. I had the amplifier and put it inline, but it isn't necessary. It was actually used in place of a transition. At the time, I was missing a WR-42 to SMA transition and ended up using the amp in its place.

Here's a block diagram of a typical signal flow without the additional amplifier.



The Challenge

Portable satellite operation is always a challenge. K Band operation is no different from any other operation except higher precision is required. There are a series of major variables you will need to deal with.

1. Tracking.
2. Pointing – both azimuth and elevation.
3. Frequencies – Doppler shift and LO drift.

If you are able to eliminate or minimize the error in any of these variables, your chances of success increase significantly.

Tracking

For most of us, tracking is relatively easy. We do it all the time with our satellites. The only difference here is the need for more precision. There's not much room for error. One degree can be the difference between success and failure. Operators who use large dishes for S Band reception can begin to appreciate the precision required. However, they have the advantage of listening for loud signals.

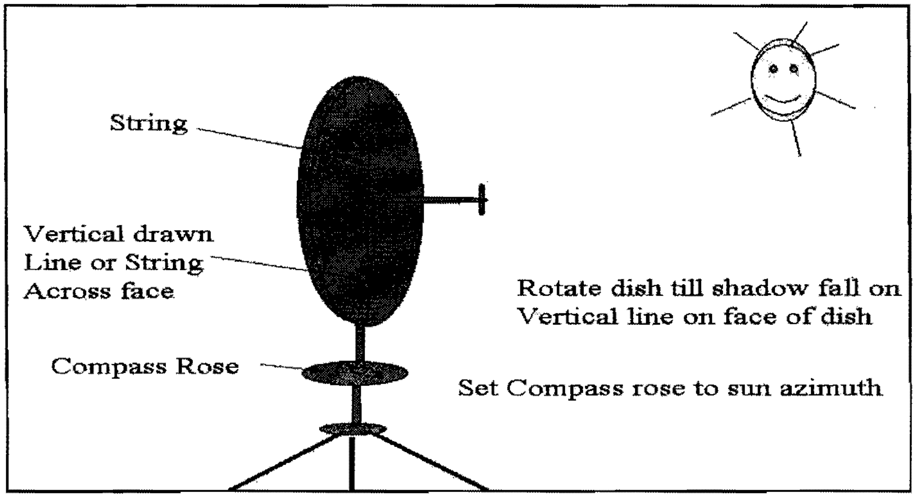
I use Nova for Windows© for tracking. As well as giving me the usual azimuth and elevation data I need, I also make use of the scheduling feature to input the MA versus transponder modes for AO-40. This way I can easily see when the K Band window will be available.

Pointing

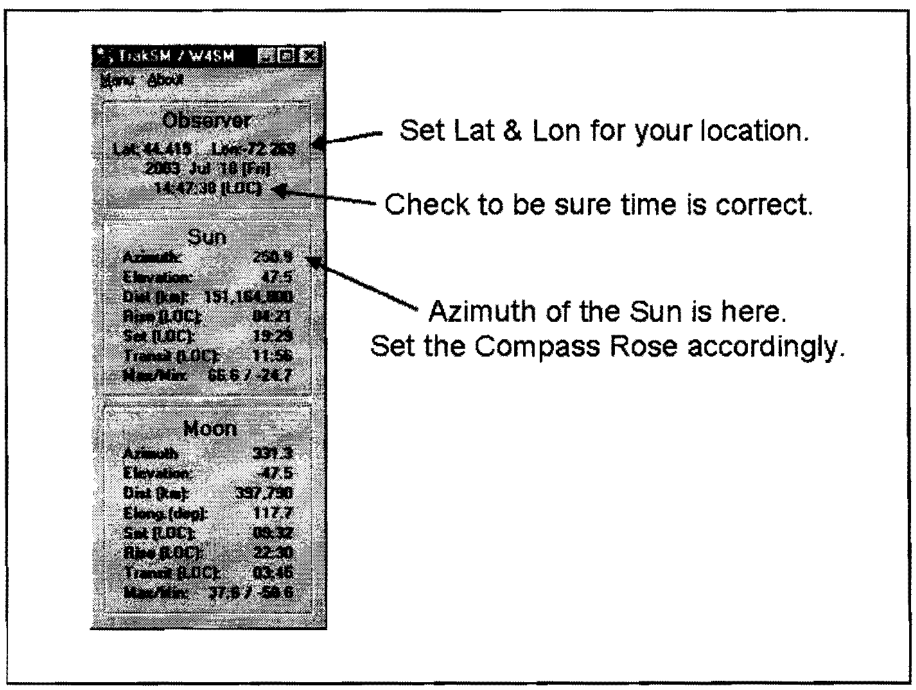
I can't over emphasize the importance of having an accurate means of pointing the dish both with respect to azimuth and elevation. A 0.5 meter dish on 24 GHz has a little over 2 degrees beam width. This is both in the vertical and horizontal plane. In a portable situation, you must have some way to determine where you're pointed or, unless you're very lucky, you're doomed from the start.

First, for azimuth, I have an accurate compass rose mounted on my tripod. My favorite source for these is Oregon Rule Company[6]. For elevation, I use a simple inclinometer. An inexpensive device that works well is the "Angle Finder" from Dasco[7]. They are available at hardware stores.

To set the compass rose, I use sun alignment. I'm sure some are thinking of sun alignment as trying to peak a receive signal while pointed at the sun. This is not how I do it. This method involves using the sun to cast a shadow from the feed on the face of the dish. Using this method, I can usually set the compass rose within 1 degree. Here's how it works:



To determine the position to set the compass rose, I use Stacey, W4SM's wonderful little program TrakSM[8].



This method of alignment obviously requires the sun. If it's cloudy, a compass can be used, but it's far from accurate.

WHAT'S THE FREQUENCY KENNETH?

By the time I had gotten to assemble my system, I had the means to measure frequency to beyond 12 GHz. This proved to be very helpful in setting the LO as close to 11.952 GHz as possible. In microwave operation, frequency drift is a way of life. We're getting better at minimizing it, especially with the introduction of GPS disciplined oscillators and phase lock systems.

Usually our systems start with a basic crystal oscillator in the 100 MHz range that is multiplied up. This is the case for my 24 GHz system. The fundamental oscillator is at 124.5 MHz. This is multiplied 96 times to reach 11,952 MHz and then doubled again in the mixer. As you can imagine, there's quite a bit of room for error. The crystal does have a thermistor heater attached, but even with this, you will see a slow drift up and down of 4-5 KHz as the crystal heats and cools. The bottom line is to be ready to tune to find the beacon.

K BAND DOPPLER

During a typical K Band operating window, you should expect to see up to 60 KHz of Doppler shift plus LO drift. I use the frequency display in Nova for Windows© to help determine the beacon frequency. I have it set for 24,048.035 MHz. It's reasonably accurate and gives a good indication of where to begin listening. Even so, be prepared to tune.

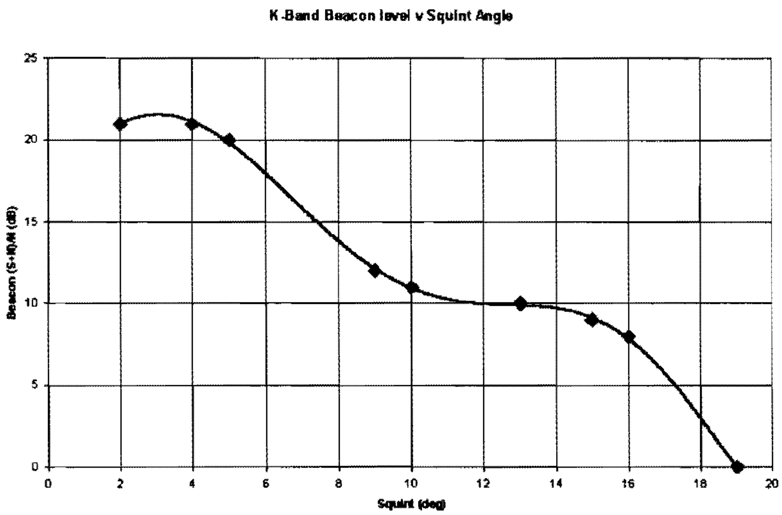
THE NEXT STEP - LISTEN FOR THE BEACON

Armed with a working system, I set out to first hear the beacon. Since trees surround my house, I chose an operating location not far away that had good line of sight down to the elevation in the 2 prime directions that I needed to look for AO-40 during the K Band windows. You must have an unobstructed view for K Band operation otherwise you won't hear it.

What can you expect for a signal level with a system such as mine?

About the strongest signal I've heard is S5 on peaks. A more typical signal is only about 3 S units above the noise. With a linear feed, I see maximum signal when the polarity matches the satellite. If you convert to circular, it will minimize the fades at the expense of about 3 dB in signal level.

K band windows are scheduled to minimize the squint angle. Charlie, G3WDG made the following graph of squint vs. signal level.



As you can see, with my system I really need to have a squint below about 5 degrees or copy starts to get rough. Remember, 3 S units is a peak level.

A typical K Band window is about 10 MA units long. Usually the first few minutes (2 MA units) are dedicated to "beacon only" operation. The uplink receivers are shut down. This is significant because the transponder is hard limited. This means that normally the beacon and any uplinks share the transponder downlink power. If there is a very loud signal in the passband, it will rob power from the beacon, to the point that it's sometimes very hard to detect. Having a set amount of time where the beacon has full transponder power makes detection easier.

On April 14, 2002, I set up about an hour before the scheduled K Band beacon activation. One reason I set up early was to allow my LO to temperature stabilize to minimize drift. Right on schedule, the K Band beacon was fired up and I began to search. Within about 5 minutes of searching I found the beacon! The QSB was as predicted. A big temptation was to tune or move the dish as the signal faded. I soon learned this was a bad thing to do as I lost the signal more than once. In the coming days, I made several more successful attempts. Finally satisfied with my ability to find the beacon and track AO-40 consistently, it was time to try a qso.

The First Voice QSO

I sent email to Jerry, K5OE to see if he would be interested in trying to work me. On April 20, 2002 Jerry and I exchanged calls and reports. I was using L Band up and K down. Jerry used U up and S down. The following day, I also worked Steve, KB8VAO.

One trick I learned when I first began to operate satellites was to load the beacon frequency of the bird I was operating into the second VFO on my radio. That way at any time, I could switch to the beacon to see the downlink level. This is a tremendous aid in K Band operation. You do have to compensate quite often for Doppler on the beacon, but being able to quickly shift to the beacon and verify transponder signal level is a big help.

Up until my success, the only other ham with K Band capability in the U.S. was Al, W5LUA. I contacted Al to see if he'd like to try a K Band to K Band contact, but found out he couldn't elevate his dish enough so we could work during a mutual window.

Shortly there after, I contacted Charlie, G3WDG to see if he'd like to try. I figured as well as this being my first K Band to K Band contact, it would also be the first ever transatlantic one as well. On May 7, 2002 Charlie and I had a successful qso both using K Band down.

Audio of these contacts is available at: http://members.aol.com/mike73.

THE BOX SCORE

Since that time, I've made quite a few contacts. Here's a list as of July 2003:

G3WDG *	K5OE
F6GBQ *	KB8VAO
OE1VKW *	KO4MA
I8CVS	K5AXW
DK2ZF	WC9C
OM3WAN	K2IYQ
HB3YEV	
UU9JJ	

* Indicates K Band equipped station.

All contacts were made using SSB. Typical distance was 60,000 km+. Most contacts were made at about 20 kHz below the beacon. Care must be taken to not go too low because the transponder is only 50 kHz wide (± 25 kHz of the beacon). Sadly, as I write this, there has yet to be a successful K Band to K Band contact between two US operators. Hopefully that will change soon.

RECOMMENDATIONS

1. **Find an Elmer!**
   More importantly, find an Elmer with test gear! It will make your life a lot easier.

2. **Work with as big a dish as you can.**
   With these small signal levels, bigger is better. It is a tradeoff. Bigger is harder to point.

3. **Use Circular Polarization.**
   If you can use a bigger dish, by all means try circular polarization. It makes it a lot easier to not have to deal with the fades.

4. **Build a Weak Signal Source/Marker.**
   I recently built one of these and it's a great tool to help verify system performance. My system is based on a Qualcomm 3036 synthesizer programmed for 2672 MHz. The ninth harmonic is loud on 24.048 GHz. It's not real expensive to build. The synthesizer can be programmed for numerous frequencies. I have mine switch selectable for use at 24.048, 24.192 and 47.088 GHz. If you'd like details, please email me.
   n1jez@amsat.org

THE FUTURE

I'm currently in the process of building a dedicated K Band receive only system. This one will be based on a P-Com receive mixer. It will initially utilize a slightly larger 24" dish and circular feed. If it all works out, I hope to increase the dish size once again to 1.2 meters also with a circular feed.

I'm also working on Phase Locking my LO to address the frequency drift issue. I will be using either a 10 MHz or 1 pps GPS reference in conjunction with a CT1DMK[9] board for locking.

On February 23, 2003 the S1 receiver was successfully tested. To utilize this receiver, the S transmitter must be shut down so the only operating downlink is K Band. We will hopefully be given more S1/k windows in the future. I look forward to operating this mode!

I'm currently writing this paper in July for submission in early August. K Band will be re-activated in mid August. I hope to report more findings of my experimentation at the Toronto AMSAT Symposium in October.

Good Luck! I hope to work you via the K Band downlink on AO-40!

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4. **SSB Electronic USA http://www.ssbusa.com**
5. **QuickSet http://www.tripods.com/index.html**
6. **Oregon Rule Company http://www.oregonruleco.com**
7. **Dasco http://www.tools-plus.com/das.html**
8. **Stacey Mills, W4SM http://www.cstone.net/~w4sm/ham1.html**
9. **Luis Cupido, Phase lock a VCXO to a standard 10MHz or to a GPS(1pps) http://gref.cfn.ist.utl.pt/cupido/reflock.html**

S BAND DOWNCONVERTER PERFORMANCE

Bob Seydler Jr., K5GNA

There are a few considerations in how well your downconverter will perform in the real world at the microwave frequencies that we are using for S band on the satellites. Probably the foremost factor that affects the performance at higher frequencies is noise figure, also expressed as noise factor or noise temperature. Also affecting performance and noise figure is the filtering that is incorporated before the mixer, in the RF amplifier or front end of the downconverter. Filtering also affects image rejection and how well the downconverter performs with interfering signals present, so it can be as important as the noise figure. Downconverter gain has some affect on system design and will be discussed here. RF amplifier stability, oscillator frequency stability and a few other factors will also affect the performance of the downconverter and will not be discussed.

PREAMP AND DOWNCONVERTER GAIN

The gain of the downconverter has little affect on the system performance in our properly designed S band receive system. Noise figure and antenna performance, which is mostly antenna gain (dish size), are the main factors in determining how well your system will perform. Other factors, including the noise temperature of various components, will have less of an influence on the performance.

In a properly designed system, once you have the gain distributed properly throughout the system and the noise figure and dish gain have been established, there is nothing to be achieved by additional amplification of the signal. In a poorly designed system, too much gain in one stage can cause instability and oscillations and too little gain degrades the signal to noise ratio. In a properly designed system, adding excess gain in the RF stages would be about the same as putting an audio amplifier at the speaker terminals – the noise just gets louder.

The catch word here is a properly designed system. The gain of each stage in a properly designed receiver system should have enough excess gain to overcome the losses to the next stage. We have little control over the gain inside an existing receiver; but on an external downconverter we can compensate for any discrepancies in gain with external attenuation or amplifiers. There is some consensus of opinion that we will need about 10 dB of excess gain between the stages in a receiver system. A few dB higher and a few dB lower numbers have also been discussed.

Since all preamps and many S band downconverters are located remotely from the communications receiver, cable loss can be a factor in the system gain. Too little gain in the downconverter will not overcome the cable losses to your receiver and will cause the signal to noise ratio to be less than desired. Choosing the correct downconverter or preamp gains (proper system design) will give optimum performance. If you have a separate dish mounted preamp with 15 dB of gain and a downconverter near the receiver that is connected with coaxial cable that has 10 dB of loss, then you will need a minimum of 5 dB of additional gain at the preamp, or less cable loss, to overcome the losses. This also applies to the downconverter at the IF frequencies. A second amplifier directly at the output of the preamp (or downconverter) is needed here. It will do no good for the amplifier to be placed at the downconverter (or receiver) end of the coax; at this point you are again just amplifying the noise.

With a downconverter having 20 to 30 dB or more of gain and the cable loss being only a few dB at the IF frequency, you could end up with a rather high S meter reading with no signal input. This noise is just downconverter noise and makes for very good S meter reports. Excess gain is not usually a problem between a remote preamp and downconverter, since high cable losses are the norm at 2.4 GHz. For a downconverter with excess gain, a attenuator pad with 6 or more dB of attenuation at the receiver input will tame down the gain. Some of those who know a lot more than me have already provided some excellent papers on justification for reducing excess gain.

The other advantage of the attenuator is it can act as a fuse. Most of our receivers that follow the downconverters are transceivers, and people key up into the downconverters accidentally, no matter how careful they are. The 6 dB or larger F type attenuator usually contain one-eight watt resistors and 6 dB of attenuation and will absorb 37.5 watts of a 50 watt signal. If you accidentally key up, the attenuator burns up before the downconverter, thus eliminating a repair on the downconverter.

NOISE FIGURE

Noise figure can basically be stated as how much worse, stated in dB, your device performs compared to a perfect device. The formula is P(noise) = kTB. Basically it says that a perfect receiver at ambient temperature (290K) with a one hertz bandwidth will have a noise floor of -174 dBm. That noise floor is where the signal has a signal to noise ratio of 0 dB. ; the minimum discernible signal could be a little less. The formula is for 1 Hz of bandwidth, a 10 Hz bandwidth is 10 dB worse; a 100 Hz bandwidth is 20 dB worse and so on. With today's digital signal processing, and some very slow CW, bandwidths below 1 HZ are now practical.

So, any cable losses, connector losses and some other factors will simply add to the noise figure the same as putting an attenuator in front of your preamp. A preamp with a noise figure of .5 dB, but with a 1 dB attenuator in front of it has an actual noise figure of 1.5 dB. Cable and connector losses are simply attenuators. Adding 1 dB of attenuation to the input of the preamp increases the noise figure and the signal to noise ratio is reduced by more than 1 dB. Adding the 1 dB of attenuation to the output of the preamp changes almost nothing, since the noise figure has been determined and the attenuation is now considered in the next stage. With good gain and noise figure in the first stage, second stage NF, third stage NF, etc., has almost no contributions to the total noise figure

IMAGE REJECTION

Image rejection is the amount of filtering, or rejection, which occurs at the image of the input signal on your downconverter. On many S band downconverters, with low side injection, the local oscillator is 2256 MHz to give an IF of 144 MHz for 2400 MHz input. The image frequency is calculated as 2256 MHz minus 144 MHz, which equals 2112 MHZ. With no image rejection, you are looking at both sidebands of the signal or a double sideband signal. The upper sideband is the received signal resulting from the LO plus the IF frequency and the lower sideband is the received signal of the LO minus the IF frequency. Noise figure measurements with a double sideband signal (no image rejection) will be about 3 dB higher than a single sideband signal (good image rejection).

Most noise figure measurements at the noise figure measuring contests at various functions are measured as an SSB noise figure and the 3 dB penalty must be added to give a real noise figure when calculating a downconverter with poor image rejection. So with poor image rejection, or none, you will end up with about a 3 dB worse noise figure than you think you have at these events.

Measuring image rejection is not complicated; just count the vertical divisions on your network analyzer from the peak signal at 2400 MHz to the image at 2112 MHz. For those without a network analyzer, and also for the best reality check for your network analyzer, there is simple way. You will need to measure the output of the downconverter with a relative indicating device that has no AGC.

You can use a spectrum analyzer or a communications receiver with the AGC off for the indicator. Inject a weak signal at 2400 MHZ into the downconverter to produce a signal that is at least 10 dB (or a couple of S units) out of the noise on the spectrum analyzer (or receiver). With this weak signal, you will not overload or saturate the downconverter. I use this method to check what I see on the network analyzer -- to see if it is real. Record the signal generator level in dBm and then move the signal generator to 2112 MHz (or the image frequency). Bring the signal generator level up to a point where the signal is the same on the indicator (it only has to be at the same point, so it is relative) as it was at 2400 MHz. The difference in dB on the signal generator's attenuator is the amount of image rejection.

With a receiver for the indicator, you will need to have a fairly stable signal source since the bandwidth is fairly narrow. With a spectrum analyzer, you don't need so much stability because the bandwidth can be much wider. You must have a calibrated attenuator on the signal generator though; however, the absolute calibration of the signal generator is not important, just the difference between the two signals.

FILTERING INTERFERENCE

Good filtering at 2400 MHz in your downconverter will eliminate the image frequency and the problem with image rejection and the associated noise figure penalty is solved. The filtering at 2400 MHZ will not matter as much in the preamp stages -- if you live in a perfect RF environment. However, we do not live in a perfect RF environment and that is one reason for this discussion. In order to put a filter in the place where it would do the most good would mean adding it between the antenna and the preamp; putting it here can cause other problems with increased noise figure.

The popping sound in your downconverter which sounds like the old Russian "woodpecker" radar will probably be either a cordless phone or a wireless LAN operating spread spectrum at 2.4 GHZ. The signal is coming in where you want to receive the satellite at 2400 MHz, so additional filtering will not help your situation. Turn your phone or wireless LAN off and it should go away. If the signal belongs to your neighbors, then it is a bit more complicated to eliminate it. However, the FCC seems to be giving us Amateurs some help with this problem now, because the other devices are secondary, non interfering, users. Try the noise blanker, it may help somewhat.

An increase in the noise floor on your system when pointing toward a major metropolitan area is a problem some of us may encounter. There is a lot of RF floating around from the various systems at around 2400 MHZ and with such a large concentration; you may see some excess RF in your system. Usually some front end filtering before or after the preamp will help with this mild form of desense in your system.

Our "mates' in Australia and other locations are experiencing interference on 2112 MHZ from 3G systems. This system transmits at the 2 meter image frequency and presents some serious problems at the 144 MHz IF frequencies. It is not on the input frequency at 2400 MHz, but it is still coming in on top of the satellite at 2 meters from the image frequency. Some hams located close to these powerful transmitters have needed image rejection in excess of 60 dB. This amount of image rejection is not common in Amateur downconverters and could require external filters either before or after the preamp.

The main problem we experience with satellite operation occurs because we want to operate full duplex on the satellites. When we transmit on one antenna at 435 or 1269 MHz and receive on another antenna close by at 2400 MHz, we may experience desense in the downconverter or preamp from our transmitter. When you stack a 435, 1269 and 2400 MHz patch antenna a fraction of an inch apart, the problems increase by a few orders of magnitude. With poor filtering, not only will you suffer receiver desense due to out of band signals in the preamp, you may actually burn out the GAsFET in the front end of the preamp.

DOWNCONVERTERS

Most amateur preamps have little more than the gate of the GAsFET connected to the antenna input; there may or may not be a filter at the output. With no input filter at the input, it does help make the noise figure lower, since a filter is always going to have some loss. Remember, those losses occurring before the preamp input will result in an increase in noise figure. You can add an external filter at the input, but your noise figure will go up by the amount of loss in that external filter, it works just like an attenuator. Adding an external filter after the preamp will not help the front end, but it will help with the image rejection.

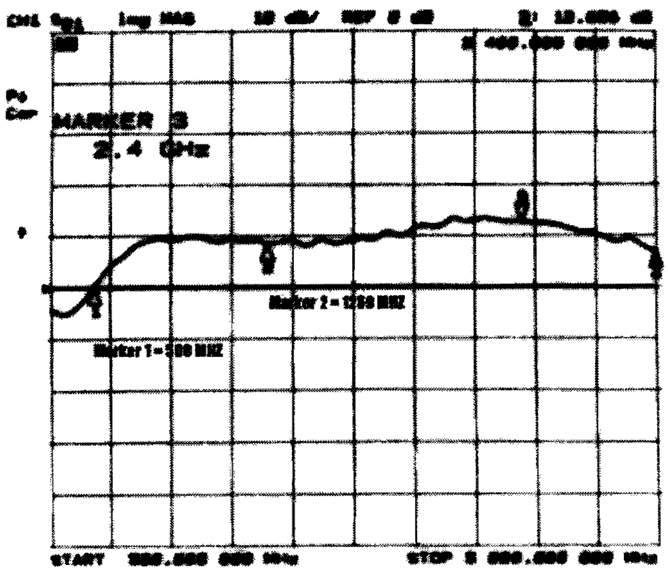


Figure 1 – DEM Preamp

Figure 1 shows the frequency response of a preamp from Down East Microwave, model 13LNAWPF. This is an excellent preamp with a noise figure of .66 dB and a gain of 13.47 dB. It has no filter at the antenna input or at the output of the preamp. It has a gain peak near 2304 MHz and performs well at 2400 MHz. It also has gain from about 500 MHz to 3000 MHz. With this wideband response, it will not attenuate the 435 MHz uplink signal very much and will amplify the 1269 MHZ uplink signals. With a lack of filtering, it will desense in the presence of strong signals

The frequency response that is displayed in Figure 2 is from a Kuhne model MKU 232A low noise preamp. The preamp has a two pole helical filter in the output of the preamp, but no filter at the input of the preamp. It shows about 35 dB of image rejection at 2112 MHz. The gain is listed as 38.5 dB at 2400 MHz and the noise figure is .62 dB. The preamp offers some excellent image rejection and out of band rejection, but since it has no filter at the input, it will desense in the presence of strong uplink signals

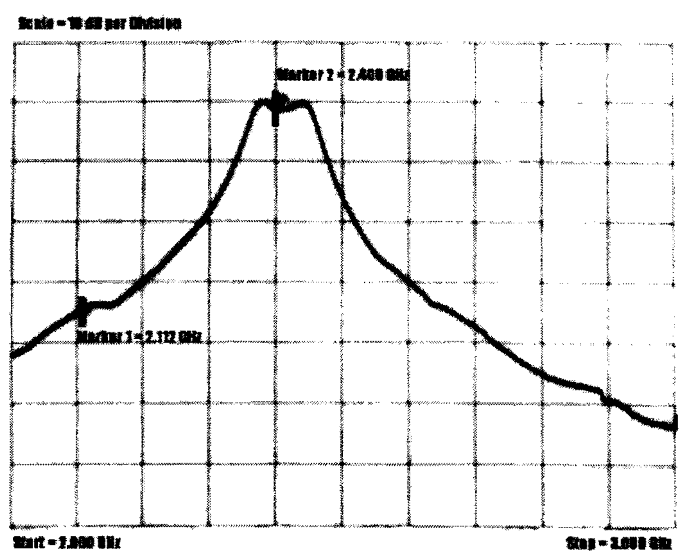


Figure 2 – Kuhne Preamp

Figure 3 shows the frequency response of the Kuhne model MKU 232A preamp, as illustrated in Figure 2, preceding the Kuhne model MKU 24 Oscar downconverter. The 38.5 dB of gain in the preamp was reduced with a 20 dB attenuator between the preamp and the downconverter. These losses should be equivalent to the losses in the cable between the remotely mounted preamp, with the downconverter near the receiver. The cascaded preamp and downconverter with their 4 combined helical filters provide a better response than either the preamp or the downconverter alone. The image rejection is about 47 dB. The downconverter has a noise figure of .5 dB and a gain of 33 dB. As with the preamp, it has a 2 pole helical filter at the output of the preamp section, but it has no filters at the input, so the gate of the GAsFET is directly connected to the antenna input.

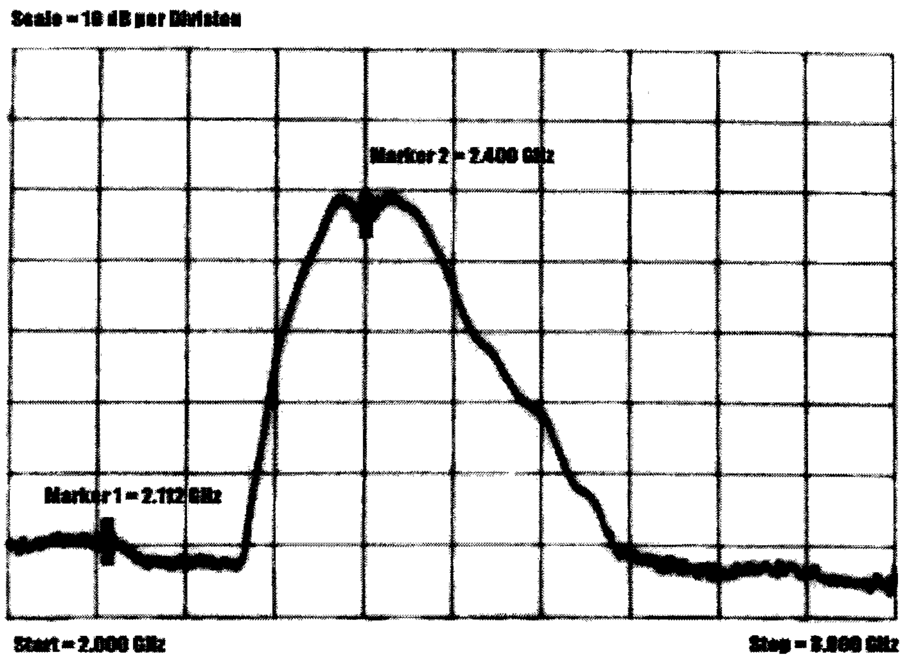
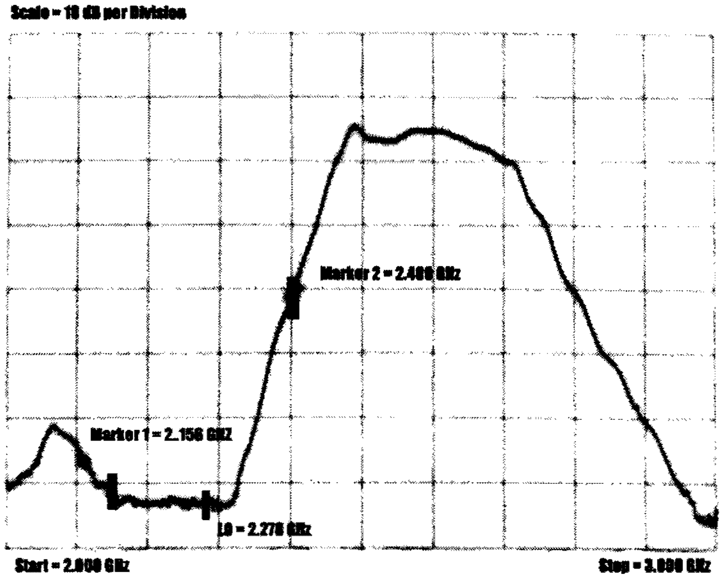


Figure 3 – Kuhne Preamp & Downconverter

The commercial MMDS downconverters in the USA were designed for operation from 2500 to about 2700 MHz and many are now in use in the Amateur service. The original MDS system used about 2150 to 2180 MHz. Some of these MDS/MMDS downconverters covered both sets of frequencies with either 2 sets of separate filters or one continuous filter in the front end. These MMDS and MDS frequencies vary in other countries.

Many of these downconverters have fixed PCB or ceramic filters in the front end before the preamp and at the output of the preamp. Others, such as the Drake 2880 have only PCB filters at the output of the preamp. Many of the conversions available require moving the filters down to 2400 MHz through various means such as extending the lines or adding tape to lower the frequency. Some conversions have removed the fixed front end filters and bypassed them and then modified the output filters. I measured the results on one such popular modification and found almost no image rejection. Very few downconverters have mechanically tunable filters. Some downconverters such as the

Drake 2880 have poor gain in the IF below 200 MHz without the modifications, others have excellent IF response down below 50 MHz.



An unmodified Drake model 2880 is shown in figure 4. It has a good passband from about 2480 MHz to 2630 MHz; the marker at 2400 MHz is down by about 25 dB. It has the original LO and that results in an IF of 122 MHz. Since it has poor IF response at 122 MHz, some of the steep passband slope is attributed to the lack of IF response and not filtering.. The noise figure is 20 dB and it has a loss (not gain) of 1.5 dB at 2400 MHz. You will need a very good preamp, or large dish to make it work.

Figure 4 – Unmodified Drake

Figure 5 shows the response of a modified Drake 2880 downconverter. The simple modifications are well documented and consist of cutting out two coils plus capacitors to bring the IF response closer to the 122 MHz needed in the IF amplifier. There is about 30 dB of image rejection in this configuration, but the 2400 MHZ signal is 12 dB down. The noise figure is now 7.2 dB and the gain is now 15 dB. Many of us have used these modified downconverters with preamps or larger dishes.

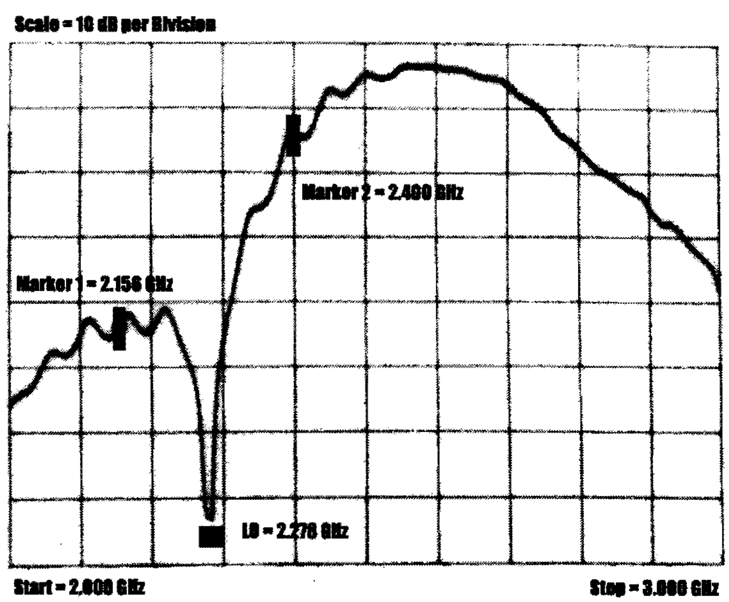


Figure 5 – Modified Drake

Figure 6 shows an AIDC 3731 series downconverter that has had the passband mechanically retuned for the best noise figure at 2400 MHZ and has had the LO changed to provide an IF of 144 MHz. The retuned front end passband is now good from about 2480 MHz to 2600 MHz. The measured noise figure at 2401 MHz is .95 dB, the gain is 37.6 dB and the image is about 65 dB down. It has a 4 pole filter at the antenna input to the preamp and another 4 pole filter at the output of the preamp section. This input filter will prevent any desense associated with out of band RF in a nearby antenna. It measures no desense with the triband patch feed using a 435 or 1269 MHZ transmitter, with antenna separations of just a fraction of an inch.

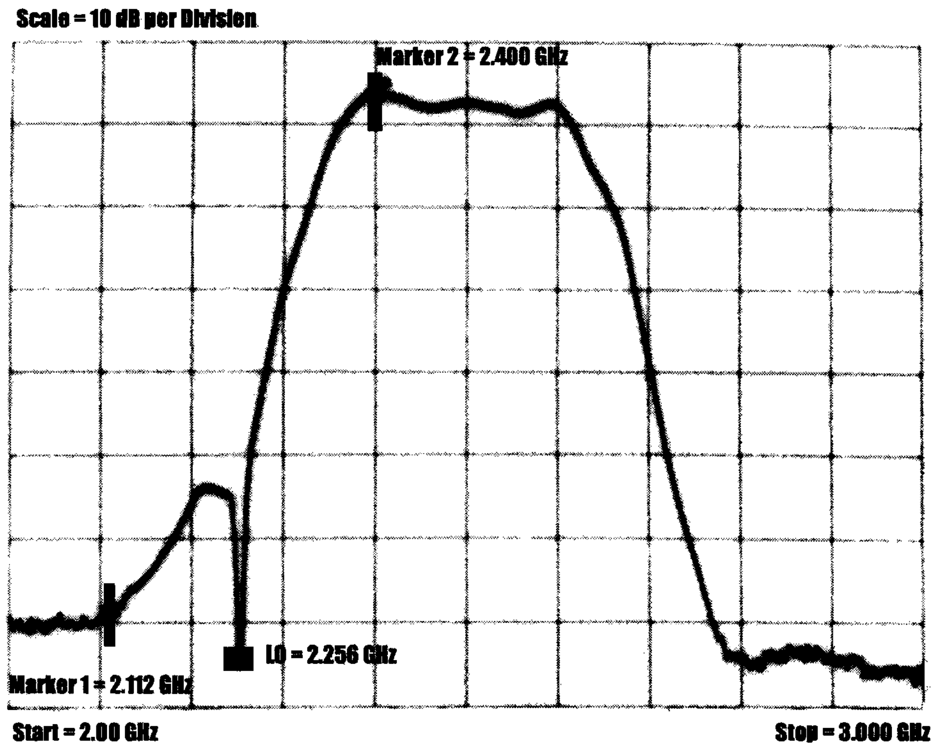


Figure 6 – Modified ADIC 3731

EXTERNAL FILTERS FOR DOWNCONVERTERS

In order to prevent desense with uplink antennas that are in close proximity, a bandpass filter can be installed at the input to your existing preamp. However, the loss in the filter could add .6 or more dB to the noise figure of a very good .6 dB preamp and you end up with a less respectable 1.2 dB noise figure. A notch or reject filter at the interfering frequency installed at the preamp input will have a little less loss, but it will only reject one frequency and not the broader spectrum caused by some interference. A single stub notch filter at the input generally will not eliminate desense on close coupled antennas.

Adding the same bandpass filter or an image frequency notch filter to the output of the preamp will increase the image rejection, but will do little for strong signals that directly affect the GAsFET preamp's unfiltered front end. There have been some designs for 2.4 GHz bandpass filters in various publications which could be duplicated with more effort than most of us will want to undertake. Most commercially available bandpass filters are not centered on 2401 MHZ, so you must take what you can get.

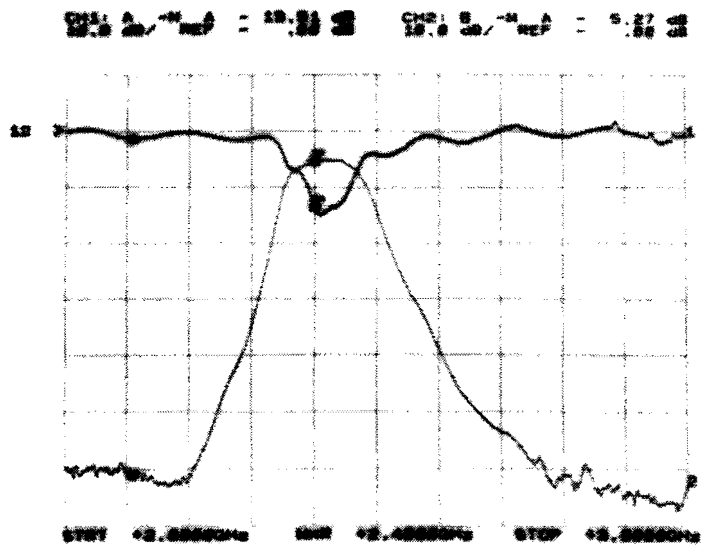


Figure 7 shows the bandpass filter that had been available from Electro Mavin a couple of years ago. It measures about 55 dB of image rejection, but also shows 5.27 dB of insertion loss and 13.51 dB of return loss at 2400 MHz. It would do some good at the output of the preamp, but would increase the noise figure a lot if placed at the input.

Figure 7 – Electro Mavin Filter

Figure 8 shows a bandpass filter for 2400 MHz that is now available from Avitar Unlimited. Web address is www.avitarunlimited.com. It has more poles than the filter from Electro Mavin and much steeper skirts. It has a measured insertion loss of .76 dB, 60 dB image rejection and a return loss of 20.06 dB at 2400 MHz. It could be mounted at the input of a preamp, but the .76 dB must be added to the system noise figure. It would work without increasing the dish size a lot. It is made by Trilithic.

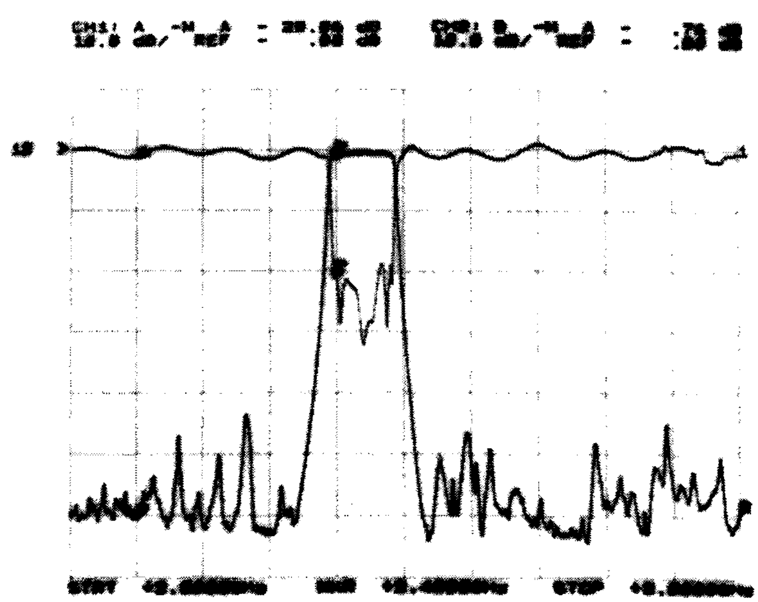


Figure 8 – Metricom 8CC2441.5/X83-1-AA Filter

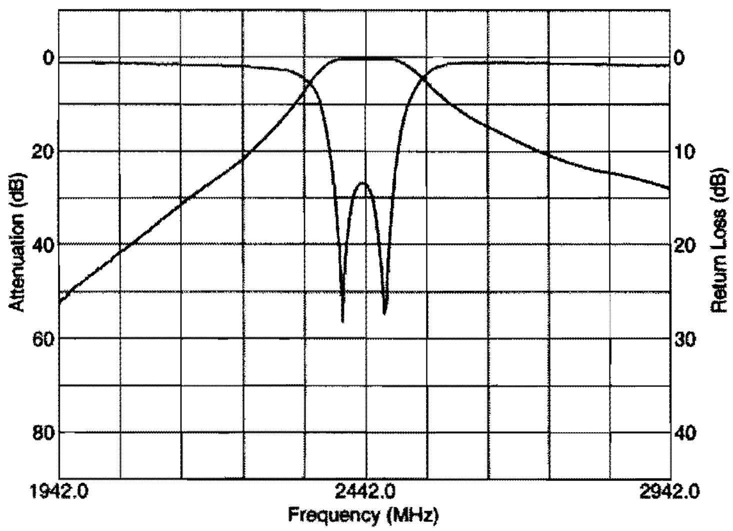


Figure 9 – Murata Filter DFC22R44P08BHD

Figure 9 shows the response of the 2 pole Murata surface mount ceramic filter which I use in my conversion for the AIDC 3733 Downconverters. The unit is very small and can be mounted almost anywhere to improve the image rejection in an existing downconverter. It has a passband from 2400 MHz to 2484 MHz, the insertion loss is 1.2 dB and the image rejection is about 35 dB.

There are a lot more designs for bandpass filters in the various publications than there are for notch filters. A simple notch filter can be constructed out of an open or a shorted piece of coax that provides rejection at the desired frequency. The AIDC 3733 downconverters used both types to reject signals at 2400 MHZ. One version used a shorted piece of small hardline coax that was connected by a PCB capacitor of which the copper could be trimmed to tune the reject frequency. The other version used an open (and longer) piece of hardline coax connected by a PCB capacitor. Frequency trimming was done by simply cutting the end of the coax, since it was not shorted.

CONCLUSION

Keep the gain in your system at the proper levels; S-9 of noise with no signal is not necessarily good.

A good SSB noise figure is desirable; a DSB noise figure (no image rejection) is automatically 3 dB worse.

If you want good image rejection, or interference reduction you will need a downconverter that has the passband filters or rejection filters to fit your requirements. A filter at the input of the preamp is most effective for out of band signals -- if you can accept the losses in the filter and the higher noise figure. You can add a filter to the output of the preamp to increase the image rejection with no real penalty in noise figure.

If you want protection against desense (or burnout) on the receive part of your duplex system, then you will need a downconverter that has enough filtering at the antenna input to protect it. If you want to protect what you already have, you will have to add a filter at the input to the preamp and accept the increased noise figure that it will add. At this point a bigger dish will help to make up for the increase in noise figure.

Amateur Satellite Launch Sites, Launches and Orbits

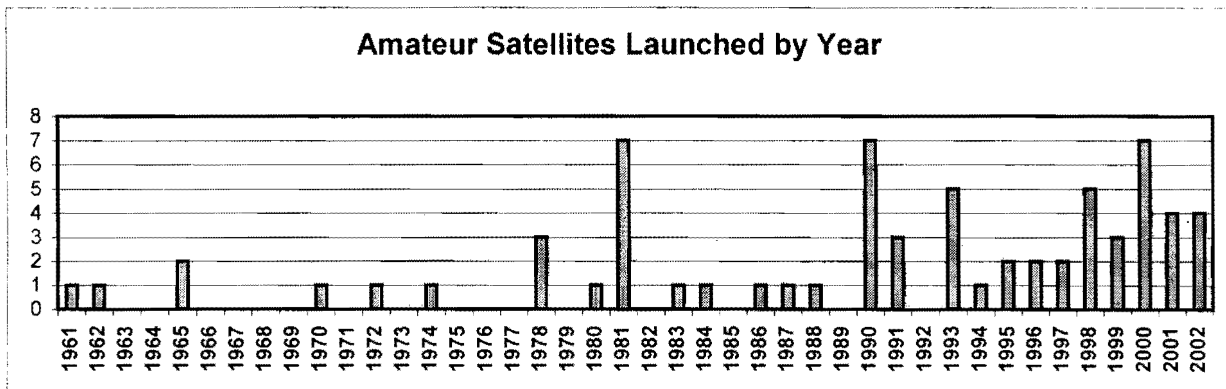
G. Gould Smith, WA4SXM

Amateur Satellite Launches

The first amateur satellite was launched only four years after the first manmade satellite achieved orbit. Since 1961 amateur satellite enthusiast have continued to put new satellites into orbit to communicate, to experiment, to push the state of the art and to explore the higher frequencies. This is an international effort with numerous AMSAT organizations from around the globe developing satellites and arranging for their launch. As you can see in Figure 1 the number of amateur satellites being launched has increased over the last decade.

Although AMSAT members are mainly concerned with designing, building, controlling and operating these satellites it is important to understand how they get into orbit, how the orbit affects the satellite operations and how the launch site effects the orbit. This paper is about "Rocket Science", but will explore these issues in an understandable fashion.

Figure 1. Amateur satellites launched by year



Amateur Satellite launch sites

Over the 42 year history of amateur satellites all 71 amateur satellites have been launched from only eight different sites. Tables 1 – 8 lists these launch sites and the amateur satellites launched from each one. Vandenberg AFB was our first launch site and did a number of the early launches. As you can see the former USSR has put a large number of our amateur satellites into orbit, as well as Kourou.

Vandenberg	13 satellites in	11 launches	62,62,65,70,72,74,78,81,84,99,00
Kourou	17 satellites in	9 launches	80,83,88,90,91,92,93,00,02
Cape Canaveral	3 satellites in	3 launches	65,98,98
Plesetsk	13 satellites in	8 launches	78,81,87,91,91,95,96,02
Baikonur	14 satellites in	9 launches	94,97,98,98,99,99,00,01,02
Tanegashima	3 satellites in	3 launches	86,90,96
Kodiak	3 satellites in	1 launch	01
Svobodniy	1 satellite in	1 launch	97

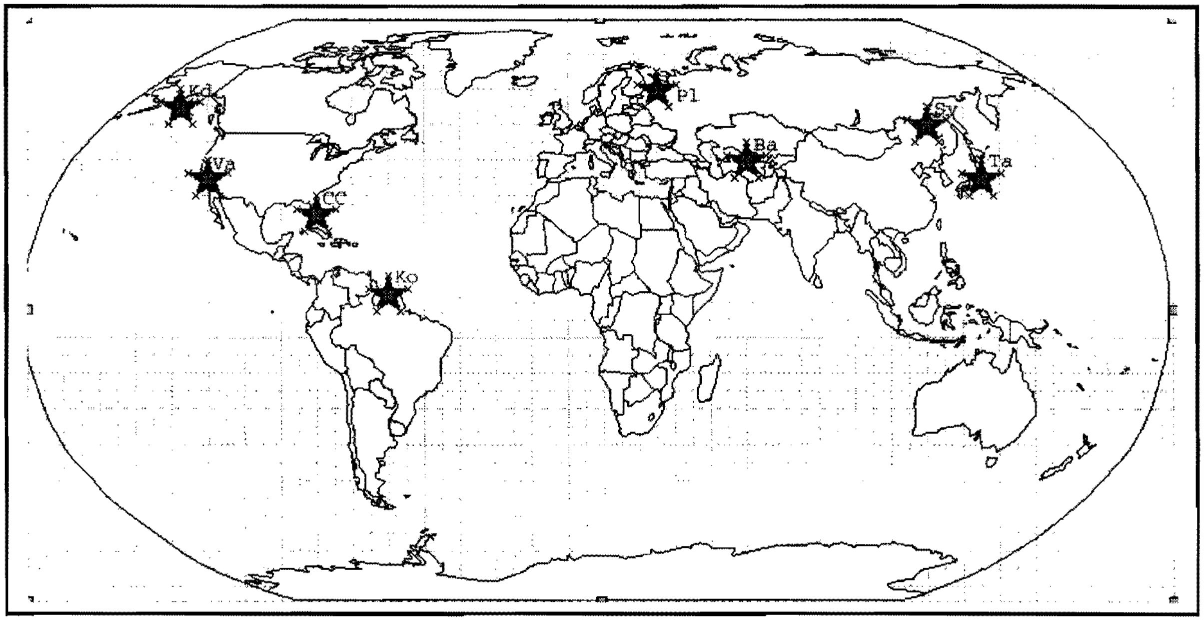


Figure 2. Launch sites for AMSAT satellites

Vandenberg AFB
Latitude: 34° 45' N   Longitude: 120° 37'W
Minimum Inclination 51.0° Maximum Inclination 145.0°

In December of 1961 a Thor rocket launched a Discoverer 36 satellite and a small satellite built by a group of amateur radio operations called OSCAR 1. This satellite sent HI in CW at a rate proportional to the temperature of the satellite. This was the world's first operational amateur satellite. Most of the amateur satellites launched for the next twenty years were launched from Vandenberg. Amateur satellite launches returned to Vandenberg in 1999 after a fifteen-year absence. See Table 1 for a complete list of amateur satellite launches from Vandenberg.

The United States Army purchased 86,000 acres of land in 1941 in a remote section of California 240 km NW of Los Angeles for Camp Cooke. The training camp for armoured divisions was deactivated in 1953. In 1955 the Air Force identified a need for a secure launch site for missile tests and launches into polar orbit. In 1956 the DOD transferred the base to the Air Force and in 1958 the name changed to Vandenberg. The base became a center for research and launch activity to respond to the Russian launch of Sputnik. The first missile launch was a Thor IRBM in December of 1958. Two months later, Discoverer I was launched and became the world's first polar orbiting satellite. In 1995 Spaceport Systems International Commercial Spaceport leased 100 acres, including a space processing facility, from the Air Force to build a commercial launch facility.

Launch azimuth is constrained between 147 and 201 degrees, although sub-orbital launches are allowed up to 281 degrees. Satellite inclinations between 56 and 104 degrees are accomplished here. All US launches into polar orbits are done from Vandenberg.

Table 1. Vandenberg AFB Amateur Satellite Launches

OSCAR	Name	**Launch Date** mm/dd/yyyy	**Launch Vehicle**	Other sats
OSCAR 1	OSCAR 3	12/12/1961	Thor-DM21 Agena-B	with KH-3 8 (Discoverer 36)
OSCAR 2	OSCAR 3	6/2/1962	Thor-DM21 Agena-B	with KH-4 5
OSCAR 3	OSCAR 3	3/9/1965	Thor-DSV2A Agena-D	with SECOR 3, Dodecapole 1, Solrad 6B, Solrad 7B, GGSE, GGSE 3, Surcal 4
OSCAR 5	Australis	1/23/1970	Delta-N6	with Tiros M
AO 6	AMSAT P2A	10/15/1972	Delta-300	with NOAA 2
AO 7	AMSAT P2B	11/15/1974	Delta-2310	with NOAA 4, Intasat
AO 8	AMSAT P2D	3/5/1978	Delta-2910	with Landsat 3, PIX 1
UO9	UoSat 1	10/6/1981	Delta-2310	with SME
UO-11	UoSat 2	3/1/1984	Delta-3920	with Landsat 5
SO-35	Sunsat	2/24/1999	Delta-7920-10	with ARGOS, Orsted
AO-37	ASUSat 1	1/26/2000	Minotaur	with JAWSAT, FalconSat 1, OCSE, OPAL, STENSAT, MEM 1A, MEMS 1B, Thelma, Louise, JAK
OO-38	OPAL	1/26/2000	Minotaur	with JAWSAT, FalconSat 1, OCSE, ASUSat 1, STENSAT, MEM 1A, MEMS 1B, Thelma, Louise, JAK
WO-39	JAWSAT	1/26/2000	Minotaur	with ASUSat 1, FalconSat 1, OCSE, OPAL, STENSAT, MEM 1A, MEMS 1B, Thelma, Louise, JAK

Kourou (ESA)
Other names: Centre Spatial Guyanais
Latitude: 5° 14' N   Logitude: 52° 45'W
Minimum Inclination 5.0 degrees   Maximum Inclination 100.0 degrees
Kourou is the most active launch site in history and been very important to the amateur satellite community. Seventeen amateur satellites have been launched from Kourou, more than any other launch site.
France gave up their launch site in Algeria in the agreement for its independence. So a new launch site was needed. In 1966 ELDO chose Kourou in French Guiana for their Europa II launches and built a facility there. The Europa II launch complex was later renovated and converted for the Ariane launcher. In 1979 the first Ariane rocket was launched from Kourou. AMSAT international had their P3A satellite on one of the Ariane 1 test flights and saw a great deal of effort and expense endo up on the floor of the Atlantic. Tom Clark and a number of preserving leaders continued the vision and readied a second satellite (P3B) for launch three years later. AO-10 is still semi-operational. The Ariane 4x followed and has been an exceptionally successful launch vehicle for ESA (European Space Agency). The Ariane 4x program prospered and continued to increase its efficiency down to a 25-27 day launch timetable. Since the Ariane 4 vehicle is a three stage rocket and each stage adds complexity and risk, Arianespace and ESA decided to

build a larger lift capacity, 2 stage rocket - the Ariane 5. This twelve year development project was undertaken to make ESA competitive in the 21st century. It has been somewhat plagued with problems, but successfully launched P3D in 2000.

Because of its excellent location, launch azimuths from –11 to 90 degrees are over open ocean. Inclinations from 5.2° to 100.5° degrees are achievable. Additionally, Kourou's location close to the equator gives it an advantage for geosynchronous orbits. There have been talks for many years to build launch complexes for other launch vehicles at Kourou, but funding has been difficult to come by to complete the project.

Table 2. Kourou Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
failure	AMSAT P3A	5/23/1980	Ariane-1	with Firewheel, Firewheel Subsat 1,2,3,4; CAT 2
AO-10	AMSAT P3B	6/16/1983	Ariane-1	with ECS 1
AO-13	AMSAT P3C	6/15/1988	Ariane-44LP H10	with Meteosat 3, PAS 1
UO-14	UoSat 3	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 4, Webersat, DOVE ,Pacsat, Lusat
UO-15	UoSat 4	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 3, Webersat, DOVE ,Pacsat, Lusat
AO-16	Pacsat	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 4, Webersat, DOVE ,UoSat 3, Lusat
DO-17	DOVE	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 4, Webersat, Pacsat ,UoSat 3, Lusat
WO-18	Webersat	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 4, UoSat 3, DOVE ,Pacsat, Lusat
LO-19	Lusat	1/22/1990	Ariane-40 H10	with Spot 2, UoSat 4, Webersat, DOVE ,Pacsat, UoSat 3
UO-22	UoSat 5	7/17/1991	Ariane-40 H10	with ERS 1, Orbcomm X, SARA, Tubsat A
KO-23	Kitsat 1	8/11/1992	Ariane-42P H10	with TOPEX Poseidon, S-80/T
AO-24	Arsene	5/12/1993	Ariane-42L H10	Astra 1C
KO-25	Kitsat 2	9/26/1993	Ariane-40 H10	with Spot 3, Stella, Healthsat 2, Eyesat 1, Itamsat, Posat 1
IO-26	Itamsat	9/26/1993	Ariane-40 H10	with Spot 3, Stella, Healthsat 2, Eyesat 1, Kitsat 2, Posat 1
AO-27	Eyesat 1 (AMRAD)	9/26/1993	Ariane-40 H10	with Spot 3, Stella, Healthsat 2, Kitsat 2, Itamsat, Posat 1
PO-28	Posat 1	9/26/1993	Ariane-40 H10	with Spot 3, Stella, Healthsat 2, Eyesat 1, Itamsat, Kitsat 2
AO-40	AMSAT P3D	11/16/2000	Ariane-5G	with PAS 1R, STRV 1c, 1d
BO-47/48	Idefix (BreizhSAT)	5/4/2002	Ariane-42P H10-3	with Spot 5

Cape Canaveral
Other names: Kennedy Space Center
Latitude: 28° 28' N   Longitude: 80° 32'W
Minimum Inclination 28.0°   Maximum Inclination 57.0°
Cape Canaveral is America's largest launch center and used for all of the manned launches. In 1949 the Cape was selected and activated for rocket launches. It has since grown to house a large number of launch complexes. There are four launch groups there: Kennedy Space Center, used for Saturn V and Space Shuttle launches; Cape Canaveral, run by the DOD handling the other launches like the Delta; the commercial Spaceport Flordia; and the air-launched vehicle Drop Zone.
Launch azimuth is constrained between 35 and 120 degrees due to land over flight restrictions. All launch inclinations are restricted to 28.5 and 59 degrees. This is the US launch site for equatorial launches (through orbit changes) and all manned missions.

Table 3. Cape Canaveral Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
OSCAR 4	OSCAR 4	12/21/1965	Titan-3C	with LES 3, LES 4, OV2 3
SO-33	SEDSat	10/24/1998	Delta-7326	with DS1
PO-34	PANSAT	10/29/1998	Shuttle	with Discovery F25, Spartan 201-F5

Plesetsk
Other names: GIK-1; GNIIP; Mirniy
Latitude: 62° 54' N   Longitude: 40° 30'E
Plesetsk was the world's first operational ICBM base. It's very northern location put it closest to the continental US. Four large R-7 complexes were built in the late 1950's. The missiles were only armed once, during the Cuban missile crisis (Sept to Nov 1961). In 1962 Plesetsk was selected over Baikonour for space launches. The major flaw with Baikonour was that the technicians were housed 30 km away, causing 3 to 4 hours of commute time for many vehicles. At Plesetsk the workers were housed in a planned city, Mirniy just 1 to 2 km from the technical sites. At one time Plesetsk was the busiest launch center in the world. Since the breakup of the Soviet Union found Baikonur in Kazakhstan territory, it is thought that once the Proton rocket is retired, major operations will return to Plesetsk. Russia is planning to overcome the low net payload to geosynchronous orbit problem from Plesetsk by looping the satellites around the moon to get the necessary energy to change the orbit plane.

Launch azimuths from Plesetsk are constrained to narrow bands because of over flight considerations. Launch inclinations are generally 62.8, 67.1, 73-74, and 82-83 degrees. Polar orbits can be obtained, but not retrograde. Soyuz (unmanned), Tsyklon F2, Zenit, and Molniya rockets are launched from here, but there seems to be a shift of these launches to Tyuratam.

Table 4. Plesetsk Amateur Satellites Launches

OSCAR	Name	Launch Date Mm/dd/yyyy	Launch Vehicle	Other sats
RS 1	Radio Sport 1	10/26/1978	Tsiklon-3	with Kosmos 1045, RS 2
RS 2	Radio Sport 2	10/26/1978	Tsiklon-3	with Kosmos 1045, RS 1
RS 3	Radio Sport 3	12/17/1981	Kosmos-3M	with RS4, RS 5, RS 6, RS 7, RS 8
RS 4	Radio Sport 4	12/17/1981	Kosmos-3M	with RS3, RS 5, RS 6, RS 7, RS 8
RS 5	Radio Sport 5	12/17/1981	Kosmos-3M	with RS4, RS 3, RS 6, RS 7, RS 8
RS 6	Radio Sport 6	12/17/1981	Kosmos-3M	with RS4, RS 5, RS 3, RS 7, RS 8
RS 7	Radio Sport 7	12/17/1981	Kosmos-3M	with RS4, RS 5, RS 6, RS 3, RS 8
RS 8	Radio Sport 8	12/17/1981	Kosmos-3M	with RS4, RS 5, RS 6, RS 7, RS 3
RS-10/11	Radio Sport 10/11	6/23/1987	Kosmos-3M	included in Kosmos 1861 (Tsikada #16)
AO-21 /RS-14	Informator 1	1/29/1991	Kosmos-3M	included Informator 1
RS-12/13	Radio Sport 12/13	2/5/1991	Kosmos-3M	included in Kosmos 2123 (Tsikada #17)
failure	Techsat 1 (Gurwin 1)	3/28/1995	Start	with EKA 2, Unamsat a
failure	Unamsat a	3/28/1995	Start	with EKA 2, Techsat 1
MO-30	Unamsat b	9/5/1996	Kosmos-3M	with Kosmos 2334 (Parus #86)
RS-20	Mozhayets	11/28/2002	Kosmos-3M	with AlSat 1, Rubin 3

Baikonur (Tyuratam) –

Other names: GIK-5; NIIP-5; Tyuratam, Baykonur(Kazak); Leninsk

Latitude: 46° 00' N Longitude: 63° 00'E

Minimum Inclination 49.0° Maximum Inclination 99.9°

Tyuratam is Russia's largest cosmodrome and the site from which all manned and planetary missions originate. Tyuratam is actually in Kazakhstan, but these republics have agreed to cooperate and jointly benefited from the launch complex. Tyuratam is the original site designation and the location from which Yuri Gargarin was launched into space in 1961. The story goes that in order to register the achievement with the International Aviation Federation the launch site must be named. Since this was during the cold war, the Soviet policy was not to confirm the location of their missile sites. So to register the event, the soviet's declared the launch site to be Baikonur, 300km NE of Tyuratam. This became the published location for many years and the name stuck.

This remote location was selected because the original R-7 rockets were controlled by three radio control stations arranged in a triangle 150-200km away from the launch site. The Kaputsin Yar site would require a station in the Caspian Sea or Iran, which was unacceptable. So a new location in an isolated site was chosen for security. The complex is extremely large, 85 km N to S by 125 km E to W. As internally guided rockets were developed building a new launch site in a more accessible area was constantly discussed, but the existing infrastructure made conversions to Baikonur more economical.

Numerous launch azimuths are possible from here, 65 degrees to –13 degrees, producing orbital inclinations between 50 – 99 degrees. Launches to the east are prohibited due to the likely impact of the stages on China. Most missions are typically 62.5 degree azimuth giving an inclination of 51.6 degrees. All Proton, Tsyklon F1 and Zenit rockets are launched from Baikonur.

Table 5. Baikonur/Tyuratam Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
RS-15	Radio-ROSTO	12/26/1994	Rokot-K	
RS-17a	Sputnik 40	10/5/1997	Soyuz-U	with Progress-M 36, Inspector 1, Sputnik 40-2
RS-17b	Sputnik 40-2	10/5/1997	Soyuz-U	with Progress-M 36, Inspector 1, Sputnik 40
TO-31	TMSat 1	7/10/1998	Zenit-2	with Resurs-01 2,Techsat 1B, FASat Bravo, Safir 2, WestPac
GO-32	Tecsat 1B (Gurwin 1B)	7/10/1998	Zenit-2	with Resurs-01 2,TMSat 1, FASat Bravo, Safir 2, WestPac
RS-18	Sputnik 41	10/25/1998	Soyuz-U	with Progress-M 40
RS-19	Sputnik 99	4/2/1999	Soyuz-U	with Progress-M 41
UO-39	UoSat-12	4/21/1999	Dnepr-1	
SO-41	Saudisat 1A	9/26/2000	Dnepr-1	with Megsat 1, Unisat 1, Saudisat 1B, Tiungsat 1
SO-42	Saudisat 1B	9/26/2000	Dnepr-1	with Megsat 1, Unisat 1, Saudisat 1A, Tiungsat 1
MO-46	Tiungsat 1	9/26/2000	Dnepr-1	with Megsat 1, Unisat 1, Saudisat 1B, Saudisat 1A
RS-21	Kolibri 2000	11/26/2001	Soyuz-FG	with Progress-M1 7
AO-49	Safir-M (AATiS Oscar)	12/20/2002	Dnepr-1	included in Rubin 2; with Unisat 2, LatinSat 1, LatinSat 2, SaudiSat 1C, TrailBlazer-Dummy
SO-50	SaudiSat 1C	12/20/2002	Dnepr-1	with Rubin 2, Unisat 2, LatinSat 1, LatinSat 2, TrailBlazer-Dummy

In 1991 the US and Russia signed the Start Treaty that calls for the removal of nuclear missiles from their arsenals. The Russian SS-18 ICBM is the most powerful ICBM in the world and the Soviets decided that they would constructively dispose of them. ISC

(International Space Company) Kosmotras was established in 1997 for development and commercial operation of the Dnepr Space Launch System based upon the SS-18 ICBM technology. This is one of the largest conversion programs with a 150 SS-18 missiles to be converted into commercial satellite launch vehicles. With the dissolving of the USSR, this venture has encouraged the cooperation of the Russian Federation, Ukraine and Republic of Kazakhstan. Twelve satellites have been launched to date with customers from UK, USA, Italy, Saudi Arabia, Malaysia and Germany. AMSAT-NA's ECHO is scheduled for launch in March 2004 on the Dnepr rocket from Baikonur.

Tanegashima Space Center
Latitude: 30° 24' N Longitude: 130° 58'E
Minimum Inclination 28.5° Maximum Inclination 99.0°
Tanegashima is the main Japanese launch facility located on an island about 1000 km SW of Tokyo. Japan's large H2 and J1 vehicles are launched from here during a 'launch season' dictated by the local fishing season. All three of the JAMSAT amateur satellites have been launched from Tanegashima.
Launch azimuth is nearly unrestricted, with possible inclinations from 28.5 to 100 degrees.

Table 6. Tanegashima Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
FO-12	JAS 1a (Fuji 1)	8/13/1986	H-1 (9 SO)	with EGS, MABES
FO-20	JAS 1b (Fuji 1b)	2/7/1990	H-1 (9 SO)	with MOS 2, DEBUT
FO-29	JAS 2 (Fuji 2)	8/17/1996	H-2	with ADEOS 1

Kodiak
Latitude: 57° 26' N Longitude: 152° 20'W
In January 1998 the Alaska Aerospace Development Corporation leased 1200 hectares of land on Kodiak Island to build a commercial spaceport. Kodiak Island is 400km south of Anchorage. The Island is advertised as an excellent location providing a wide range of launch azimuths into polar orbit. The facility can launch up to 3500kg into LEO or Molniya orbit. The weather is surprisingly mild due to the warm Japanese currents and similar to the northwestern part of the US. It has an excellent port and rail facilities, making it a more favorable launch site than one would imagine. In 2001, the first Athena rocket launch carried three amateur satellites successfully into orbit.

Table 7. Kodiak Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
SO-43	Starshine 3	9/30/2001	Athena-1	with PCSat, PICOSat, SAPPHIRE
NO-44	PCSat	9/30/2001	Athena-1	with Starshine 3, PICOSat, SAPPHIRE
NO-45	SAPPHIRE	9/30/2001	Athena-1	with PCSat, PICOSat, Starshine 3

Svobodniy
Other names: GIK-2
Latitude: 51° 42' N Longitude: 128° 00'E
Minimum Inclination 51.0° Maximum Inclination 110.0°
Following the breakup of the Soviet Union, Russia found Baikonur in Kazakhstan territory and Plesetsk without the facilities to launch large vehicles or place objects into low inclination orbits. So Russia decided to develop a new cosmodrome to give her a versatile launch port in her territory. Svobodniy, a decommissioned ICBM base located 8000 miles east of Moscow, was chosen 1996 to be new launch facility. A crash program was begun to build a facility that would handle both large and medium launch vehicles. Launch complexes for the Rokot and Start rockets were completed first and then the funding for the conversion dried up. Svobodniy can launch into polar orbit and to the ISS (International Space Station).

Table 8. Svobodniy Amateur Satellites Launches

OSCAR	Name	Launch Date mm/dd/yyyy	Launch Vehicle	Other sats
RS-16	Zeya	3/4/1997	Start-1.2	

Other launch sites
Currently there are less than two dozen active launch sites in the world. There are a dozen or more inactive sites that could be reactivated and converted, but this is an expensive proposition. There are also numerous companies and US states that have acquired space launch sites in various locations attempting to make a business of launching satellites, but these have not matured to date. There appears to be more capacity than major organizations willing to fund primary payloads. However, there are many groups and organizations wanting to participate as secondary payloads, which makes it more difficult for AMSAT, because they must to compete for these spots.

Jiuquan
Latitude 41.3° N Longitude 100.3° E
Inclinations: 57 - 70°
China's first launch site, but lately has been inactive. It has been undergoing renovation to prepare it for manned launches and there is an expectation that China will launch a man into space in Oct/Nov of 2003.

Sea Launch
Latitude 0° N Longitude 154.0° W
Inclinations: 0 - 100°
Long Beach, CA based multi-national corporation. They use a converted Norwegian oil platform to launch Russian Zenit 3SL rockets. The platform is towed out to the equator for launches. You want watch the entire process on the Internet.

Kagoshima
Latitude 31.2° N Longitude 131.1° E
Inclinations: 31 - 100°
Used for Japanese scientific missions. Launches the M-V vehicle.

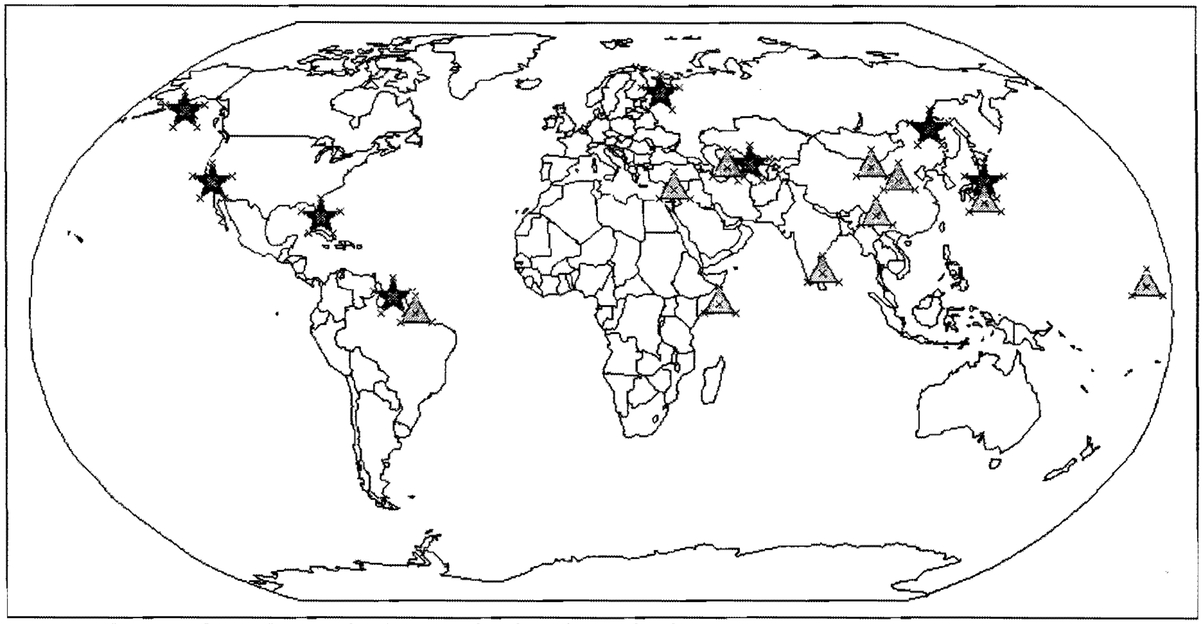


Figure 3. AMSAT Launch sites and other launch sites

Kapustin Yar (Volograd)
Latitude 48.6° N   Longitude 46.3° E
Inclinations: 51°
Russian launch site from 1961-1984 for satellite launches into 48-51° inclination orbit. Reactivated in 1999 for Kosmos 3M launches.

Xichang
Latitude 28.2° N   Longitude 102.0° E
Inclinations: 27.5 – 31.1°
Primary Chinese launch site for GTO playloads. Long March 2E, 3, 3A, 3B, and 3C vehicles.

Taiyuan
Latitude 38.7° N   Longitude 111.5° E
Inclinations: 87° and 96 - 98°
Launch site for smaller Chinese launches. Supports the LM-4 and LM-2C/SD vehicles.

Sriharikota (Satish Dhawan Space Center)
Latitude 13.9° N   Longitude 80.4° E
Inclinations: 18 - 50°, SSO with dogleg
Indian space launch center for their PSLV and GSLV vehicles. Scheduled to launch India's first amateur satellite late 2003.

Alcantara
Latitude 2.3° N   Longitude 44.4° W
Inclinations: 2.2 - 100°
Brazilian launch site for their VLS and VLM vehicles. They have been trying to establish a launch program for a number of years, but have been unsuccessful in launching a rocket, the latest failure was in late August 2003. There have been numerous discussions with other countries to launch their rocket here since this is a prime location, but to date none of these have worked out.

Palmachim AFB
Latitude 31.9° N   Longitude 34.7° E
Inclinations: 143°
Israel launch site for the Shavit 1 rocket. This must launch over the Mediterranean to avoid over flying neighboring countries. Not a very active site.

San Marco, Kenya
Latitude 2.9° S   Longitude 40.3° E
Inclinations: 2.9 - 38°
This is an Italian sea-based platform located near Kenya. Used to launch the US built Scout until 1988. Now is launching the Start, Start 1 and Taurus rockets. Basically used to launch medium weight scientific payloads into LEO.

Some basic launch and orbital physics.

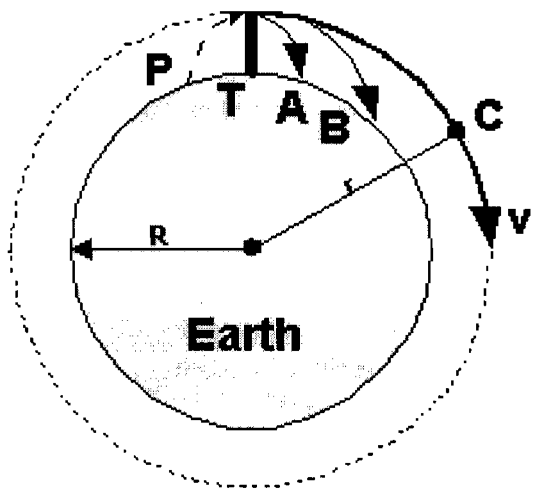
Let's take a look at some of the physics that affect the launch.
We all know that gravity causes objects to be attracted to the center of the earth. The same is true of objects in space around the earth, but the effect decreases the further from the earth's center.

Using Figure 4, visualize a projectile launched horizontally from the top of the tower **T** above the earth's atmosphere at different velocities.

- **A.** Launched with a low initial velocity would fall to earth a short distance away following a parabolic path.
- **B.** Launched with a medium velocity also falls to earth, but at a greater distance.
- **C.** Launched with a high velocity around 18,000 mi/hr also falls to earth, but it follows a curved path, keeping its distance from the center constant.

Now let's launch a rocket from the ground vertically at location P. As the rocket speed increases, the guidance system gradually turns the rocket so that at the instant the fuel is exhausted the last stage has the proper speed and direction for the selected orbit. The precision required to do this is quite difficult to attain, so all initial orbits are not quite as predicted. How accurate the launch system has been in hitting the proposed orbit is an advertising point for most launch organizations.

Figure 4. Basic launch diagram



For a satellite to have a circular orbit around the earth, the satellite must achieve a velocity such that its centripetal acceleration $\mathbf{v^2/r} = \mathbf{g_r}$ (acceleration due to gravity). We determine that velocity using the following equation:

$$v = \sqrt{\mathbf{g}\ (\mathbf{R^2/\,r})}$$

where **v** is the velocity, **g** is the acceleration due to gravity at the earth's surface ($9.8\ m^2/s^2$), **R** is the earth's radius (6360 km), and **r** is radius of the satellite orbit. The Period is the length of time it takes the satellite to make one revolution.

To place a satellite in circular orbit at 800 km we substitute in the formula above

$$v = \sqrt{[9.8 * (6{,}360{,}000)^2\, m^2/s^2 \,/\, 7{,}160{,}000m]} = \sqrt{(55.4 \times 10^6\ m^2/s^2)} =$$

satellite velocity @ 800 km orbit = 7441 m/sec = 16,644 mph

Table 9. Representative altitudes, satellites and velocities for circular orbits

Orbital altitude	Satellite velocity	Satellite velocity	Period in min
300 km	7,715 m/sec	17,258 mph	90.3
350 km (shuttle, ISS)	7,686 m/sec	17,193 mph	91.3
400 km	7,658 m/sec	17,130 mph	92.4
500 km	7,602 m/sec	17,004 mph	94.4
600 km (UO-11)	7,547 m/sec	16,882 mph	96.5
700 km (OO-38)	7,493 m/sec	16,762 mph	98.6
800 km (AO-27, UO-14)	7,441 m/sec	16,644 mph	100.7
900 km (RS-10/11)	7,389 m/sec	16,529 mph	102.8
1000 km	7,339 m/sec	16,417 mph	104.9
1100 km (FO-29)	7,290 m/sec	16,306 mph	107
1200 km (met-3/5)	7,241 m/sec	16,198 mph	109
1300 km (FO-20)	7,147 m/sec	15,988 mph	111
1,450 km (AO-7)	7,124 m/sec	15,937 mph	114
35, 768 km (GSO)	3,068 m/sec	6,862 mph	1434
391,000 km (moon)	1,000 m/sec	2,237 mph	41,392

After examining the data in Table 9, your initial impression is probably that the data is incorrect, since the satellite velocity decreases as you get further away from the earth.

Intuition tells you that the speed should increase the further from the earth you go, but actually the opposite is true. In fact, to move a satellite into an orbit further from the earth you slow it down. And even more counter intuitive, to get a satellite like the shuttle to return to earth it must speed up to lower its orbit. The closer a satellite is to the earth the faster it goes.Of course thrust in the intended direction is also necessary to change the orbit. Velocity is crucial and determines shape of the orbit.

To achieve a circular orbit the satellite must have the correct velocity when it is separated from the launch vehicle. Too fast or too slow will result in an elliptical orbit.

Orbits

The orbital plane of a satellite runs through the center of gravity of the earth. Since the earth rotates under the satellite the orbit actually changes constantly since the earth is not round and consistent. Inclination is the angle measured as the satellite goes from south to north, called the ascending node between the orbital and equatorial planes. See Figure 5. Note the inclination angle measurement *i* at the equator and the satellite direction. Inclination is also defined as, the angle between H - the angular momentum vector, and the earth's rotation vector. This explanation "is left to the student."

If the inclination of the satellite orbit is less than 90° it is called a **Prograde** orbit ($0° \leq i < 90°$). The orbit is **Retrograde** if the satellite movement is against the rotation of the earth ($90° \leq i < 180°$). For a **Geostationary** orbit the inclination has to be exactly 0° (not $i = 180°$). A **Polar** orbit is one that is perpendicular to the equator with ($i = 90°$).

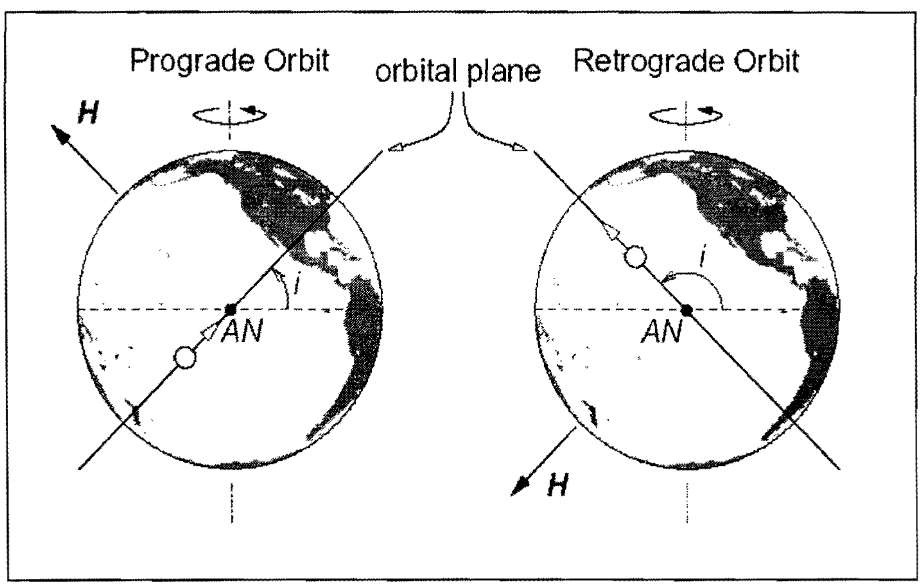


Figure 5. Orbits diagram; Delft Lecture, *Orbit maintenance and perturbations*

Satellites in elliptical orbit like AO-10, AO-13 and AO-40 constantly change their distance and velocity during the orbit. The fastest speed is at the closest point in the orbit, perigee, and slowest at the furthest point, apogee. This is much like a swing, as you approach the most distant point from the earth you slow down, until you reach maximum height, then start picking up speed again until you reach maximum speed at the bottom.

Types of orbits

There are a number of ways to categorize orbits; generally this is done by shape and altitude. The shapes are circular (with low eccentricity) and elliptical with higher eccentricity – oval-shaped. Basically the circular orbits are relatively close to the earth, while the elliptical orbits are further. See Table 10 for a better comparison.

A **Polar** orbit is the simplest orbit type. The orbit is circular and inclined 90°(or close to 90°) to the equator with the satellite passing over each of the poles during each orbit. This orbit allows all points on earth to be in view of the satellite twice each day. Typical polar orbits are at an altitude of 850 km with a period of 100 minutes. There are just over 14 orbits per day. At this altitude the satellite has a ground view of an area about 3000 miles wide.

Sun-synchronous is a special case circular, polar orbit. It has an inclination of 98.7°, a retrograde orbit. This precession of the orbit matches the apparent motion of the sun relative to the earth, about 1° per day. The key feature of this orbit is that in each half of the orbit, the satellite always crosses a particular line of latitude at the same local solar time each day. The angle of the sunlight will therefore be consistent, only varying slowly as the seasons change in the course of a year.

Geosynchronous orbits allow a satellite to appear stationary from the point of view of an observer on earth. The orbital period matches the rotation rate of the earth. The rotational rate is the sidereal day (23h 56m 4s), not the twenty-four hour civil day. Often geosynchronous and geostationary are used interchangeably, but they are not the same. The definition of geosynchronous does not specify the shape or orientation of the orbit. So, a geostationary is a special case of a geosynchronous, with the added stipulations that the orbit is circular and lies in the equatorial plane. To save energy by not having to correct their location as often, most geosynchronous satellites oscillate in a figure 8 pattern, but the receive antennas are designed to cover this. Actually most satellites considered geostationary are actually geosynchronous, because their orbits are slightly elliptical and not quite on the equatorial plane, thus extending their lifetime.

n-th resonant orbit is one that completes an integral number of orbits in one day. A 15^{th} –order resonant orbit will complete 15 orbits in a 24 hour day. The shuttle often uses a 16^{th} order resonant orbit because it permits same day synchronization if work and sleep schedules.

Molniya orbits are highly elliptical orbits with inclinations of 63.4° or 116.6° and perigee values between 200 – 1000 km. These orbits allow views of the northern hemisphere for 11 hours out of 12 for either the US or Russia. If the perigee is in the southern hemisphere, it stays there and does not move into the northern hemisphere as other orbits.

Table 10. Typical orbit parameters for general satellite classes

	Altitude, km	Eccen-tricity	Inclination	Period	Mean Velocity
LEO	500 - 1500	Low	30° - 90°	1 – 2 hr	~7.3 km/s
MEO	5,000 – 10,000	Low	30° - 90°	5 – 8 hr	~ 5 km/s
GSO	35,786	0	0°	23h 56m	~3 km/s
HEO: Ellipso	520 – 7846	~ 0.35	116.4°	3 hours	~6.5 km/s
Archimedes	1000 – 26,800	0.63	63°	7 h 59 m	~5 km/s
Molniya	500 – 39,400	0.74	63.4°	11 h 58 m	~4 km/s
Tundra	25,250 – 46,300	~0.25	63°	23 h 56 m	~3 km/s

GSO – Geostationary Earth Orbit (Direct Broadcast, Fixed Satellite, Intersatellite links)

Non- GSO {
- LEO – Low Earth Orbit (voice, high speed data, rescue, remote sensing)
- MEO – Medium Earth Orbit (voice, data, radio navigation, reconnaissance)
- HEO – Highly Elliptical Orbit (communications services)

Changing orbits

Almost all satellites start off in elliptical orbits because it is so difficult to get the exact release speed needed for a circular orbit. Most satellites fire rockets when they are above the earth's atmosphere to correct the orbit. To change an orbit a satellite must actually be in an elliptical orbit. An in-orbit burn is generally necessary and may be done by the upper stage of the rocket if it is restartable. After the current orbit is determined, then the correction is calculated and the burn commences. A horizontal burn will increase or decrease the velocity of the satellite, making the orbit more elliptical or circular depending up where in the orbit the burn takes place, how long it takes place and which direction the burn occurs.

A posigrade burn is one done in the opposite direction that the satellite is moving to increase its velocity. If done at perigee in a circular orbit, the orbit will change to elliptical with an apogee further away. Looking at Figure 6 this would change the orbit from A (circular LEO) to B, same perigee, but new apogee at a greater altitude. **The new orbit will always intersect the old orbit at the burn point**. Starting with elliptical orbit B and doing a retrograde burn at apogee will keep the same apogee, but will result in a new perigee at a greater altitude and close to a circular orbit if the correct velocity is reached.

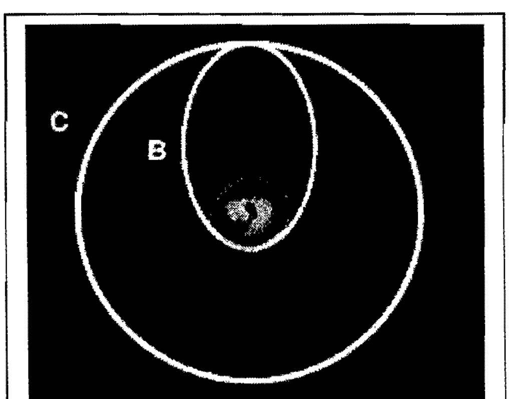
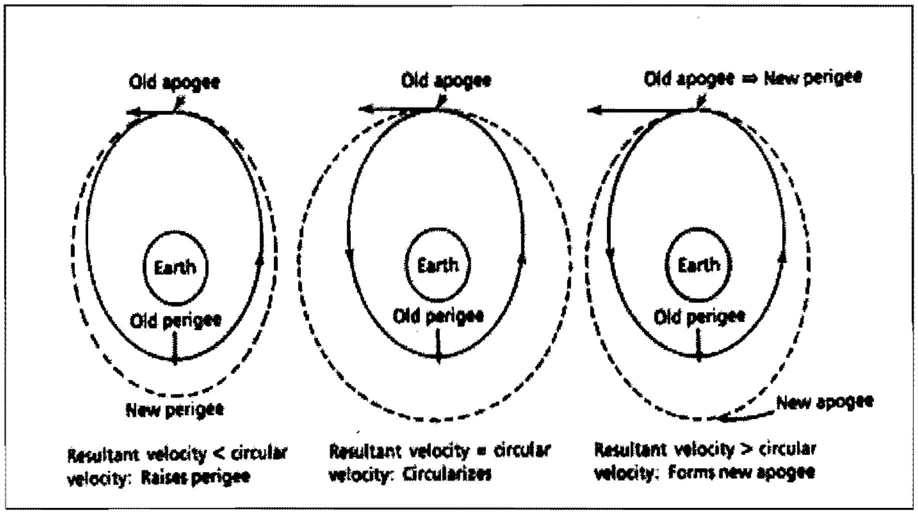


Figure 6. General orbit burn diagrams, from NASA Aeroscholars lessons

Remember that you want to decrease the velocity to go into a higher orbit. After the burn, the resulting velocity of the satellite determines whether the orbit is circular or elliptical.

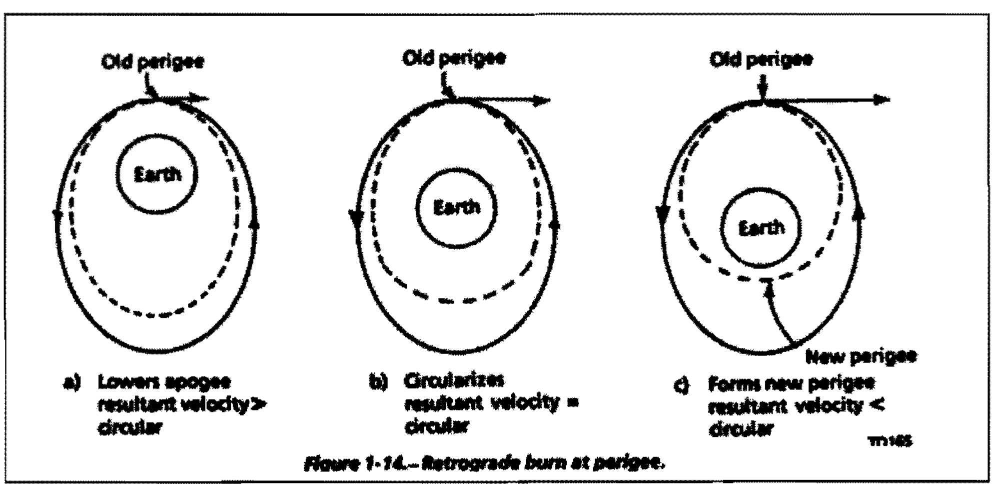
Figure 7. Apogee burn diagrams, from NASA Aeroscholars lessons



. When the Posigrade burn takes place at perigee the apogee changes, and the perigee stays the same. If the burn takes place at apogee the perigee changes and the apogee stays the same with the orbit becoming more circular (decreasing eccentricity) if the correct velocity results.

Retrograde burns are in the same direction as the satellite is traveling, like reversing the engines during a jet landing and will slow the space craft down. Using the diagrams in Figure 8 and doing the retrograde burn at perigee will lower the velocity causing one of three results depending upon the amount of velocity change, ΔV. If the velocity is greater than needed for a circular orbit the apogee will decrease. If equal to the circular orbit velocity, then the orbit will indeed become circular. And if the velocity is less than that need for a circular orbit the perigee will decrease to a point closer to the earth.

Figure 8. Retrograde burn diagram, from NASA Aeroscholars lessons



This ability to change orbits is very important to getting a satellite into its prescribed orbit, but doesn't come cheap – a great deal of energy is needed. The most efficient method to change from a circular orbit to another circular orbit in the same plane is known as the Hohmann Transfer. The description around Figure 6 is actually a Hohmann Transfer and the reason it is fuel efficient is that the second burn only has to slow the craft down to the correct velocity for a circular orbit at that altitude.

The Space Shuttle can deliver a satellite into an orbit with an inclination of 28.5° and a altitude of 300 km. If the satellite is destined for geosynchronous orbit then the satellite must move to an inclination of 0° and an altitude of 35,786 km. This will involve both an inclination change and an altitude change. The Hohmann Transfer we discussed is used to change the altitude, but plane change is a different matter. It requires a great deal of energy for a spacecraft to change planes. Since the point in an orbit when a burn occurs becomes part of the new orbit, it is necessary to make this plane change when the current orbit crosses the 0° plane. These two planes only interest at two points during the orbit. Since we have already achieved the correct altitude the only action will be to plan the necessary vector direction to move the spacecraft from 28.5° inclination to 0°. This requires a burn at an angle of –75.7° and a change in velocity from 7.726 km/sec to 3.801 km/sec. Normally the plane change is accomplished in two steps. About 2° of the plane change occurs during the first burn from circular to elliptical (A to B). Then 26° of the plane change occurs during the second burn - elliptical to circular.

Orbit selection

There are a number of companies that specialize in computing the best orbit for a particular project or mission. The web site has a JABA Orbit Simulator so you can experiment entering different launch parameters and see the resulting orbit. This can be found at: http://www.met.ed.ac.uk/courses/projects/gavin/Projects.html

Some of the factors to determine the type of orbit are:

- Payload Mass
- Capability and objective of the sensors
- Mission lifetime
- Necessary altitude to perform the functions
- Sun-synchronous orbit or not
- Orbital precession
- Stationary position or constantly changing position
- Launch reliability
- Launch cost

The Launch site and its relationship to a satellite's inclination

The most efficient way to launch a payload into orbit is to launch it due east. This will take maximum advantage of the earth's rotational speed at the surface. But to launch directly into an orbit it is necessary to wait until the launch base crosses the intended orbital plane, hence the launch window. At the equator this velocity is 1,037 mph, at Cape Canaveral the speed has already been reduced to 915 mph and is 0 mph at the poles.

Launches in any direction other than east necessitate the expenditure of extra fuel. It is easy to see why Kourou and Sea Launch both offer advantages; this boost from the earth's rotation can be used to carry more mass into orbit. This is the same advantage you get when throwing a ball when running forward, like in cricket or a javelin.

If a rocket is launched due east, with no directional changes, it will result in an orbit with an inclination equal to the latitude of the launch site. Cape Canaveral is at 28.5° N latitude, so a launch due east will result in a satellite orbit with an inclination of 28.5°, which is a common orbit for the Space Shuttle. The down side to a 28.5° inclination orbit is that areas above latitude 48° cannot see the satellite.

Launch sites can physically launch directly into any orbital inclination that satisfies this relationship: $|\phi| \leq \mathbf{i} \leq \mathbf{180°}-|\phi|$, where ϕ is the latitude of the launch site. Many of the launch sites are further restricted in the actual launch angles because of safety concerns that the burned out rocket stages might fall on populated areas. As such, the minimum launch angle from Cape Canaveral is 35° and the maximum is 120°. China had problems with many of it early launches from Xichang because parts of the rocket fell on populated areas. A launch in 1998 from Vandenberg was held up for weeks, because the standard United Nations population census had become out of date and a small island in the Pacific had become inhabited and was in the flight path. The flight path was altered. The formula to compute the orbital inclination based upon the launch location and launch angle is: **cos (inclination) = cos (latitude) * sin (launch azimuth)**

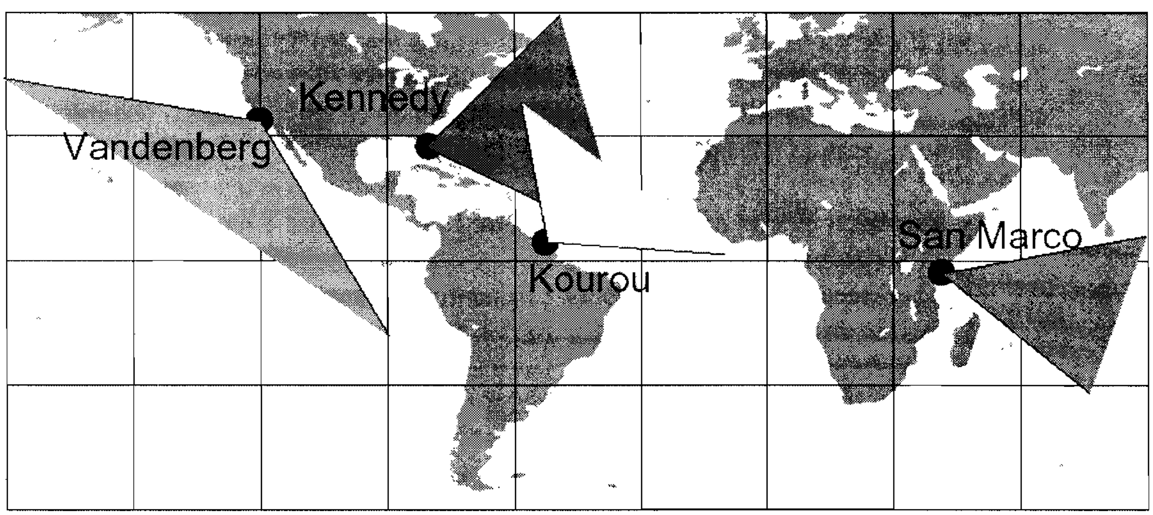


Figure 9. Possible launch angles from selected launch sites. Drawing from Delft Lecture, *Orbit maintenance and perturbations*

The orbital velocity of an object directly determines the altitude and shape of the orbit. Achieving this velocity is quite difficult because a great deal of energy is necessary to develop this velocity for the satellite. A great deal of energy means a great deal of mass for the fuel, rocket and payload that must also achieve this speed.

How much power does it take to launch a satellite?

According to Strong, 97% of the total launch mass is fuel, this leaves only 3% of the liftoff mass for the rocket itself, the satellite and its container.

$\Delta V = U \ln(M_i / M_f)$

where

ΔV = change in velocity of the rocket
U = velocity of exhaust gases relative to the rocket
M_i = initial mass of the rocket and fuel
M_f = final mass of the rocket

For a satellite in LEO, $\Delta V = 7$ km/s while $U \approx 2.4$ km/s, typically
$\therefore \Delta M = 0.95 M_i$, or the fuel should be 95% of the initial mass
Taking gravity into account, this increases to 97%, so only 3% of the initial mass is available for the rocket and payload!
It is easy to see why single stage rockets can only put small masses into orbit.

Launching into GEO (Geostationary Equatorial Orbit) requires quite a bit more energy that LEO, but most of the energy is consumed during the initial part of the launch.

~35 MJ/kg are needed to reach 850 km
1 joule per second = 1 Watt,
so to put 2.2 lbs(1 kg) into an 850 km orbit would require 35 million Watts
746 joules/sec = 1 hp, thus 2.2 lbs would require 46,917 hp to reach this orbit
each pound needs 21,325 hp or 15,909,090 Watts to reach an 850 km orbit
each ounce needs 1,332 hp or 994,318 Watts

Nearly a million Watts of power are needed to orbit just 1 oz. at 850 km.

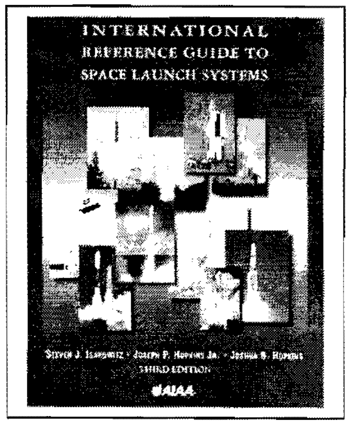
~23 MJ/kg more are needed to reach GEO (42 times further from the surface)
58 MJ/kg are needed for GEO (58 million Joules for each kg of mass)

So, it is very obvious why fuel efficiency and weight is so important in launching satellites. As I have said, it is most fuel efficient to launch directly into the desired inclination. Changes in the orbit plane are very expensive in terms of fuel. So the launch site plays a big part in determining the amount of fuel needed to lift a certain mass. The closer the launch site is to the intended inclination the more fuel efficient the launch can be and thus the more mass can be lifted for the same amount of fuel compared to a different latitude.

Launch Vehicles

One of the best resources I have found that describes the launch vehicles in extraordinary detail including the lift capacity, launch history and launch cost is the book *International Reference Guide to Space Launch Systems*. You can get this at many university libraries

or order it for about $75. I highly recommend this for very interesting reading and a great introduction to a field many of us have little to no knowledge.
Just as there are many satellites with many functions, there are many launch vehicles with many capacities. It requires a great deal of research to find the correct launch vehicle that can lift the necessary mass to the orbit you need at the cost you can afford. **In fact it may be the case for many non-profit and academic groups seeking launches that the payload is dictated by the launch opportunity.**



As already discussed space craft mass is at a premium. Looking at Tables 11-15 you can see the diversity of launch vehicle lift capabilities to different altitudes and inclinations. These range from the small Start and Taurus rockets that can only lift 100-200 kg into an 800 km orbit to the powerful Ariane rocket that can lift 7500 kg into the same orbit – 50 times the mass. The reason that there are so many different types of launch vehicles is the cost to put the satellite into orbit differs greatly. Those wishing to launch a satellite find it is well worth the effort to comparison shop, the launch cost varies from $9 million for the Start to $85 million for the Ariane.

Keep in mind that the old adage "You get what you pay for" is still appropriate in selecting launch vehicles. Often the inexpensive launches may be for untested vehicles or rockets that haven't proven their reliability or they may just be smaller rockets with fewer stages. A number of military launch vehicles have been converted to launch vehicles for satellites rather than nuclear weapons.

Table 11. San Marco platform launches payload mass to different altitudes

Launcher height km	Start1 Payload kg	Start Payload kg	Taurus Payload kg
400	232.55	306.93	562.63
500	190.68	289.59	463.14
600	160.10	267.61	369.59
700	125.99	232.54	297.23
800	111.0	201.99	232.11

Table 12. Athena 1 launch vehicle curves from Kodiak launch site

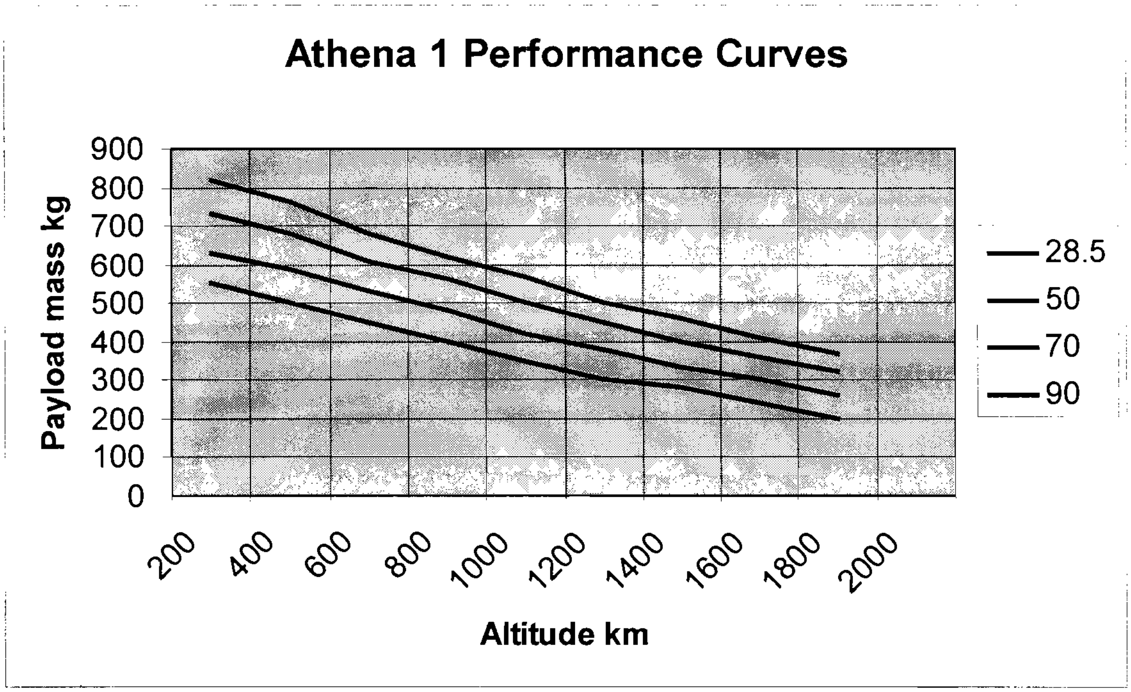


Table 13. Kosmos-3M Performance Curves

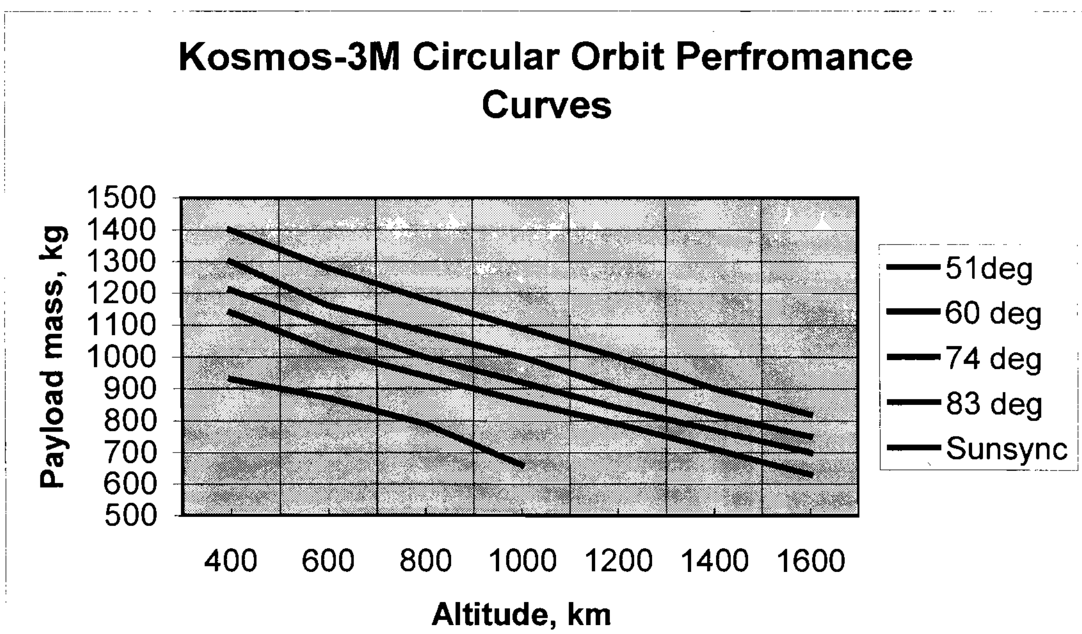


Table 14. Dnepr-1 Performance curves for circular orbits – ECHO launch vehicle

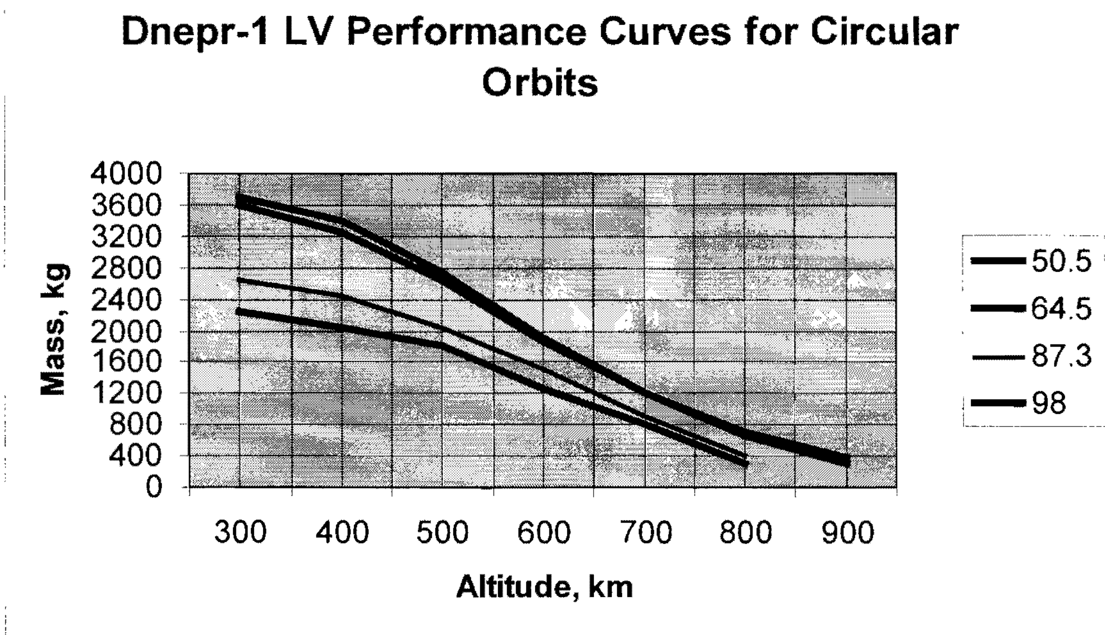


Table 15. Ariane 4x Performance curves

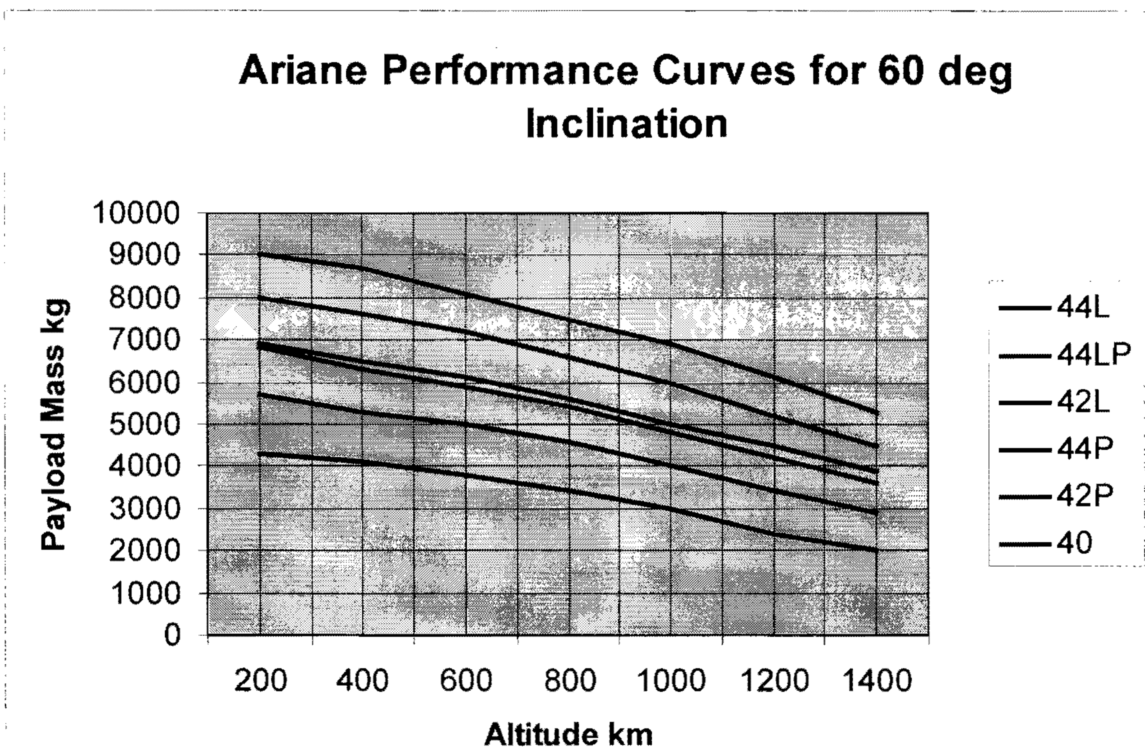
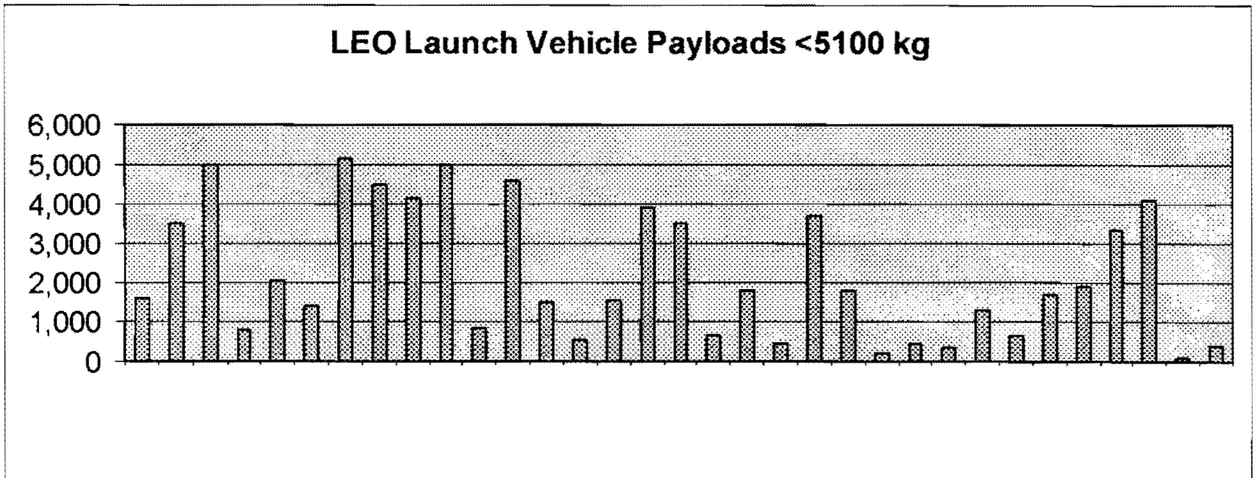


Figure 16. LEO Launch Vehicle Payloads in kg for various launch vehicles



What does it cost to launch a satellite?

This is a very difficult question to answer. There is little public data available and much of that is given in a range of millions of dollars. The launch fee is a very negotiable item; as such the fees are not often published that leaves the field wide open for the next opportunity and negotiation. Below are tables of most of the current launch vehicles.

Table 16. United States launch vehicles, capacity and costs

Country	Vehicle	LEO Max(kg)	SSO kg	GTO kg	Launch cost ($M)	first flight	Launch site(s)
United States	Athena I	820	360	n	16-17	1995	Vandenberg,Cape C. ,Kodiak
United States	Athena II	2,065	1165	590	22-26	1998	Vandenberg,Cape C.,Kodiak
United States	Atlas IIA	7,316	?	3066	75-85	1992	Cape Canaveral, Vandenberg
United States	Atlas IIAS	8,618	?	3719	90-105	1993	Cape Canaveral, Vandenberg
United States	Atlas IIIA	8,640	5671	4037	90-105	1999	Cape Canaveral
United States	Atlas IIIB	10,718	5885	4477	90-105	2000	Cape Canaveral
United States	Atlas V 400	12,500	?	5000	75-90	2001	Cape Canaveral, Vandenberg
United States	Atlas V 500	20,050	?	8200	85-110	2001	Cape Canaveral, Vandenberg
United States	BA-2	17,000	11,500	5800	?	2000	Sombrero Island
United States	Delta II	5,140	3220	1870	45-60	1990	Cape Canaveral, Vandenberg
United States	Delta III	8,290	6100	3810	85	1998	Cape Canaveral
United States	Delta IV Medium	8,600	6300	3900	75-90	2001	Cape Canaveral, Vandenberg
United States	Delta IV Medium Plus	13,600	9600	6120	85-110	2001	Cape Canaveral, Vandenberg
United States	Delta IV Heavy	25,800	19,200	12,400	140-170	2003	Cape Canaveral, Vandenberg
United States	K-1	4,600	1250	n	17	2000	Woomera, Nevada Test site
United States	Minotaur	639	336	n	12.5	1999	Vanenberg, Others
United States	Pegasus XL	443	190	n	12-15	1994	Vandenberg, Cape Canaveral
United States	SSLV Taurus	1,320	660	400	18-20	1994	Vandenberg, Others
United States	Comm Taurus	1,380	720	448	18-20	1998	Vandenberg, Others
United States	Titan II	1,900	?	?	30-40	1986	Vandenberg
United States	Titan IVB	21,680	?	?	350-450	1997	Cape Canaveral, Vandenberg
United States	Space Shuttle	24,400	n	n	300	1981	Kennedy Space Center

Table 17. ESA and CIS launch vehicles, capacity and costs

Country	Vehicle	LEO Max(kg)	SSO kg	GTO kg	Launch cost ($M)	first flight	Launch site(s)
Europe	Ariane 40	5000	2845	2175	65-85	1990	Kourou
Europe	Ariane 42P	6,600	3845	2890	70-90	1990	Kourou
Europe	Ariane 44P	7600	4560	3465	80-100	1991	Kourou
Europe	Ariane 42L	7,900	4810	3590	80-100	1993	Kourou
Europe	Ariane 44LP	9100	5660	4290	90-100	1988	Kourou
Europe	Ariane 44L	10,200	6485	4790	100-125	1989	kourou
Europe	Ariane 5	18,000	12,000	6800	150-180	1996	Kourou
Russia	Angara 1.1	1,600	?	n	?	2001	Plesetsk
Russia	Angara 1.2	3,500	?	1800	?	2002	Plesetsk
Russia	Angara 5L	24,500	?	6800	?	2003	Plesetsk
Russia	Kosmos 3M	1,500	775	n	12	1967	Plesetsk
Russia	Proton K	19,760	3620	4910	90-98	1967	Baikonur
Russia	Proton M	21,000	?	5500	100-112	2000	Baikonur
Russia	Rockot	1,800	1000	n	13-15	1994	Plesetsk, Baikonour
Russia	Shtil-1	430	?	n	0.1-0.3	1998	Delta IV Submarine
Russia	Shtil-2	350	?	n	?	?	Delta IV Submarine
Russia	Start-1	632	167	n	9	1993	Svobodny, Plesetsk
Russia	Start-1	?	?	n	10.5	1995	Svobodny, Plesetsk
Russia	Strela	1,700	?	n	10.5	2000	Svobodny
Russia	Soyuz U	7,000	2750	1350	30-50	1963	Baikonur, Plesetsk
Russia	Soyuz ST	7,800	4500	1450	30-50	2001	Baikonur, Plesetsk
Russia	Molniya	n	1500	n	30-40	1960	Baikonur, Plesetsk
Ukraine	Dnepr-1	4,500	140	n	10-20	1999	Baikonur
Ukraine	Dnepr-M	4,140	1600	n	10-20	2001	Baikonur
Ukraine	Tsiklon 2	3,350	2100	n	20-25	1967	Baikonur
Ukraine	Tsiklon 3	4,100	n	n	20-25	1977	Plesetsk
Ukraine	Zenit 2	13,500	5000	n	35-50	1985	Baikonur
Ukraine	Zenit 3SL	?	?	5000	75-95	1999	Sea Launch

Table 18. Launch vehicles, capacity and cost from other countries

Country	Vehicle	LEO Max(kg)	SSO kg	GTO kg	Launch cost ($M)	first flight	Launch site(s)
Brazil	VLS	380	80	n	8	1997	Alcantara
Brazil	VLM	100	18	n	4	2002	Alcantara
China	LM-2C	3900	?	1400	20-25	1975	Taijun, Jiuquan
China	LM-2D	3500	?	n	15-Oct	1992	Taijun
China	LM-2E	9500	?	3500	45-55	1990	Xichang
China	LM-2E(A)	15,300	?	n	?	2000	Xichang, Jiuquan
China	LM-2F	?	?	?	?	2000?	Jiuquan
China	LM-3	?	?	1500	35-40	1984	Xichang
China	LM-3A	?	?	2600	45-55	1994	Xichang
China	LM-3B	11,200	6000	5100	50-70	1996	Xichang
China	LM-3B(A)	?	?	7000	?	2002	Xichang
China	LM-3C	?	?	3800	55-75	?	Xichang
China	LM-4	?	1650	n	20-30	1988	Taiyuan
China	LM-4B	?	2800	n	25-35	1999	Taiyun
Japan	H-II	10,060	4220	3930	165-170	1994	Tanegashima
Japan	H-IIA 202	9940	4350	4100	75	2000	Tanegashima
Japan	H-IIA 212	17,280	?	7500	?	2001	Tanegashima
Japan	J-1	850	n	n	30-45	1996	Tanegashima
Japan	M-V	1,800	?	1250	55-60	1997	Kagoshima
India	PSLV	3,700	1200	800	15-25	1993	Sriharikota
India	GSLV	5,000	2200	2500	35-45	2000	Sriharikota
India	Shavit 1	225	n	n	10-15	1995	Palmachim
India	LeoLink 1	550	?	n	10-15	2000	various
India	LeoLink 2	1,550	?	n	18-20	2001	various

Table 19. First ten countries to launch vehicles into space

Country	launch complex	to launch	first launch		Lat	Long
Russia	Baikonur Cosmodrome - Tyuratam	1	4-Oct-57	Sputnik I & Yuri Gagarin	45.6 N	63.4 E
United States	Cape Canaveral Air Station	2	31-Jan-58	Titan, Atlas,Delta	28.5 N	81.0 W
France	Hammaguir, Algeria & Kourou	3	26-Nov-65		31.0 N	8.0 W
Japan	Kagoshiuma on Kyushu Island	4	11-Feb-70	sounding & 24 orbital	31.2 N	131.1 E
China	Jiuquan Space Launch Center - Shuang Cheng Tzu	5	24-Apr-70		40.6 N	99.9 E
Australia	Woomera	6	Oct 28,1971		31.1 S	136.8 E
Great Britian	Woomera	6	Oct 28,1971		31.1 S	136.8 E
Europe	Kourou, French Guiana	7	24-Dec-79	equatorial & polar	5.2 N	52.8 W
India	Sriharikota Island	8	18-Jul-80	polar & GEO	13.9 N	80.4 E
Israel	Palmachim Air Base	9	19-Sep-88		31.5 N	34.5 E
Iraq	Al-Anbar	10	5-Dec-89			

Summary

- All 71 amateur satellites have been launched from only eight sites.
- There are less than two dozen active satellite launch sites in the world.
- A number of countries have combined resources to build and launch rockets.
- A satellite launched due east will have an inclination equal to its latitude.
- It takes a great deal of energy to launch a satellite.
- Most launch sites are restricted in their launch direction by where the rocket stages fall.
- Satellites travel slower the further from the earth.
- Orbit plane changes require a great deal of energy.
- 97% of a launch vehicles mass is fuel.
- There is very wide range of fees charged to launch rockets.

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The Design and Operation of

The Canadian Advanced Nanospace eXperiment (CanX-1)

Luke Stras, Daniel D. Kekez, G. James Wells, Tiger Jeans,
Robert E. Zee, Freddy Pranajaya, Daniel Foisy

Space Flight Laboratory
University of Toronto Institute For Aerospace Studies
4925 Dufferin Street, Toronto, Ontario, Canada, M3H 5T6
E-mail: rzee@utias-sfl.net, Tel: (416) 667-7864, Fax: (416) 667-7799

Abstract

The Canadian Advanced Nanospace eXperiment (CanX) Program of the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS/SFL) is a Canadian first, allowing engineering researchers to test nano- and micro-scale devices rapidly and inexpensively in space. CanX is a "picosatellite" program for research and education, with graduate students leading the design, development, testing, and operations of Canada's smallest satellites, each having a mass of under 1 kg. The first UTIAS/SFL picosatellite, CanX-1, was launched on June 30, 2003 together with CubeSats from other university and industry developers. The objective of the CanX-1 mission is to verify the functionality of several novel electronic technologies in orbital space. Communications with the satellite is accomplished through amateur-satellite frequencies. This paper outlines the features, capabilities and performance of CanX-1, including horizon and star-tracking experiments using two CMOS imagers, active three-axis magnetic stabilization, GPS-based position determination, and an ARM7 central processor. This paper emphasizes the communication system, and the events that have occurred post-launch are also discussed.

1. Introduction

CanX is the first Canadian picosatellite program. The CanX program of the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) is based on the CubeSat program started by Stanford University and California Polytechnic State University (CalPoly) [1]. The primary goal of the CubeSat program is to provide students the opportunity to develop complete satellite systems and perform space-based experiments using relatively small and inexpensive satellites. The CubeSat picosatellite is 10x10x10 cm in size and 1 kg in mass. The first spacecraft of the CanX program CanX-1 is based on this design. See Figure 1.

The objective of CanX-1 was to verify the functionality of several technologies in orbital space. Color and monochrome CMOS imagers were to be tested for imaging star fields, the moon, and the Earth. The images would be used to verify the ability to perform star/moon/horizon tracking as part of a complete attitude determination system. CanX-1 would also verify the functionality of a custom-built housekeeping on-board computer (OBC). A CMC Electronics Global Positioning System (GPS) receiver and an active magnetic control system would also be tested. In addition, the spacecraft was to collect telemetry from several key components, such as the Emcore gallium-arsenide solar cells, and a Honeywell three-axis magnetometer.

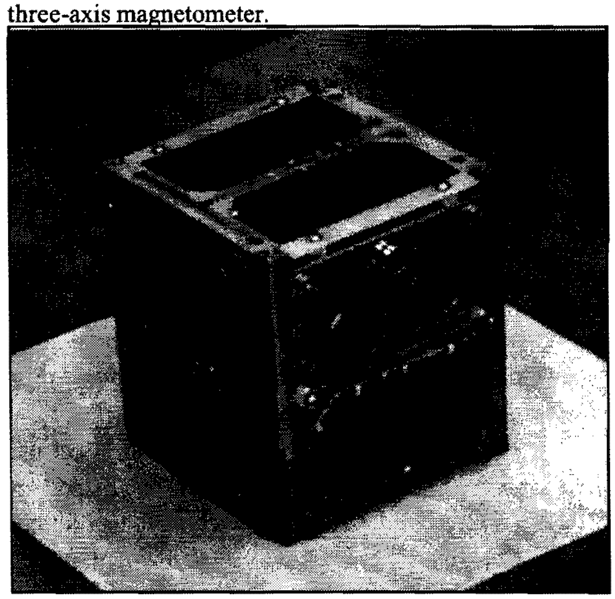

Figure 1 - CanX-1 Picosatellite (antennas stowed)

One of the goals of the CanX program is to provide the hands-on training for the next generation of Canadian space engineers. As the amateur community has a strong heritage of both advancing the state-of-the-art and encouraging self-education amongst its members, a number of already licensed team members suggested the use of the amateur-satellite service for the mission. During the development of CanX-1, the remainder of the team members were inspired to obtain their licenses.

CanX-1 was launched aboard the Multiple Orbit Mission (MOM) on June 30, 2003 at 14:15 UTC by Eurockot Launch Services from Plesetsk, Russia, as shown in Figure 2. Other payloads were the Canadian MOST microsatellite [2-3], the Czech Republic's MIMOSA microsatellite [4], the Russian MONITOR satellite mockup (mass frequency simulator) [5], the QuakeSat science mission [6], and four CubeSats from Japan (CUTE-I [7] and CubeSat XI-IV [8]) and Denmark (DTUsat [9] and AAUsat [10]).

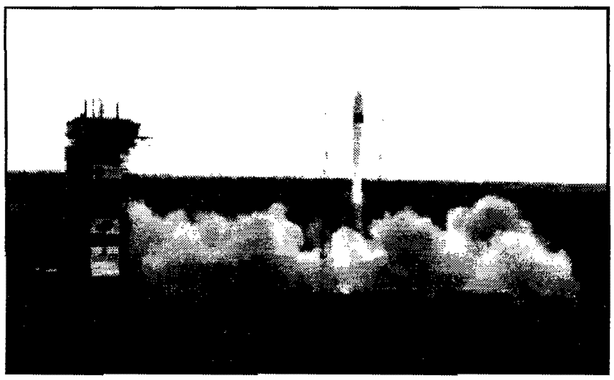

Figure 2 - Launch of Rockot Multiple Orbit Mission

2. Mission Specifications

2.1 Payloads and Experimental Subsystems

The CanX-1 mission was intended to demonstrate a highly capable spacecraft, and it incorporated a number of payloads and experimental subsystems. They were as follows:

1) CMOS Imagers;
2) ARM7-based On-Board Computer (OBC);
3) GPS Receiver;
4) Active Magnetic Attitude Control System (ACS).

The imager payload consisted of two Agilent CMOS imagers. The color imager in conjunction with a wide-angle lens was to be used primarily to take pictures of Earth. The monochrome imager in conjunction with a narrow-angle lens was to be used to test the feasibility of taking star/moon/horizon pictures that can be used for attitude determination and control.

CanX-1 flew a custom-designed housekeeping computer based on the low-power ARM7 core, operating at 40 MHz. There are many C compilers available to program the microprocessor. This OBC offers great speed and flexibility in use. The functionality of this OBC was to be monitored throughout the entire lifetime of CanX-1.

A commercial-off-the-shelf (COTS) GPS receiver connected to two omni-directional antennas flew on CanX-1. If successful, the GPS receiver could have been used to help determine the orbital position of CanX-1. In future CanX missions, the GPS receiver can be used for position determination as part of a formation flying system configuration.

CanX-1 has a COTS magnetometer along with three custom-built magnetorquer coil systems as part of an active magnetic ACS. The magnetic ACS was to be used to detumble CanX-1 to assure that any images taken would not be blurred due to the rotation of the picosatellite. In addition, CanX-1 would attempt to perform active coarse pointing.

2.2 Launch and Orbit

The final orbit for CanX-1 was defined very late in the mission design process and was driven by the requirements of the MOST mission. As such, the CanX-1 design took into account a wide variety of orbits. For both thermal and communication purposes, the worst-case scenarios were considered for power generation and cold thermal conditions (noon-midnight line of nodes) as well as hot thermal conditions (dawn-dusk line of nodes) expected at the baseline orbit. For communication purposes, the limiting factor is the orbital altitude; 650 km was chosen as the worst-case scenario.

Using Satellite Tool Kit to simulate this orbit for a one-month duration, single contact and daily contact duration information was determined (see Table 1) for an acquisition-of-signal/loss-of-signal angle of 10°. On average, there were four contact periods per day with a total daily contact time of between 28 and 29 minutes.

There was enough margin in both the contact link budget and the data budget to compensate for any changes in the selected orbit altitude or inclination, which would alter the expected contact time and up/downlink signal-to-noise ratio. Since the power system and thermal designs already took into account the possibility of very different eclipses, it was not required that CanX-1 be placed into a particular sun-synchronous orbit.

Table 1-CanX-1 Contact Time Data (STK Simulations)

Minimum Elevation Angle	10°	
Sun Synch, alt.=650 km, 6 pm-6 am Orbit Oct. 1 to Oct. 30		
Min Single Contact Duration	87	s
Max Single Contact Duration	544	s
Mean Single Contact Duration	427	s
Total Simulation Contact Duration	51,646	s

No. Days in Simulation	30	
Daily Contact	1,722	s
	29	min

3. System Specifications

Figure 3 is a diagram of the system architecture of CanX-1. The system architecture is centralized on the housekeeping OBC, with some backup systems. This simple architecture was quick to design and takes up minimal volume and mass. Due to the centralized nature of the system architecture, all critical design points have been identified. Extended ground testing focused on these critical components to increase the confidence in the overall system.

The interior structure of CanX-1 consists of six circuit boards, which are parallel to the XY plane, as can be seen in Figure 5 and Figure 6. The boards are numbered 1 to 6, with Board 1 being closest to the +Z aluminum panel and Board 6 being closest to the -Z aluminum panel. The magnetometer is located on Board 1, the CMOS imagers are located on Board 2, while power switches and battery are located on Board 3. Board 4 contains the radio transceiver. Board 5 is the custom-built OBC, while Board 6 has been reserved for payloads; on CanX-1 this is the GPS receiver. The boards are spaced such that components do not interfere with each other, while the satellite mass center remains within 2 cm of the geometric center. The boards are held in place using four columns of aluminum spacers. These columns also act as structural supports along the Z-axis. The total mass of the interior and exterior structure is 373 g, or 37% of the total satellite mass.

From the structural design, the satellite was literally built from the inside out. This means the interior electronics were populated and assembled first using the aluminum spacers. Next the -Z aluminum wall was attached, followed by the +/-X walls, and the +Z wall. Attaching the +/-Y walls completed the assembly.

Vibration testing was performed on the satellite at MDRobotics. It was subjected to sinusoidal vibrations, random vibrations, and low-level sinusoidal vibrations over a wide-spectrum in all three axes. The low-mass and high-stiffness design resulted in a first natural frequency of approximately 800 Hz.

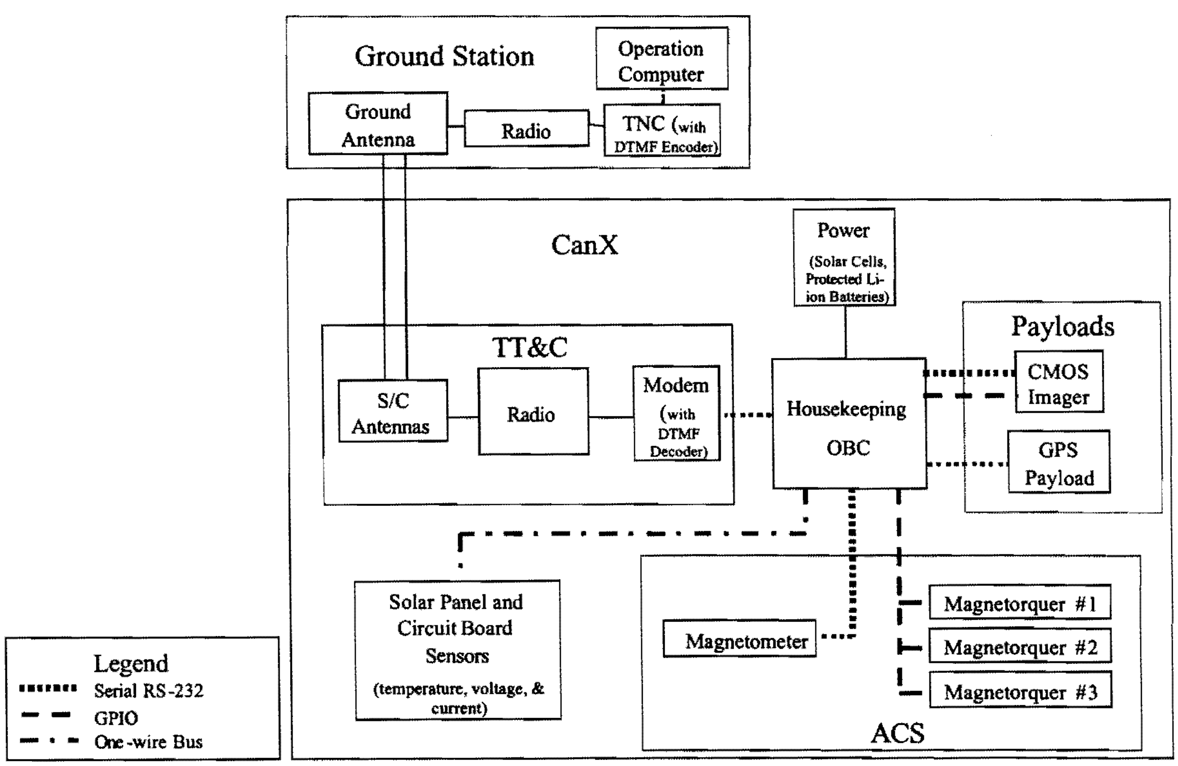

Figure 3 - CanX-1 System Architecture

3.1 OBC & Software

The CanX-1 on-board computer, as shown in Figure 4, is responsible for

1) Control of all spacecraft subsystems;
2) Communications with the ground;
3) Fault detection and management;
4) Telemetry generation;
5) Payload control;
6) Payload data management.

In order to accomplish these tasks, a custom single-board computer has been designed and built. The CanX-1 OBC is based on the low-power ARM7 core, operating at 40 MHz with 2MB of external RAM and 32MB of external FLASH. Both external memories have error detection and correction (EDAC). In addition, a small (128 kB) boot ROM contains the bootstrap code, which is capable of very basic spacecraft operations: initialization code, keep-alive functionality, and communication code. This ROM is pre-programmed on the ground before flight, and its contents cannot be changed after launch. Although the boot ROM does not utilize hardware EDAC, the type of memory cell utilized is inherently resistant to radiation upset.

The use of a popular, off-the-shelf processor ensures that multiple development tools, such as compilers and debuggers, are available. Although the processor is not radiation-hardened or otherwise explicitly space-qualified, prior flight experience with similar processors [11] indicates that such devices can function reliably in low Earth orbit for suitable periods.

A minimum set of software that will allow for low-level operations of the spacecraft resides on the boot-ROM. Higher level functions as well as software updates are uploadable through the Telemetry and Command (T&C).

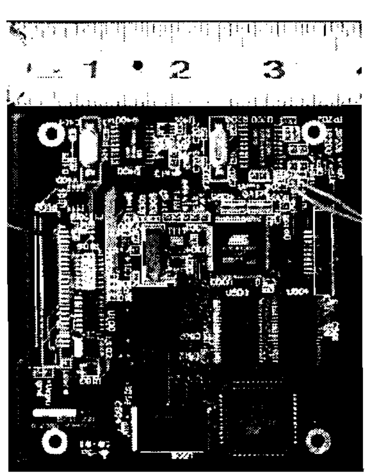

Figure 4 - CanX-1 On-Board Computer (OBC)

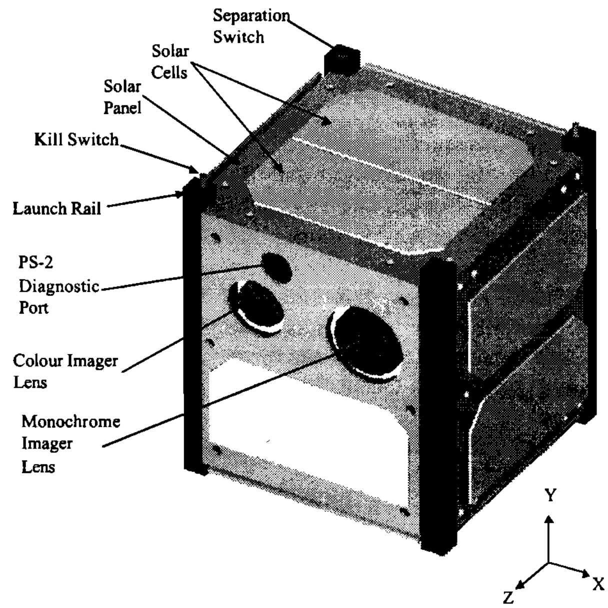

Figure 5 - CanX-1 Exterior Structure

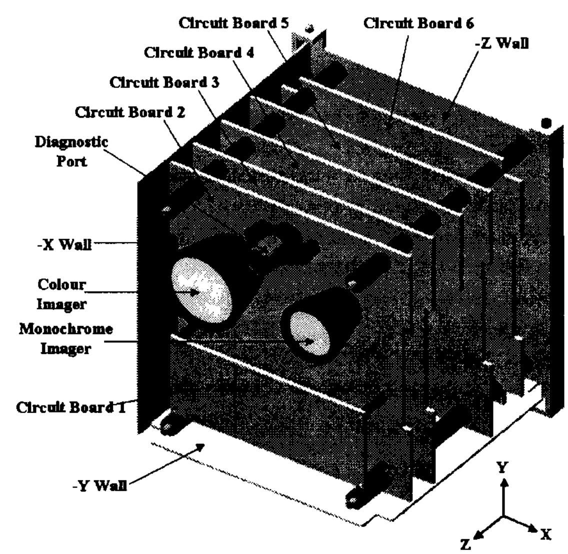

Figure 6 - CanX-1 Interior Structure

3.2 Telemetry & Command

The T&C subsystem is responsible for communication between the spacecraft and the ground station.

3.2.1 Spacecraft Segment

The spacecraft segment consists of a radio receiver, a radio transmitter, antennas, antenna switching hardware, and a terminal node controller (TNC).

The spacecraft transceiver is based on a half-duplex design operating in the 70 cm band. In order to simplify the design, the spacecraft radio operates on fixed frequencies for both uplink and downlink; Doppler correction is performed by the ground station. The frequencies are determined by a crystal reference oscillator and cannot be changed after launch.

The transmitter is an FM design utilizing a phase-locked loop (PLL)-based frequency multiplier which is locked to the reference oscillator. Modulation is achieved by injecting the baseband data at the reference oscillator. Thus the deviation of the output signal is equal to the deviation of the reference oscillator multiplied by the PLL's multiplier. The PLL's output is then buffered and fed into a power amplifier IC giving a final output power of 27 dBm.

The receiver consists of a low-noise amplifier followed by a single-conversion heterodyne receiver. After down-conversion to the intermediate frequency (IF), the signal is demodulated using a phase-coincidence demodulator, filtered by a baseband filter and coupled to a MSK modem. The modem's output is processed by the OBC.

The spacecraft antenna system consists of two quarter-wave monopoles oriented at 90°. The antennas are combined in phase, leading to a linearly polarized signal. The antennas are attached to corner where the +X, +Y and -Z faces meet. They are stowed along the +X face of the spacecraft during launch. Post-launch, the two antennas are deployed by a hot-wire line cutter, providing nearly omni-directional coverage.

In order to verify the performance of the antennas, a simple antenna-pattern measurement was performed. As a sufficiently large anechoic chamber was not available, the tests were performed in an open-field using a calibrated signal source and a reference antenna. Figure 7 shows the measured antenna patterns. The half-duplex nature of the radio means that the same antenna is used for both receiving and transmitting. The switch-over is accomplished using a solid-state switch, keyed and sequenced by the OBC.

3.2.2 Ground Segment

The ground station is located at the University of Toronto Institute for Aerospace Studies located in Toronto, Ontario (grid-square FN03gs). See Figure 8 and Figure 9.

It consists of two circularly polarized Yagi antennas which are phased to provide a combined gain of 22 dBi.

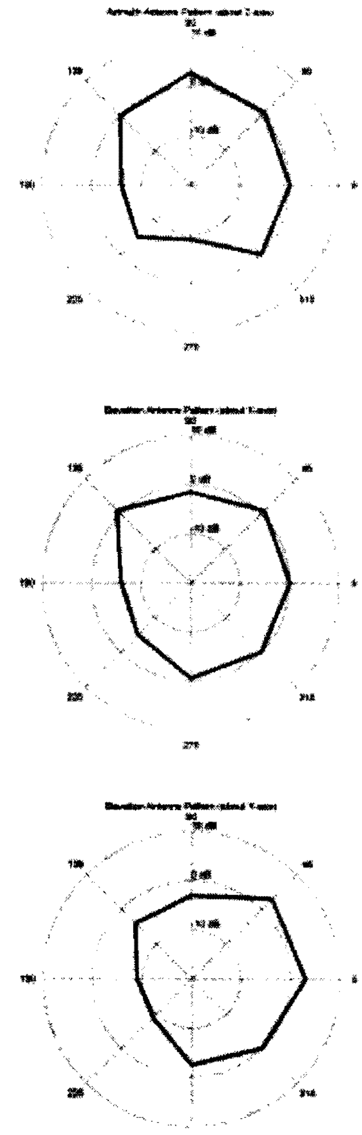

Figure 7 - Antenna pattern around Z, X, and Y axes

The use of circular polarization is necessary to prevent polarization fading between the ground and the spacecraft, whose orientation cannot be determined ahead of time. A very low noise preamplifier provides 16 dB of gain on the received signal. A roof-mounted electronics box contains the power-supply and power amplifier for the uplink transmission; the box is located so as to minimize the power loss between the power-amplifier and antennas. The nominal uplink power is 50 dBm leading to an effective isotropic radiated power (EIRP) of 72 dBm.

Figure 8 - Ground station computer, radio and TNC

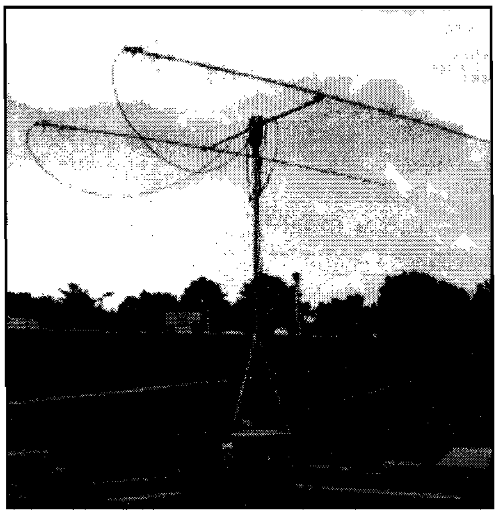

Figure 9 - Ground station antennas

The radio, TNC and antenna rotator controller are located in the UTIAS Space Flight Lab. Antenna tracking is provided by a Yaesu Azimuth-Elevation rotator and is controlled by NOVA for Windows software via a Kansas-City-Tracker Card. The same computer which provides tracking capability also runs an in-house satellite command and control program, and communicates with the ground station radio through a custom TNC. The TNC is responsible for the modulation and packet-framing aspects of the communications protocol used in the CanX-1 system.

3.2.3 Spectrum Usage

An amateur satellite is defined as one designed to conduct technical investigations relevant to the development of radio technique [12]. This includes technical investigations in the realm of attitude determination and control methods, development of transceivers, development of spacecraft computers, and other novel technologies.

CanX-1 meets this criteria: it is designed as an orbital platform for technology demonstration and evaluation, built and operated by students who are licensed amateurs and acting without pecuniary interest. Thus, a request for frequency coordination was made to the International Amateur Radio Union (IARU) describing the function of our satellite. In addition, a similar notification was made to Industry Canada, the government body that regulates radio-communication and spectrum allocation in Canada. The Industry Canada representative agreed that CanX-1 met the criteria for an amateur satellite and acknowledged the use of CanX-1 uplink and downlink frequencies in the 70 cm band.

3.3 Power

The power system consists of a battery pack, solar arrays, peak power tracker, shunt regulator, and power distribution module.

The battery pack is a three-cell Lithium-Ion battery providing a capacity of 3600 mAh nominal capacity at 3.7 V; total weight is 114 g.

Solar arrays are used as the power source during sunlight. The solar arrays consist of six solar panels connected in parallel and located on the outer surfaces of CanX-1. Five of the six panels employ one solar cell string consisting of two Emcore solar cells. The solar cells are triple-junction gallium-arsenide, having a minimum efficiency of 25% at end-of-life (after one year). These cells are connected in series to give 4.4-5.0 V of output voltage. Each panel has a worst-case power output of 1.63 W. The supporting electronics for each solar panel are located on the under surface of the solar panel. Due to the imager bore sights located on the +Z face of CanX-1, the solar panel on that face has only one Emcore solar cell. Therefore, a peak-power tracking system is implemented for this solar panel to keep its power output balanced with the other panels. The peak power tracker software on the OBC is based on the Perturbation and Observation method [13-15] and uses the solar cell voltage and current telemetry to adjust the duty-ratio of the peak power tracking circuit to track the peak power point.

For charge regulation, a shunt is present on each of the solar panels. This regulator directs the recharge current from the solar cells into a resistive load once the battery voltage exceeds its maximum overcharge voltage.

Power is permanently supplied to the OBC and radio, while power to the rest of the subsystems and payloads are switchable and are controlled by the OBC. Each power distribution line incorporates a current-limit switch that cycles the power in the event of over-current condition.

CanX-1 power consumption varies depending upon its orbit and operation scenarios. Therefore, the worst-case scenario is assumed for power budgeting and margin analysis. The worst-case assumes a complete operation per orbit, in which all subsystems and payloads are being used at their respective allocated time. This case further assumes worst-case power generation. Analysis shows that there is a positive energy margin of 0.19 Wh per orbit, assuming a 97 minute orbit with 60 minutes of sunlight.

3.4 Attitude Control System

The design requirements for the ACS on CanX-1 are driven by the CMOS imager payload. It is desired to have control over the tumbling rates of CanX-1 such that clear pictures of the Earth and stars can be taken. However, it should be noted that the goal of the ACS is not to detumble the satellite such that rotation rates about each body axis are zero. As both imager bore sights are located on the +Z face of the satellite, slow rotations about the Y and/or X axis are desired so that pictures of both stars and Earth can be taken in relatively short periods of time.

The most stringent constraints for the ACS are mass, power, and volume. It is desired that the total mass of the ACS be approximately 10% of the satellite total mass. Also, the maximum power allocated to the ACS is 1 W. The ACS must also be small enough to fit inside CanX-1, and be able to operate without interfering with the other satellite systems.

To control the angular momentum of the satellite, the ACS must be able to overcome disturbance torques experienced during its orbit. Worst-case disturbance torques are estimated according to Wertz [16]. From these calculations it is determined that control torques on the order of 10^{-6} N·m are required to sufficiently control the satellite.

Three orthogonal copper coils are used as the actuators for the ACS (see Figure 10). When current is supplied to the coils, magnetic dipole moments are generated, which interact with the Earth's magnetic field to produce control torques. In designing these coils the goal is to maximize the resulting magnetic dipole moment, while complying with the constraints of the ACS. The coils are located between the exterior solar cell PCB panels and the aluminum structure, on the -X, -Y, and -Z faces of CanX-1. An AWG 32 gauge magnet wire coil is optimal given the constraints. This coil has average dimensions of 75x55x3 mm, with 380 turns. The mass of each coil is 21 g, while the maximum power dissipated by each coil is 333 mW. The resulting magnetic dipole moment is 0.106 A·m^2 per coil, resulting in a worst-case control torque of 2.33×10^{-6} N·m, and therefore has authority over disturbance torques experienced during orbit.

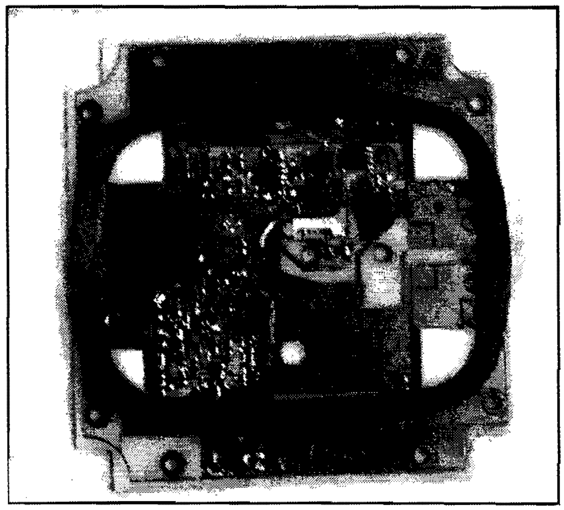

Figure 10 - Mounted magnetorquer coil

A three-axis magnetometer is required to measure the Earth's magnetic field. The magnetometer aboard CanX-1 is a Honeywell HMR2300 smart digital magnetometer. Data is outputted from this magnetometer serially, making it easy to interface with the OBC. Some advantages of this magnetometer over other alternatives include, low mass, small size, high sensitivity, fast response, and high reliability. The magnetometer board weighs 28 g and has dimensions of 74.9x30.5 mm, while consuming a maximum power of 0.228 W; therefore, it meets mass, volume, and power constraints. With a range of ±2 gauss, a resolution of 70 μgauss, and a selectable sampling rate between 10 and 154 samples/s, this magnetometer can be used to accurately calculate changes in the Earth's magnetic field.

The OBC receives three values from the magnetometer using a serial RS-232 port, and the control software has access to these signals and decides which, if any, of the torquer coils to turn on. Each coil is controlled using digital I/O lines. The circuit controlling the torquers is capable of changing the polarity of each coil and ensures that a constant current is supplied to each coil. This means that each coil is either full on or full off.

The main requirement for the ACS control algorithm is to detumble the satellite once it is ejected from the deployment system. This can be done using the B-dot magnetic control law. This control law reduces the kinetic energy of the satellite (due to rotation about its mass center). When implementing the control law on CanX-1 several factors need to be taken into account, including initiating the control algorithm, the location of the magnetometer, and available power. Due to limited space, there are no rate sensors on board CanX-1. Therefore there is no way of getting tumbling rate readings. As a result, detumbling is initiated by a command given to the housekeeping computer from the ground station. The command contains the run time of the detumbling algorithm. To conserve power, only one torquer coil will be turned on at a time by the B-dot algorithm. Other subsystems are shut down during detumbling, therefore the magnetic dipole of the satellite should remain relatively constant during the process and can be subtracted from the magnetometer readings.

Preliminary simulations have been performed to determine the effectiveness of the control law. The simulations are obtained by numerically integrating Euler's equations using Euler parameters as attitude parameters. The following assumption are used: (a) the orbit is a 650 km altitude, sun-synchronous orbit, with a dawn-dusk line of nodes, (b) the magnetic field is a tilted magnetic dipole, and (c) CanX-1 is a homogenous cube having a mass of 1 kg. To simplify the simulation, disturbance torques are neglected. In simulation, the satellite is given initial rotation rates of 5°/s about each body axis. The Δt for calculating B–dot is set to 2 seconds, and the torquers are turned on for 10 seconds each time. The torquers are turned on when the required magnetic moments are greater than 0.05 $A{\cdot}m^2$, or less than -0.05 $A{\cdot}m^2$. The results show that the satellite detumbles to rates lower than 1.0°/s about all three body axes in 600 seconds. These results are promising and show that this system meets the requirements for the ACS system of CanX-1.

3.5 Imager Payload

CanX-1 carries two independent high-resolution CMOS imagers, together with associated optics and electronics. The purpose of these imagers is to

1) Validate the use of spaceborne CMOS imagers for science and engineering;
2) Provide starfield images for the purpose of attitude determination via star- and Moon-tracking, as well as Earth-horizon tracking;
3) Provide educational images of the Moon and the Earth.

In order to accomplish these tasks, two independent imagers are used. The imagers are COTS CMOS imaging chips manufactured by Agilent Technologies. Details on the imagers are available in Table 2. The imagers, along with their support electronics and frame buffers, are mounted on their own circuit board (see Figure 11) and have boresights in the direction of the +Z-axis of the spacecraft. Communication with the OBC is achieved via a high-speed serial bus.

Each imager has its own lens system. The color imager utilizes a wide field-of-view (FOV) lens, making it suitable for imaging the Earth and the Moon. The monochrome imager uses a narrow FOV lens system. The lenses are of fixed focal length and fixed focus. As a result, they need to be focused while on the ground and fixed in position.

At present, only a minimum of image processing is to occur on-board the satellite, and the images are downlinked to the ground station for processing.

Table 2 - Imager Characteristics

	Color	Monochrome
Model	HDCS-2020	ADCS-2120
Quantum Eff.	33%	38%
Fill Factor	42%	42%
Lens Focal Length	2.1 mm	25 mm
Lens Aperture	f/2	f/2.5
Diag. FOV	112°	14°
Res. @ Nadir	1.5 km/pixel	200 m/pixel
Power	200 mW	200 mW

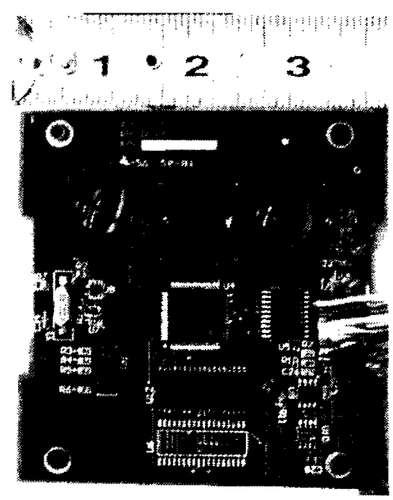

Figure 11 - CanX-1 Imager Board

3.6 GPS

CanX-1 carries a compact commercial GPS receiver along with associated antennas. This receiver will be used for coarse determination of orbit parameters.

The receiver is a Superstar GPS OEM board, from CMC Electronics (see Table 3). This board is a complete GPS receiver, capable of tracking 12 satellites and communicates with the OBC via a standard serial link. The antennas used are T-type antennas, printed on two opposite (+/-Y) satellite faces. In order to simplify the system, each antennas has its own low-noise preamplifier system. The preamplifier outputs are combined before feeding into the GPS receiver.

Table 3 - GPS Characteristics

Power	1.2 W max
Dimensions	46 x 71 x 13 mm
Weight	22 g
Sensitivity	-135 dBm

4. Launch and the Hunt for CanX-1

CanX-1 was launched on June 30, 2003 at 14:15:25 UTC. The MIMOSA spacecraft separated at 15:02 UTC into a highly-elliptical orbit. Following this, the Blok-3 upper-stage fired to circularize its orbit at 820 km, and the remaining payloads were deployed sequentially. Table 4 shows the deployment times. Early tracking data was provided by Eurockot. NORAD acquired the satellites quickly and provided subsequent tracking data. Due to the small size and close proximity of the satellites, it was not obvious which object corresponded to which NORAD identifier, and it was not until several weeks later when satellites had separated sufficiently that a clear determination could be made (using AOS/LOS times). CanX-1 is believed to be NORAD #27847.

MOST passed over its UTIAS ground station at 20:49 UTC and was promptly acquired by its operations. At the same time, the CanX-1 team was listening for its beacon but no signal was heard. During successive passes, the ground team sent ping frames to the satellite and commanded a system reset with fire-codes.

In order to verify the performance of the CanX ground station, the team was able to track and acquire the beacons of other satellites launched on this mission. This also verified that all objects had separated correctly from the launch vehicle. The other CubeSat teams, as well as the amateur satellite community at large proved very helpful in providing pass reports for all of the objects being tracked. Unfortunately, there were no contact reports on the frequencies assigned to CanX-1.

The team considered several possible failure modes. If the antennas failed to deploy from their stored configuration, for instance, then the received signal strength would be reduced. To test this hypothesis, a sufficiently large antenna could be used to communicate with the satellite. If this antenna was unable to receive a signal from the satellite then most-likely a different failure mechanism was in play. To this end, the team was able to negotiate access to the 46 m dish at the Algonquin Radio Observatory (ARO). Unfortunately due to hardware limitations of the dish, the antenna was unable to rotate fast enough to track an object in low-earth orbit (LEO), and the experiment proved inconclusive.

Plans are currently underway to use a dish at the Defense Research and Development Canada facility in Ottawa (DRDC-Ottawa). Although this dish is much smaller (9.1 m), it has the capacity to track LEO satellites and, as such, should be able to track CanX-1.

In addition, our ground station has been fully automated to track and monitor all orbital passes.

Table 4 - Deployment times for MOM Satellites, June 30, 2003

Time (UTC)	Event
14:15:25	Rockot-MOM lift-off
15:02:31	MIMOSA separation
15:42	First contact to MIMOSA reported
15:46:46	MOST Separation
15:47:56	XI-IV and CUTE-I (Japanese CubeSat) separation
15:49:11	QuakeSat separation
15:49:11	CanX-1, DTUsat, AAUsat separation
17:06	QuakeFinder detected CW-Beacon from QuakeSat
20:49	UTIAS/SFL reported first contact with MOST

5. CanX Program

The UTIAS/SFL CanX program is intended as a research and development vehicle providing cost-effective access to space for industry and researchers in Canada as well as abroad. The program and its spacecrafts are suitable for various activities:

- Testing new technologies;
- Validating advanced subsystems to be used in larger, future missions;
- Validating initial experimental hypotheses;
- Performing full on-orbit experiments.

The internal design and arrangement of the CanX picosatellite has been made as flexible as possible with plans for future missions in mind. This allows the picosatellite to incorporate almost any payload that meets the overall volume, mass, and power restrictions of the picosatellite. The only permanent circuit boards in the CanX picosatellite are the power/radio and OBC circuit boards (Boards 3, 4, and 5 in Figure 6), leaving over 50% of the volume and 25% of the mass to the payloads. These circuit boards can also be placed anywhere along the Z-axis of the picosatellite so that payloads of various sizes can be accommodated. The current design provides access to the external environment through half of the -Z face. If necessary, more access area can be made available through redesign of the solar array.

Despite the post-launch problems, the design, construction and testing processes have provided invaluable experience to a ten graduate students at the University of Toronto. A new team of students is currently conducting preliminary design work on a next-generation satellite called CanX-2 and there are plans for a future series of satellites.

6. Acknowledgments

The authors want to thank the National Science and Engineering Research Council (NSERC) of Canada for its generous support of their university studies.

The authors and advisors want to thank the following funding partners of the CanX program: CRESTech, MD Robotics, and UTIAS.

Thanks also goes to the following sponsors: Agilent Technologies, Altium, ARC, CalPoly, CMC Electronics, E. Jordan Brookes, EDS, Emcore Photovoltaics, Honeywell, and Stanford University.

The authors and advisors are indebted to the following individuals for their contributions to the CanX program: Alex Beattie, Hugh Chesser, Gi-Yun Chung, Cordell Grant, Paul Harrison, Doug Johnson, Sangtak Park, Dan Rankin, Mark Sdao, Henry Spencer, Ta-Wei Wang, and Lawrence Yee.

The authors and advisors gratefully acknowledge the assistance of the staff and management of the Algonquin Radio Observatory, Deference Research and Development Canada, and the other CubeSat teams. Finally, we would like to thank Emily Clarke (W0EEC), Cliff Buttschardt (K7RR), Don Woodward (KD4APP), and the rest of amateur satellite community.

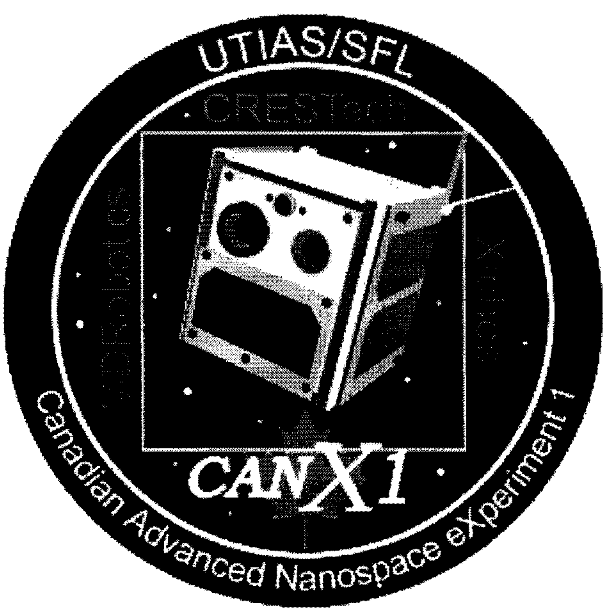

Figure 12 - CanX-1 Mission Patch

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AO-40 for Us Appliance Operators

by Bill Tynan, W3XO

"S Band is too hard." "I lost interest in AO-40 when it exploded not long after launch." How often have we heard statements like that? Perhaps you even said them yourself.

But, despite its problems following launch, AO-40 remains a functioning satellite. Let's figure out how to make the most of it. What systems DO work on AO-40 and how can we take advantage of them? For us appliance operators, and I'll admit to being one, the important thing is that the 70 cm (435 MHz) uplink and one of the two S Band (2.4 GHz) downlinks perform just fine. Also vital, but less obvious, is the fact that the on-board power system, magnetic attitude control, central computer, and other systems needed to operate the satellite are all in good working order. Two of the L Band (1269 MHz) uplinks are also operating, as is the 1 Watt 24 GHz downlink. But for now, being appliance operators, we'll leave those to other hams who don't consider themselves such. We will concentrate on what we can buy, or perhaps fashion from a sheet of copper with not much more than a hacksaw, drill and tin snips.

Using AO-40 is Not That Hard

"But I'm not a microwave guy. I can't do the fine work required to assemble high performance gear for S Band - even from kits. So, I'm not about to tackle the task of building a precision low-noise 2,400 MHz receiving system. Besides, it would have to be weatherproof, or I'd have to use some huge low loss hardline to get from the antenna to the shack. It's just too hard! So I'll just give up on AO-40 and wait for Eagle, or P3E which AMSAT-DL is building." This is another too frequently heard remark! While the promise of these hoped-for future satellites excites us all, why wait for them? Even an appliance operator, like me, can get on AO-

40 right now. There are a number of ways of doing it, but in this paper, I'll concentrate on the approach I took.

OK, you're not microwave guy. Actually, you may be and just don't know it. If your family gets its TV from what is termed "wireless cable," you are receiving signals only 100 MHz removed than those coming down from AO-40. If you use one of the small-dish satellite TV systems, you're receiving at 12 GHz - six times higher than AO-40's S Band downlink.

So you didn't build the widgets that convert those short wavelengths to something your TV set can receive. The wireless cable, or satellite TV, guy installed them. Well, you don't have to build the high performance weatherproof widget to convert AO-40's 2,401 MHz signals down to what your SSB/CW 2 meter transceiver can receive, either. So where do you go to find such a widget? There are several approaches to this. Downeast Microwave[1] has both kits and pre-built units especially intended for AO-40 reception. There are several European firms offering similar equipment. But, I said I would cover how I did it. Remember, I mentioned wireless cable and said that the frequencies used for it are close to the AO-40 S Band downlink? The devices used in this application convert the wireless cable signals in the 2500 to 2700 MHz band to the cable TV channels. Once more, they are meant to be installed outside on a dish, so they're weatherproof. The specific unit I chose is the AIDC-3731, as modified by Bob Seydler, K5GNA.[2] This particular one is superior to some other wireless cable units available, as it has a quite acceptable noise figure and a front-end filter very effective at eliminating unwanted signals.

For a dish, I decided to take the conservative approach, but still one within the capability of an appliance operator. Yes, many use smaller dishes, including the so-called Bar-B-Q grills. These, like the downconverters already mentioned, are designed for wireless cable service. I selected a somewhat larger dish, but not one too massive for my Yaesu 5400 rotators I had used for AO-10 and 13. It is a solid aluminum dish about 90 cm (34 inches) in diameter from Downeast Microwave.[3] It's light and easy to mount. I'll say how I did that in a bit. As I mentioned, I chose the AIDC-3731 downconverter which K5GNA modifies and offers to hams. Bob's modification consists of changing the crystal so that 2,400 MHz signals are converted to 144 MHz. Before the modification, 2400 MHz would come out at about 122 MHz. Once modified, AO-40's S Band signals can be copied in on a standard 2 meter SSB/CW receiver. The AIDC-3731 is only about 1 inch square and about 5 inches long. K5GNA can supply it with an attached dipole, so it can be mounted in the center of a dish without having to do anything else. However, this provides only linear polarization, whereas circular is preferred. So, I opted for the unit with an N connector. The only other connector on the device is an F Type for 75 ohm TV cable. The downconverter gets its power through this cable, so you do need to provide a device for sending DC power up the line while blocking it from your 2 meter receiver or transceiver. I used an old Radio Shack unit originally intended to power a mast-mounted TV preamp. I simply cut the wires that connected the unit to its "wall wort" and connected them to a well filtered DC power supply.[4] Most wall worts don't provide very good filtering, and this one had quit working anyway.

Now I have the dish and downconverter, what do I do for a feed? If you are satisfied with the additional QSB, you can select the downconverter with the built-in dipole and settle for linear polarization. But I decided I wanted to go circular. Many on AO-40 use helixes which can be home-brewed using a few turns of heavy solid copper wire. Numerous articles have been published on constructing such feeds. But, I had become intrigued by the patch antenna as a dish feed. Several articles have appeared on constructing both dual-band (L and S Band) patches as well as those meant for a single band. They don't seem too difficult to build. But, being appliance operator, I obtained a ready-made S Band unit from Robert Suding, W0LMD.[5] If you prefer to roll-your-own, that's where the sheet of copper, hacksaw and tin snips come in. Design information can be found on W0LMD's Web site. Another patch feed design is available on K3TZ's Web site.[6] His is square, rather than circular, but I'm told it works well too.

Now I had everything I needed. I already had the azimuth/elevation rotator and a 70 cm circularly polarized antenna left over from the heydays of AO-10 and 13.[7] Of course, there would be no need for the 2 meter crossed Yagi and preamp which served so well back then. All that was left was find a way to mount the dish to the crossboom and the feed/downconverter assembly at the dish's focal point. The idea for mounting the dish was suggested by Jim Akers, W5VZF. He used an old fry pan, removed the handle, drilled holes through it and matching holes in the dish. Then, using U bolts, he mounted the pan on the crossboom and ran screws through the holes in the pan and dish and fastened with nuts and lockwashers. I wasn't able to talk my wife out of one of her fry pans, so I went to a local store and came home with an aluminum cake pan stout enough to support the dish. Downeast Microwave sells a ring which also provides an appropriate support for this size dish as well as larger ones.

I have already noted that I chose the AIDC-3731 downconverter with the female N connector. The W0LMD patch also came with a female connector. So all I needed was a double male N-type adaptor to connect them together. Thus, the downconverter is directly connected to the patch feed - no feedline and almost zero loss.

Now for mounting the assembly at the focal point. Where is that? Since this is a symmetrical dish, not one of the off-center-fed type, it's at the center. But, how far out? There are several approaches for finding the focal point of a dish. Since it's a solid aluminum dish, it reflects sunlight very well. So I simply propped the dish up on the woodpile facing the afternoon sun, took a piece of paper and moved it in and out until I got a concentration of light. By the way, it got warm rapidly. Then I measured the distance to the dish center. I later checked the result with a formula from the *RSGB VHF Handbook* and obtained a nearly identical number.

OK, so I know where I want to mount the patch feed/downconverter assembly, how do I do it. The dish comes with three 1/4 inch holes, spaced around the center hole. Being the conservative type, I drilled them out to take 3/8 inch screw stock which I obtained from a local hardware store. I now believe that 1/4 inch stock would have been adequate. Then I made three simple brackets to fasten the patch to the three pieces of screw stock. It came out within a few tenths of an inch of the focal point I had both measured and calculated. At this point, I decided I was close enough - and quit. Then it was simply a matter of connecting the 75 ohm coax to the downconverter and running it into the shack. I connected it to my Icom R-7000 receiver through the Radio Shack coupler. I had decided to use the R-7000 rather than my FT-736, so there's no way I can put RF into the downconverter. Believe me, people have done it, then wondered why their downconverters suddenly went deaf. By the way, Downeast Microwave offers a device to prevent this catastrophe.

Operating on AO-40

Now it was time to turn on the computer and bring up InstantTrack.[8] I noted that AO-40 was within range and pointed the dish at the indicated azimuth and elevation, then tunned around. Don't expect the beacon to be exactly where you think it should be. For one thing, Doppler will shift it by up to more than 30 kHz either side of its actual frequency. In addition, your downconverter crystal may not be on exactly the right frequency to convert 2,400 MHz to precisely 144 MHz. Thus, the 2,401.323 MHz mid-band beacon may not appear at 145.323 MHz, even at zero Doppler. You may have to tune up and down as much as 50 kHz or more before you acquire the raspy sounding beacon signal. Once you do, adjust the dish azimuth and elevation for maximum signal. You will find that, once you have done this, you won't have to move it oftener than about every 20 to 30 minutes. Tune UP from the beacon. Most operation is above it. If the transponder is activated, and it is throughout most of each orbit, you should start to hear CW and SSB signals.

A word about the uplink is in order. For the antenna, I use a 70 cm M^2 30 element circular Yagi. Some employ linearly polarized antennas but, just as in the case of the downlink antenna, linear polarization will cause your signal into the satellite to fade more than it will with circular polarization. But, linearly polarized uplink antennas do work. My trusty FT-736 and the same 100 Watt solid state amplifier I use for 432 MHz terrestrial operation, serves as the uplink transmitter. But I must cut the power back, to about 10 to 20 Watts or I'm greeted by the warbling tone of LILA telling me to turn down the wick. Working AO-40 is just like it was on AO-10 and 13. You pick a clear spot in the passband, tune your transmitter to a spot you calculate should put you near that point and send dots while tuning your transmitter back and fourth until you hear your signal coming back. Adjust power so that you have a readable signal but not too strong, or LILA will be on you in an instant. She represents the only major difference from what we were used to with AO-10 and 13. By the way, LILA doesn't merely put out an annoying warbling sound, she also inserts a notch at that point in the passband. So, your former S-7 signal becomes almost inaudible. Once you have found your frequency and turned your power down enough to avoid LILA's scolding, call CQ on CW, or switch to LOWER sideband and put out a voice call. Just as AO-10 and 13 did, AO-40 inverts, the uplink signals, so LSB comes out as USB. And when you tune UP the band on the downlink, you must tune your transmitter DOWN in frequency.

This is how one appliance operator got on AO-40. It wasn't hard, and I have had lots of nice QSOs all over the world. However you decide to do it, the bird provides many hours at a time of great satellite hamming. Many DX stations, including Europeans, South Americans, Japanese plus a number of ZLs and VKs are regularly active on AO-40. There are, of course plenty of Ws and VEs to work as well.

You Say You Can't See the Satellite for the Trees?

There is one problem many face, one which I do not have down in the wide open spaces of Texas. Trees can cause significant attenuation of S Band signals. This is a particular problem in the northern states, where the elevation to the satellite is lower and trees tend to be taller than those around my QTH. Other than getting out the chain saw, all I can suggest is an elevated antenna installation, or perhaps portable operation. It would be quite easy to mount this size dish, or a smaller one, on a tripod or on a plate that can be placed in the bed of a pickup truck or on a small trailer. You'll need an SSB/CW radio which can receive on 2 meters and transmit on 70 cm, and is capable of vehicular operation. Several transceivers are available which fill this bill. Wouldn't it be fun to sit in the park, or beside a beautiful lake, while working the world on AO-40? And what a neat ready-made Field Day set-up!

One factor you should familiarize yourself with is AO-40's operating schedule. As I noted the transponder is not active throughout the entire orbit, although it is during much of it. The AMSAT-UK and AMSAT-DL webpages, accessible through the AMSAT-NA site, **amsat.org**, carry current information.

Come Join Us

Whether you operate from your shack or in the great outdoors, I'm certain you'll enjoy AO-40. I'll be looking for you.

Notes:

1. Downeast Microwave Incorporated: **www.downeastmicrowave.com.**

2. Robert Seydler, K5GNA, 8522 Rebawood Humble, TX 77346: **k5gna@aol.com.**

3. Steve Kostro, N2CEI, proprietor of Downeast Microwave, tells me that shipping this dish is too expensive, so he does not list it in his catalog. However it is available at his establishment and at conferences which he attends. These include the Dayton Hamvention, the Central States VHF Society Conference, the Northeast VHF Conference and the Southeast VHF Conference. Steve does have a 60 cm dish which can be shipped. Many stations I have worked on AO-40, particularly in Europe, are using 60 cm dishes. So, they do work.

4. K5GNA says, on the sheet which accompanies the, AIDC-3731 that it should be run on 18 volts. However, mine performs fine on just over 12 volts.

5. W0LMD provides information on constructing an S Band patch feed at: **www.ultimatecharger.com/Dish_Feed_S.html.** He might also be persuaded to supply a few pre-built ones.

6. K3TZ: **www.qsl.net/k3tz/index.html**

7. Those not already equipped with azimuth and elevation rotation systems, can use the scheme I used before I acquired my Yaesu 5400. Find an old TV rotator, the kind with a hole all the way through. Mount it horizontally, with the cross boom through the hole. Then mount the entire assembly on a conventional rotator. Some AO-40 operators do not even use rotators, merely manually adjusting the dish pointing every half hour or so.

8. InstantTrack and other satellite tracking programs are available from the AMSAT-NA office: 850 Sligo Ave. Silver Spring, MD 20910 Phone 301-589-6062.

Figure 1 Satellite Installation at W3XO/5. On the left is the 70 cm M^2 30 element crossed Yagi and on the right the no-longer-used 2 meter 14 element crossed Yagi. The 34 inch S Band dish in the center.

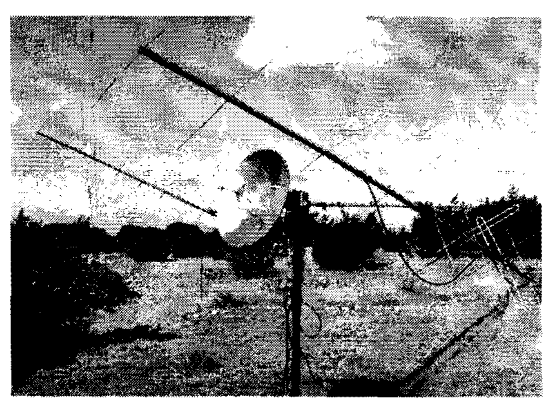


Figure 2 Close-up of downconverter/patch feed assembly.

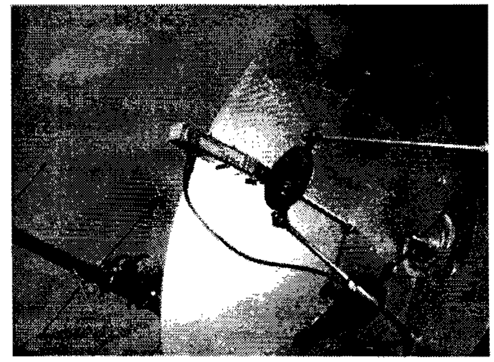
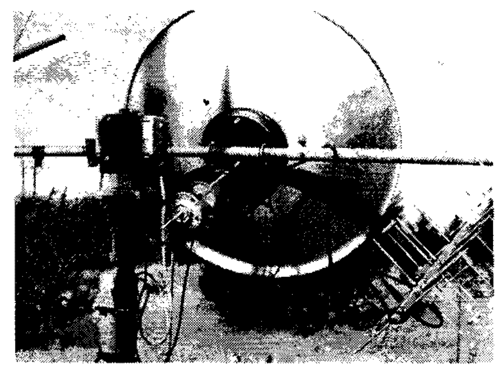


Figure 3 Dish mounting. Note cake pan used to mount dish to the cross arm. The counterweight, consisting of 2 pipe flanges and some old rotor hardware, is supported by 3/8 inch screw stock left over from that used to construct the feed support.



ARRL Technical Awards
Call for Nominations

"Necessity is the mother of invention." I don't know who said that, but I wonder if they were talking about ham radio operators? Do you know someone who has been "tinkering" with a particular aspect of ham radio? If so, now is the time to nominate yourself or your colleagues for one of the awards described below. ARRL members are encouraged to send nominations to ARRL Headquarters. Please include basic contact information for both you and the nominee. Submit support information along with a nomination letter, including endorsements of ARRL affiliated clubs and League officials. Nominations should thoroughly document the nominee's record of technical service and accomplishments.
The nomination form for these awards can be found at http://www.arrl.org/ead/award/application.html

ARRL Technical Service Award is to be given annually to the licensed radio amateur whose service to the amateur community and/or society at large is of the most exemplary nature within the framework of Amateur Radio technical activities. These include, but are not limited to:
- Leadership or participation in technically oriented organizational affairs at the local or national level.
- Service as an official ARRL technical volunteer: Technical Advisor, Technical Coordinator, Technical Specialist.
- Service as a technical advisor to clubs sponsoring classes to obtain or upgrade amateur licenses.

The Technical Service Award winner will receive an engraved plaque. In addition, the winner may request ARRL publications of a value up to $100.

ARRL Technical Innovation Award is granted annually to the licensed radio amateur whose accomplishments and contributions are of the most exemplary nature within the framework of technical research, development and application of new ideas and future systems. These include, but are not limited to:
- Promotion and development of higher-speed modems and improved packet radio protocols.
- Promotion of personal computers in Amateur Radio applications.
- Activities to increase efficient use of the amateur spectrum.
- Digital voice experimentation.

The Technical Innovation Award winner will receive a cash award of $500 and an engraved plaque.

ARRL Microwave Development Award is given each year to the amateur (individual or group) whose accomplishments and contributions are the framework of microwave development, i.e., research and application of new and refined uses and activity in the amateur microwave bands. This includes adaptation of new modes both in terrestrial formats and satellite techniques.
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I (We) ______________________________ call sign ____________
(your name)

nominate ____________________________ call sign_________ for the award marked below.
(name of person you're nominating)

Please select only **one** award for each nominee.

Technical Awards read more information at: **http://www.arrl.org/tis/info/awards.html**

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___ **ARRL Technical Innovation Award** (Develops & applies new ideas/inventions in H/R activities.)

___ **ARRL Microwave Development Award** (Contributes to H/R microwave development.)

Please provide a short summary of this nominee's accomplishments.

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Please complete the following information about the **nominee**:

Nominees Address______________________________City__________________________

State___ ZIP______ Day Telephone ( )___________ Email __________________________

Please include **your** address:

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This form must be received before March 31.