The AMSAT Microsat Satellite Program
An Example of Smaller, Cheaper, Faster, Better Communications Satellites
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During the past five years, interest in low-cost space missions has increased at a rapid rate. In some cases, what is desired is a single, low-cost, physically small and yet highly-capable satellite for some specific mission. On the other hand, some applications require networks of multiple satellites. Engineers of these systems hope economies of scale will contribute to making multiple satellite systems cost-effective to build and operate.

Microelectronics and other technologies upon which space systems are built have most certainly advanced to the point where it is possible to build small, low-cost, and highly capable satellites. However, there is still relatively little experience at actually building small satellites, getting them into space, and operating them once they are on orbit. In spite of the recent interest in small, low-cost satellites, it may not be widely known that the amateur radio community has a long and productive record of small satellite development and operation.

The idea for the first amateur radio relay satellite is attributed to Don Stoner, who, in an article in the April 1959 amateur radio publication *CQ*, suggested that such a satellite be built (16). Fred Hicks, who had been associated with the first six Discoverer launches, was one of the many readers of Don's article (3). Fred initiated the first in a long series of events that resulted in the formation of the Project OSCAR Association in California and the eventual launch of the first amateur radio satellite, OSCAR I, on December 12, 1961. The acronym "OSCAR", which has since been attached to almost all amateur radio satellite designations on a world-wide basis, stands for ***Orbiting Satellite Carrying Amateur Radio***.

Project OSCAR was instrumental in organizing the construction and launch of the first four amateur radio satellites—OSCARs I, II, III, and IV. Since OSCARs I and II were in orbits that would decay quickly, they were equipped with only battery power and beacon transmitters. The transmission rate of the continuous wave (CW) beacons was a function of the spacecraft temperature. OSCAR III was the first amateur radio satellite to support communications relay as envisioned by Don Stoner, and about 1,000 amateurs in 22 countries used its relay capabilities (3). OSCAR IV, the last satellite built under the auspices of Project OSCAR, was launched December 21, 1965. Due to a failure of the top stage of the launcher, OSCAR IV never achieved the planned orbit, and side effects of its unplanned orbit caused its early demise. Although OSCAR IV operated for only a few weeks, some amateur radio contacts were made through it, including the first two-way satellite communication between the United States and the former Soviet Union.

While Project OSCAR was operating on the West Coast, a group of people with similar interests was developing on the East Coast. In 1969, the Radio Amateur Satellite Corporation (known as AMSAT) was incorporated in Washington, D.C. As seen in Table 1, AMSAT has participated in many international amateur radio satellite projects, beginning with the Australis-OSCAR-5 project. Now, many countries have their own AMSAT organizations such as AMSAT-DL in Germany, AMSAT-UK in England, BRAMSAT in Brazil, and in Argentina, AMSAT-LU.

Because of the many AMSAT organizations now in existence, the U.S. AMSAT organization is frequently designated AMSAT-NA. All of these organizations operate independently but may cooperate on large satellite projects and other items of interest to the global amateur radio satellite community.

Beginning with OSCAR 6, radio amateurs started to enjoy the use of satellites with lifetimes measured in years as opposed to weeks or months. The operational lives of OSCARs 6, 7, 8, and 9, for example, ranged between four and eight years. All of these satellites were low-Earth orbiting (LEO) with altitudes of 800-1200 km. LEO amateur radio satellites have also been launched by groups not associated with any AMSAT organization such as the Radio Sputniks 1-8 and Iskra 2 and 3 satellites launched by organizations in the former Soviet Union.

The short-lifetime LEO satellites (OSCARS I-IV and 5) are sometimes designated the Phase I satellites, while the long-lifetime LEO satellites are called the Phase II satellites. The amateur radio community follows the usual convention of having one designation for a satellite before launch and another after it is successfully launched. Thus, OSCAR 13 was known as Phase 3-C before launch. The AMSAT designator may be added to the name, for example, AMSAT-OSCAR-13, or just AO-13 for short. Finally, some designator may replace the AMSAT keyword, such as the Japanese-built Fuji-OSCAR-20 (FO-20).

In order to provide wider coverage areas for longer time periods, design of the high-altitude Phase 3 series was initiated in the late 1970s. Phase 3 satellites provide 8 to 12 hours of communications for a large part of the northern hemisphere. After losing the first satellite of the Phase 3 series to a launch vehicle failure in 1980, AMSAT-OSCAR-10 was successfully launched and became operational in 1983. AMSAT-OSCAR-13, the follow-up to the AO-10 mission, was launched in 1988. AO-13 now provides most of the wide-area SSB and CW communications capability at certain times of the year despite the failure of its onboard computer memory. The successor to AO-13, Phase 3-D is already under construction and is scheduled for launch in 1996.

With the availability of the long-access time and wide coverage of satellites like AO-10 and AO-13, it may seem that the lower altitude orbits and shorter access times of the Phase II series would be obsolete. This certainly might be true were not for the incorporation of digital store-and-forward technology into many current satellites operating in low earth orbit. Satellites providing store-and-forward communication services using packet radio techniques are generically called *Pacsats*. Files stored in a

Table 1. Satellite Projects of the Radio Amateur Satellite Corporation in Cooperation with Other International AMSAT Organizations

NAME	LAUNCH DATE	LIFE/STATUS	NOTES
OSCAR 5	Jan. 23, 1970	52 days	Built by students at Melbourne University Australia. First satellite to have engineering and launch support from AMSAT-NA. No solar generator.
OSCAR 6	Oct. 15, 1972	4.5 yrs.	First long-lifetime satellite. In service for over four years. Battery failure.
OSCAR 7	Nov. 15, 1974	6.5 yrs.	First satellite to carry two linear transponders. Six-year lifetime. Battery failure.
OSCAR 8	Mar. 5, 1978	5.3 yrs.	Two linear transponders. Six-year lifetime. Battery failure.
PHASE 3-A	May 23, 1980	0.0 yrs.	Launch vehicle failure.
OSCAR 10	June 16, 1983	Lim. Oper.	First high-altitude orbit OSCAR. Two transponders. Operational when sun angle is favorable. Radiation-induced computer RAM failure.
OSCAR 13	June 15, 1988	In Oper.	High-altitude orbit OSCAR carrying four linear transponders. Will probably reenter sometime in 1996.
OSCAR 16	Jan. 22, 1990	In Oper.	First amateur radio “microsat”. Digital store-and-forward file server.
OSCAR 17	Jan. 22, 1990	In Oper.	Educational microsat transmitting packet radio telemetry and digitized speech.
OSCAR 18	Jan. 22, 1990	In Oper.	Educational microsat built by Weber State University. Primary experiment is earth imaging system.
OSCAR 19	Jan. 22, 1990	In Oper.	Digital store-and-forward file server like OSCAR 16.
PHASE 3-D	Est. 1996		Now under construction by international AMSAT team.

Pacsat message system can be anything from plain ASCII text to digitized pictures and voice. The first satellite with a digital store-and-forward feature was UOSAT-OSCAR-11. UO-11's Digital Communications Experiment (DCE) was not open to the general amateur radio community, although it was used by the designated "gateway" stations. The first satellite with store-and-forward capability open to all amateurs was the Japanese Fuji-OSCAR-12 satellite launched in 1986. FO-12 was succeeded by FO-20 launched in 1990. In addition to providing digital store-and-forward service, FO-12 and FO-20 also have analog linear transponders for CW and SSB communications.

By far the most popular store-and-forward satellites are the Pacsats utilizing the Pacsat Broadcast Protocol. These Pacsats fall into two general categories—the *Microsats* based on technology developed by AMSAT-NA and the *UoSATs* based on technology developed by the University of Surrey. While both types are physically small spacecraft, the Microsat type satellites represent a truly innovative design in terms of size, capability and low cost. A typical Microsat is a cube measuring approximately 23 cm (9 in) on a side and weighing about 10 kg (22 lb) and will contain an onboard computer, enough RAM for the message storage, two or three transmitters, a multi-channel receiver, telemetry system, batteries and the battery charging and power conditioning system (10).

Amateur radio satellites have evolved to provide two primary types of communication services—analog transponders for real-time CW and SSB communications and digital store-and-forward for non-real-time communications. An evolutionary process has also occurred among groups sponsoring, designing, and building satellites providing amateur radio communications. For many satellite projects, the majority of the design, construction and operations tasks are handled by radio amateurs. More recently, however, there has been a trend toward other groups interested in satellite technology to design and build satellites that provide communications services to radio amateurs. Estimates of the out-of-pocket costs of a number of amateur radio satellites can be found in Table 2.

Table 2. Amateur Satellite Program Costs

OSCAR I	1961	$26
Australis-OSCAR-5	1970	$6000
AMSAT-OSCAR-6	1972	$15,000
AMSAT-OSCAR-7	1974	$38,000
AMSAT-OSCAR-8	1979	$50,000
AMSAT-Phase-3A	1980	$217,000
AMSAT-OSCAR-10	1983	$576,000
AMSAT-OSCAR-13	1988	$385,000
AMSAT-OSCAR-16	1990	$163,000
AMSAT-Phase-3D	1996	$4,500,000[1]

Source: Reference(8) except for last two projects.
Note (1): Estimated and includes launch costs. Total for all project participants. Not just AMSAT-NA share of costs.

The Microsat Project

More than five years have passed since the launch of four Microsat spacecraft developed by AMSAT-NA and other cooperating AMSAT groups. The four satellites, their primary missions, and owner/operators are: AMSAT-OSCAR-16 (AO-16 or Pacsat), store-and-forward file server system, funded and operated by AMSAT-NA; DOVE-OSCAR-17 (DO-17 or DOVE), space science education and the promotion of international peace, funded by the Brazilian AMSAT organization BRAMSAT; WEBER-OSCAR-18 (WO-18 or Webersat), space science education, funded and operated by Weber State University; and LUSAT-OSCAR-19 (LO-19 or LUsat), store-and-forward file server system, owned and operated by Argentina's amateur satellite organization, AMSAT-LU. While the Microsats were largely developed by AMSAT-NA, there was also participation by other organizations. An engineer from AMSAT-LU performed many of the spacecraft integration tasks and a Slovenian student studying in the U.S. did much of the design work for the transmitters. The Microsat program in general, and AO-16 in particular, show what can be accomplished by amateur radio satellite enthusiasts.

The Microsats were launched January 22, 1990, on Ariane mission V-35, the first mission to use the Ariane Structure for Auxiliary Payloads (ASAP). All of the Microsats were placed in nearly-circular sun-synchronous low earth orbits (800 km). The design and construction of AO-16 cost about $163,000. After more than five years in orbit, AO-16 and the other three Microsats remain in continuous operation. Figure 1 shows the assembled AO-16 Microsat and includes an exploded view of AO-16's internal modular structure. Operational aspects of the Microsat missions can now be described in detail followed by a discussion of techniques that contributed to their success while at the same time reducing costs.

Onboard Systems

There is little doubt that the AMSAT-NA Microsats have compiled an enviable performance record (4). This is true both in terms of the spacecraft themselves as well as the onboard computer software. There have been a few subsystem and component failures, but none of these failures caused the loss of a mission. Before discussion of the broadcast file server application of AO-16, a brief overall reliability review for all four AMSAT Microsats follows.

One measure of system reliability and availability can be obtained by monitoring the downlink of each of the four Microsats. The housekeeping task (PHT) periodically broadcasts a frame containing the current date and time as well as the total elapsed time the operating system kernel has been running. Note that the elapsed time applies to the operating system kernel and not to PHT or any applications such as the file server system.

Figure 2 contains a recent date/time/uptime frame from each satellite. The date/time in the first line of the pair comes from the clock in the ground station terminal node controller (TNC) whereas the date/time in the second line is from the clock in the spacecraft. The discrepancies between the two clocks are caused by infrequent checking and setting of the ground station TNC clocks.

From Figure 2 it can be seen that PACSAT (AO-16) and WEBER (WO-18) have uptimes of 642 days and 541 days respectively. In contrast to the long uptimes of PACSAT and WEBER, DOVE (DO-17) and LUSAT (LO-19) show relatively short uptimes of 43 days and 52 days. The 43-day uptime of DOVE corresponds to the time since a new

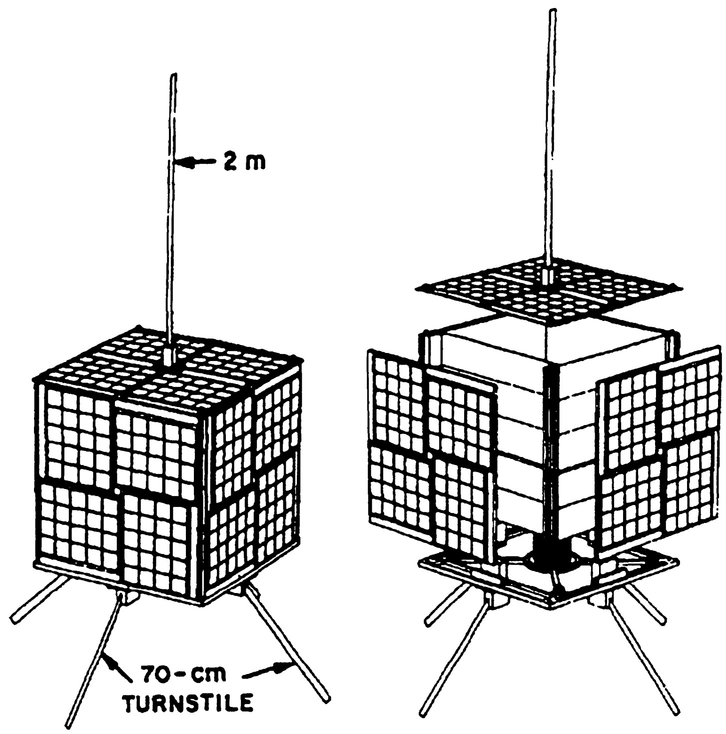

Figure 1. Assembled and Exploded Views of the AO-16 Microsat

operating system kernel was uploaded in preparation for speech synthesizer tests. LUSAT suffered an anomaly of unknown origin in mid-May 1994 that necessitated a reload of its operating system. However, prior to that incident it had accumulated nearly 1,000 days of uptime. The information in Figure 2 shows that all four satellites are currently in operation and that onboard computers and their software are quite reliable.

There have been no problems with the power generation, conditioning, and storage subsystems. Figure 3 shows a recent whole-orbit survey of available power for AO-16. For this particular survey, the whole orbit average power was 6.4 W while the average for the sunlit portion was 8.6 W. The plot does not drop to zero during eclipse because the power system design is such that during eclipse, the sensor is showing power required by all spacecraft systems except the downlink transmitter. In this case the power is being supplied by the spacecraft's battery.

Each of the Microsat flight computers uses an NEC V40 microprocessor. In addition, there is a Motorola 68HC11 in the DOVE speech module. None of these devices have experienced any type of failure, including single event latchups (SEL).

Each of the Microsats have 256 Kb of EDAC-protected static RAM for program storage and an 8 Mb non-EDAC-protected static RAM for data storage. There have been no permanent bit failures in the EDAC-protected RAMs. Bit errors in the non-EDAC-protected static RAMs are corrected by a software

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PACSAT-1>TIME-1 [07/13/94 05:51:55] <UI>:
PHT: uptime is 642/00:44:54. Time is Wed Jul 13 05:46:59 1994

DOVE-1>TIME-1 [07/23/94 18:47:50] <UI>:
PHT: uptime is 043/04:46:40. Time is Sat Jul 23 18:47:18 1994

WEBER-1>TIME-1 [07/10/94 17:52:10] <UI>:
PHT: uptime is 541/22:13:40. Time is Sun Jul 10 17:52:16 1994

LUSAT-1>TIME-1 [07/10/94 17:22:29] <UI>:
PHT: uptime is 052/00:56:11. Time is Sun Jul 10 17:20:05 1994
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Figure 2. Date/Time/Uptime Frames From Each of the Four Microsats

memory "wash" procedure. The memory wash cycle is done at a rate high enough to wash the entire 8 Mb in less time than it takes to pass through the South Atlantic Anomaly (SAA) twice.

Each of the modules within a Microsat communicates with the computer module via an interface designed around the Motorola MC14469 asynchronous addressable receiver transmitter (AART). One of a total of 16 of these communication paths has failed—the path from the DOVE speech module to the computer module. However, more than one trillion AART commands have been issued successfully by the flight computers and acted upon by the receiving modules—none have been lost or interpreted incorrectly.

AO-16, WO-18, and LO-19 have a pair of transmitters in the 70 cm band. In each pair, one of the transmitters utilizes a standard

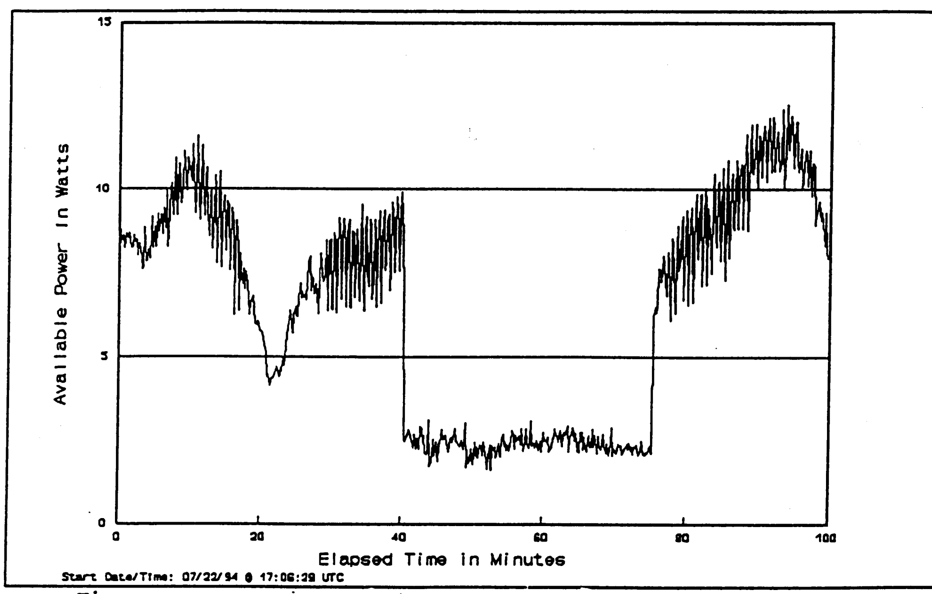

Figure 3. AO-16 Whole-orbit Survey of Available Power

PSK modulator and the other has a raised-cosine (RC) PSK modulator. LO-19 has an additional CW transmitter in the 70 cm band and AO-16 has a PSK third transmitter in the 13 cm (S) band. DO-17 has two AFSK FM transmitters in the 2 m band and a PSK transmitter in the 13 cm band. Problems have developed with the AO-16 and WO-18 70 cm and DO-17 13 cm PSK transmitter modulators. In all three cases, there has been a loss of carrier suppression, which is equivalent to a reduction in modulation index. The problem is much more serious on DO-17. In all cases, the cause is thought to be a small change in value of a piece part (capacitor).

None of the transmitter modulator problems had a permanent impact on the respective missions. For WO-18 and AO-16, operations were switched to the RC PSK transmitters. The near failure of the DO-17 13 cm transmitter modulator had a significant impact on software uploading capability. Other aspects of the mission have not been affected, however, because only the 2 m transmitter is used during normal operations.

Application Software

The primary mission of AO-16 and LO-19 is that of providing a store-and-forward communications facility in low earth orbit. During approximately the first 2 ½ years in orbit, the application software required to realize this mission evolved through several distinct stages of development.

For about the first year of operation, AO-16 and LO-19 provided what is called digipeater service. With this mode of operation, two stations within the satellite's footprint could connect to each other using the satellite as a relay. The amount of data transferred was, of course, limited by the time of co-visibility and the typing speed and proficiency of the ground station operators.

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

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

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

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

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

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Download: Priority Auto Grab Never Fill Dir  Info. View dir. Quit! Help.
Message Holes  Size Offset Rcvd Auto: Fill, msg 5904, 1 holes.
                                Dir 5935 S:LO-19    T:LU8DYF F:G3RWL
       5925    4   N/A  2684     Dir 5937 S:REPORT LUS T:ALL  F:LU2BDTA
       5933    1  1974  1220 74% Dir 592c S:BL940717  T:     F:
                                Message 5904 heard.
                                Message 5904 downloaded.
                                Auto: Start, msg 58f7, 244 byte frames.
                                Message 58be heard.
                                Message 590b heard.
                                Message 5933 heard.
                                Message 58d2 heard.

PB: VY2DCS WA9MTO VE3FRH KM4EM N8WLJ VE3BDR WB4FIN\D W9ODI
OK KA9CFD
PHT: uptime is 646/11:13:12. Time is Sun Jul 17 16:15:17 1994
OK N5AHD
I P:0x1CFF o:0 1:902 f:960, d:1 st:5
PB: WA9MTO VE3FRH KM4EM N8WLJ VE3BDR WB4FIN\D W9ODI KA9CFD N5AHD VY2DCS
Open B D: WW8T  WA4UPD
PB: VE3FRH KM4EM N8WLJ VE3BDR WB4FIN\D W9ODI KA9CFD N5AHD VY2DCS
PB: KM4EM N8WLJ VE3BDR WB4FIN\D W9ODI KA9CFD N5AHD VY2DCS VE3FRH
Open B D: WW8T  WA4UPD
PB: N8WLJ VE3BDR WB4FIN\D W9ODI KA9CFD N5AHD VY2DCS VE3FRH KM4EM
DIR: Part (03)  AUTO: 58f7        s:0000 b:003590 d:001644 e:
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Figure 4. Ground Station Computer Display
While Receiving Data From the Satellite Downlink

Details of typical ground station equipment configurations used to access AO-16 and descriptions of the software required to access the satellite's file system have been published (5). Figure 4 has been included as an example of a typical ground station computer display seen while utilizing AO-16 or LO-19. It should be noted that while Figure 4 shows the MS-DOS version of the user ground station software, MS-DOS Windows and Unix X-Windows versions of the software are now available. A version for IBM OS/2 is under development.

Activity log files are generated by the file server system on a daily basis. These activity logs can be downloaded and processed to extract usage statistics of interest. Figures 5 and 6 give a month-by-month account of AO-16 usage for 1993. In Figure 5, the left-hand bar of the pair is the transaction count and is read on the left-hand Y axis while the right-hand bar is the byte count and is read on the right-hand Y axis. Figure 5 clearly shows a decrease in activity in the summer months.

Figure 6 shows that almost all connected-mode activity results from file uploading. The total transmitted byte count for 1993 was about 650 Mbytes. At 1200 bps, about 4.75 Gbytes could be transmitted in a year. Consequently, 650 Mbytes represents about 15 percent downlink utilization excluding HDLC overhead, telemetry transmissions, and other types of downlink data. Of course, much of the time AO-16's footprint does not include any populated areas, so 100 percent utilization is not possible. On the other hand, effective utilization would be higher than 15 percent if one could estimate the data reuse factor. Remember that many stations can be using the broadcast mode data as a result of another station's request for a needed file or directory.

Table 3 shows the cash expenditures of AMSAT-NA for the construction and launch of AO-16. Readers should remember that this project was accomplished almost entirely with volunteer labor. The operating system software was donated due to the non-commercial nature of the project. The application software was designed, written, and donated by the radio amateur software team supporting the project.

Project Management

Having examined some of the design and operational details of the Microsats in general, and AO-16 in particular, along with the available cost data, we have shown reliable and low-cost satellites built by AMSAT-NA and similar cooperating organizations. What is required now is identification of specific techniques that may be applied in projects in other sectors. We will begin the discussion with the management structure and related personnel issues. However, other issues, such as parts selection, will be included because they are part of the overall project management philosophy and are important cost-reduction issues. One factor that will not be discussed to any great degree is the virtually non-existent labor costs arising from the volunteer, scientific, educational nature of AMSAT organizations. Since this aspect cannot be duplicated in any real-world commercial or governmental project, no benefit would accrue from giving

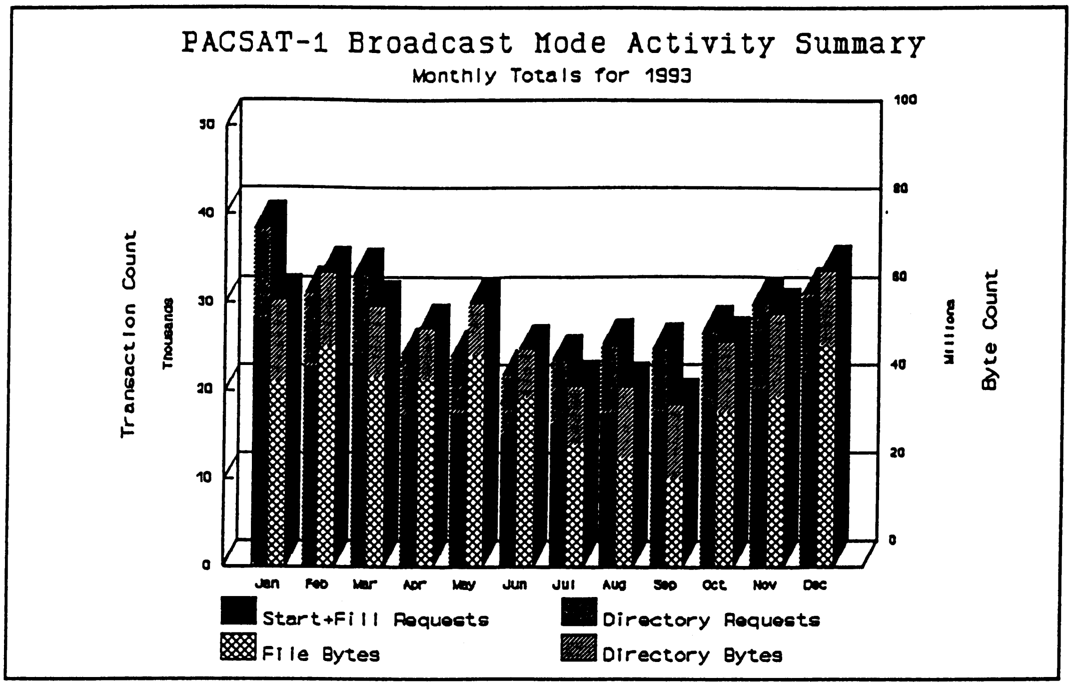

Figure 5. Month-by-month Broadcast Mode Activity Summary for AO-16

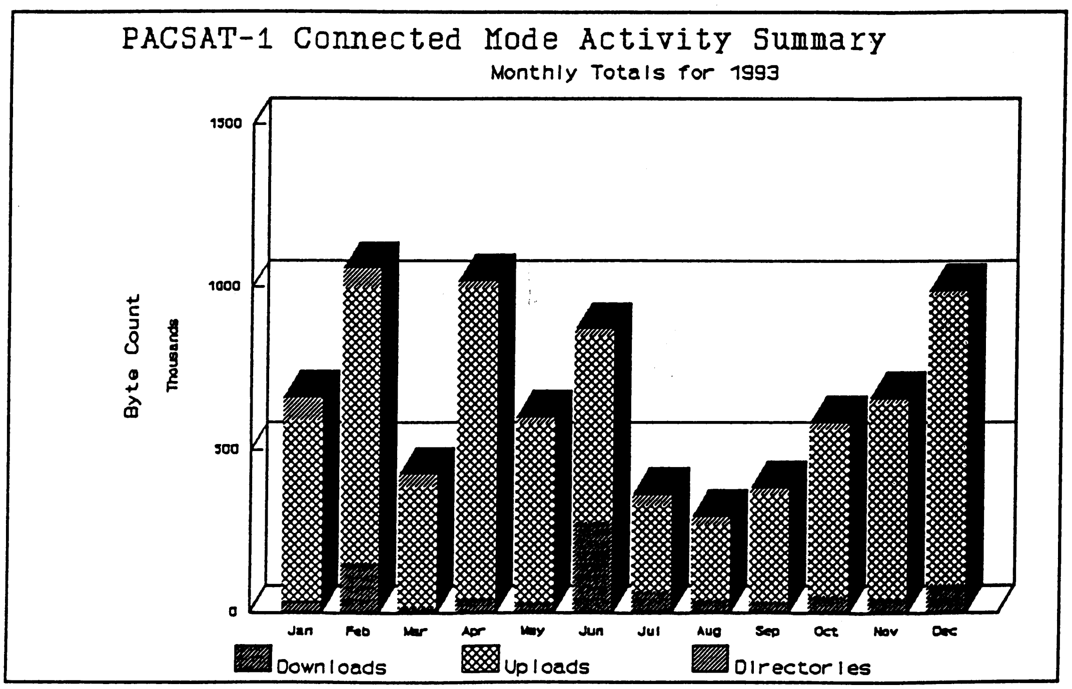

Figure 6. Month-by-month Connected Mode Activity Summary for AO-16

Table 3. Itemized List of AO-16 Project Costs
(FY1989 $)

Components	$ 14,883.01
Subcontracts	16,995.93
Non-recurring engineering	21,422.00
Salaries	3,070.76
Equipment rental	123.73
Facilities rental	3,206.71
Share of launch costs	20,352.20
License fees	1,023.85
Liability insurance	1,253.87
Other insurance	262.50
Documentation	2,675.00
Telephone	13,822.05
Electronic mail	13,531.17
Travel	38,028.47
Printing	1,530.42
Postage	4,847.15
Supplies	1,366.57
Photography	658.12
Advertising	300.00
Accounting	917.22
Miscellaneous	2,685.68
TOTAL	$162,956.41

it further attention. This is not to imply that there has never been any paid personnel working on an AMSAT project. Salaried personnel have been used at critical phases during several of the projects, but such expenses have been kept to a minimum.

It should be clear what motivated development of the AMSAT philosophy in the first place. The true motivation for reducing costs occurs when there is ***no money*** or the amount of money is very small compared to the amount that would be spent if a similar project was undertaken in the commercial sector. What develops from the lack of adequate funding is a philosophy that allows new, cost-effective techniques to be tried. The AMSAT philosophy continues to develop as more information is collected while applying and refining techniques. The refinement process includes the application of new technologies as soon as they are practical.

Management Structure

AMSAT has found it beneficial to utilize multi-disciplinary managers, engineers, and technicians in its satellite projects. Figure 7 shows the personnel mixture in a typical non-amateur satellite project (9). Some of the various technology areas are shown in the columns while the skill levels are shown in

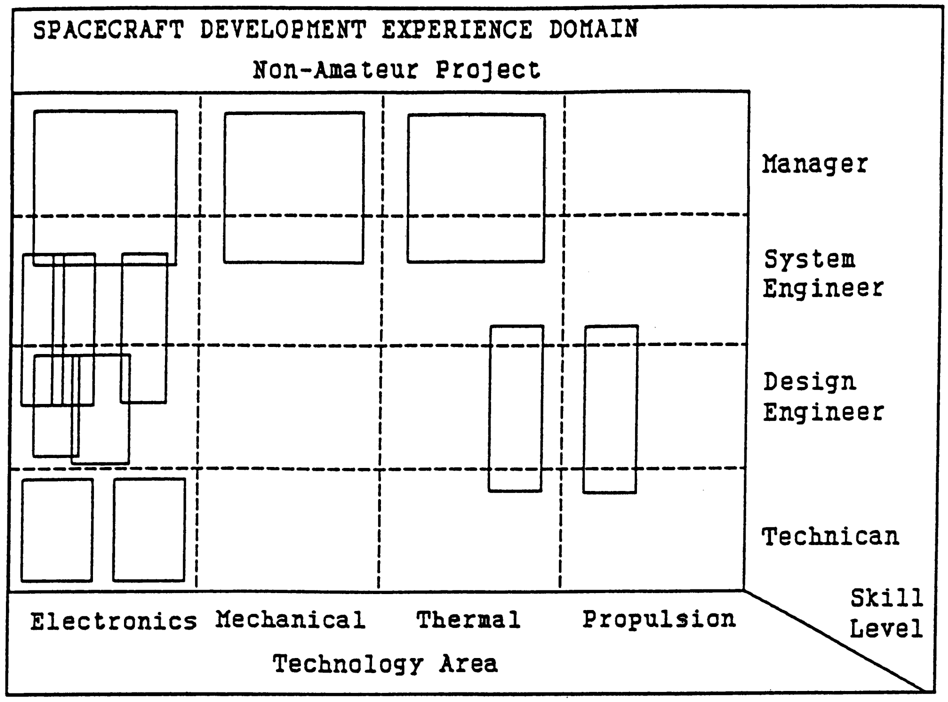

Figure 7. Personnel Mixture for a Non-amateur Satellite Project

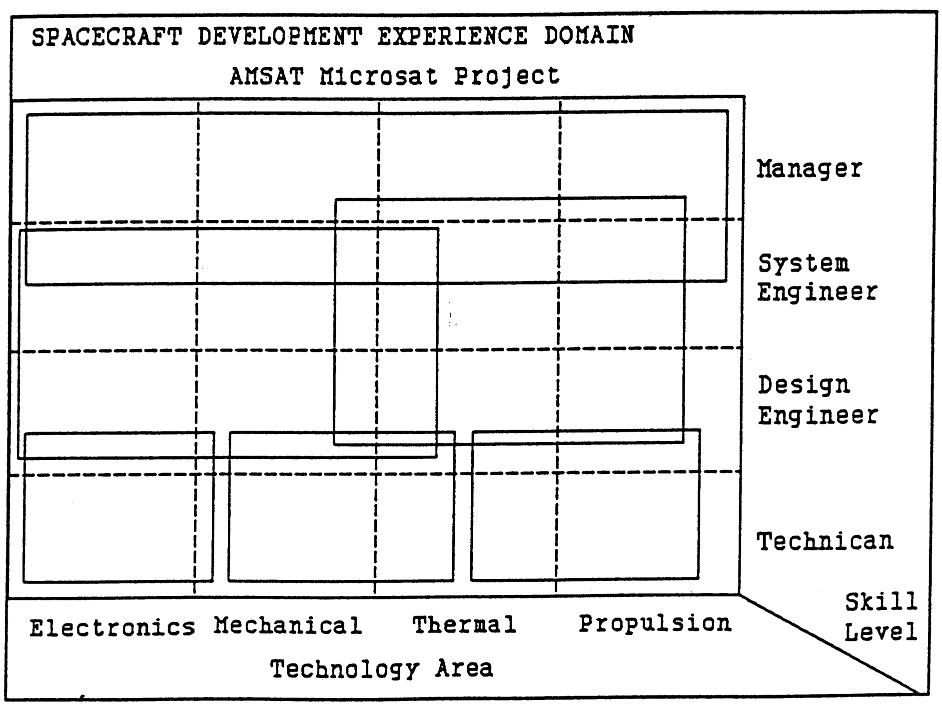

Figure 8. Personnel Mixture for a Cost-effective Satellite Project

the rows. The progression is from managers and senior engineers at the top, through the junior engineers, to the technicians. Figure 7 illustrates a personnel mix where the level of specialization is high. Moreover, the fact that personnel do not cross technology areas implies that some (probably expensive) interface control procedure must exist.

Figure 8 represents a more ideal personnel structure that is similar to that used on the Microsat project. Here, there is one broadly experienced project manager with a couple of senior engineers covering multiple skill levels and technology domains. In a similar vein, technicians also cross technology areas and have some design engineering skills. Two attributes of AMSAT personnel must be carefully considered—motivation and skill level. It has already been stated that most personnel working on AMSAT projects do not receive any monetary compensation. Why, then, are they motivated to expend their valuable time working on a satellite project?

The answer, of course, lies in the fact that they have their own particular motivations. For the project manager, it may be that a design concept could not come to fruition in any other way. For other participants there is a whole spectrum of possibilities. Perhaps the software designer wishes to take on the challenge of writing a reliable and fault-tolerant satellite-based application. Maybe, the technician has strong philosophical attachment to one or more system design concepts or to the application of the finished product. And, it could be that the person derives satisfaction in working on something that will go into space. The point is that managers of non-amateur projects must choose a staff that is similarly motivated or create the motivation within the staff—probably some of both. When the staff is not positively motivated, the reliability and performance of the systems built will suffer. Acceptable salary levels are not always sufficient motivation to do quality work. The motivation to do quality work comes about partially by training and partially by example. It is management that must first give the example and then choose personnel who can propagate the example.

In amateur radio satellite projects, skill level of the participants encompasses more than expertise in some required specialty. It means diversity of skill and the appropriate mixture of theory and practice. Many amateur radio operators, and not just those who happen to be associated with satellite projects, began the pursuit of their hobby in grade school. So, by the time they reach the prime of their careers at age 40 to 50, they have 30 to 40 years of experience behind them. From these years of experience come the abilities to cross technology area boundaries, to make cost versus performance tradeoffs, to try innovative designs, to minimize failures, and to do what cannot be done very easily on a shoestring budget.

Parts Selection

AMSAT has much experience to offer with respect to parts selection for spacecraft projects. The most important aspect of that experience is the characterization of the in-orbit reliability of the lower MIL-HDBK-217F classes and unclassified parts.

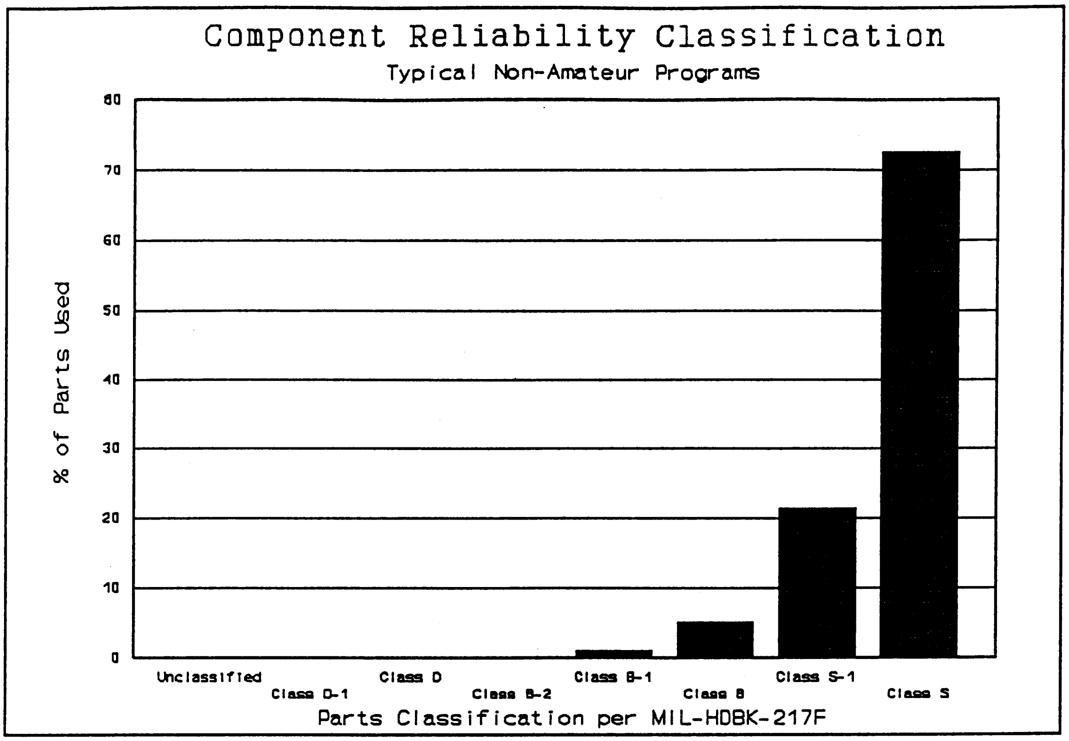

Figure 9. Typical Component Classification Mixture for a Non-amateur Satellite Project

Figure 9 shows a typical parts classification mixture for non-amateur programs. Figure 10 gives the parts mixture for the AMSAT-NA Microsat program. The in-orbit problems and subsystem failures encountered in the Microsat program have already been given, but recall that none of the failures has resulted in the loss of a mission.

The following observations have been made by AMSAT project management (9) with respect to parts mixtures:

- The best parts available rarely fail.
- Confidence exists in proven techniques.
- Not only are parts reliable, they have margin over the specified values.

But,

- The highest price is always paid.
- The schedule will always be long.
- Using good parts can mask a poor design.
- There is no knowledge about how lower-class and unclassified parts work in space.

Having employed parts mixtures of the type shown in Figure 10, AMSAT has found that:

- Good circuit design is more important than device technology.
- A practical approach to reliability must be developed based on cost.

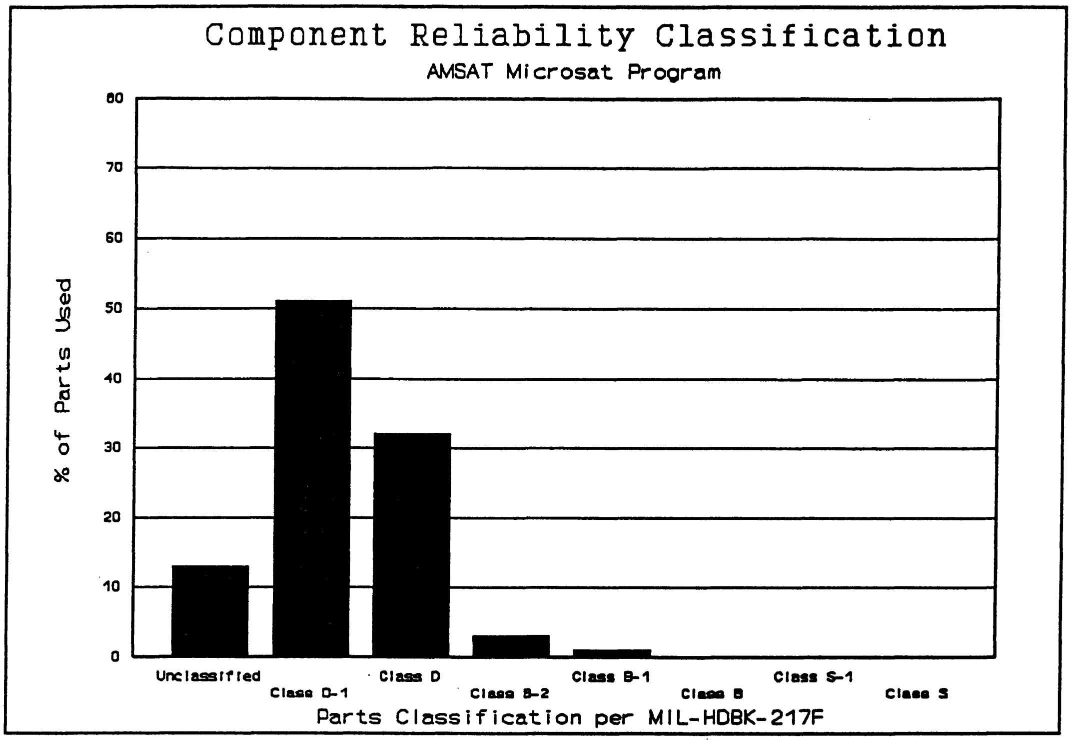

Figure 10. Component Classification Mixture for AO-16 and the Microsat Program

- Because experience is gained over a large portion of the reliability classification line a database is established that can be applied to future projects.

On the other hand, there are risks associated with the first in-flight use of components and the primary payload customer may be concerned with the parts choices made by the secondary payload customers. However, the risks can be largely mitigated by appropriate testing prior to launch.

Radiation Issues

The issue of parts reliability encompasses the question of radiation tolerance of components and systems and AMSAT's experience in this regard again differs with widely-held opinion.

Specifically, AMSAT has found that radiation hardness/tolerance requirements are actually two to three times less than industry practice. This is not to say that AMSAT satellites have not experienced any radiation-induced failures. Indeed, AO-10's flight computer is inoperative due to the radiation-induced failure of its RAM. On the other hand, though, AO-13 has now been in a Molynia orbit for nearly seven years with no radiation-induced failures.

AMSAT's experience with radiation issues (9) has led to the following philosophy:

- Use rad-hard parts if they are available and affordable.

- Use specially-processed standard parts if they are available and affordable.

- Try to use parts with gate geometries no smaller than 1.0 micron.
- Use parts that are known to exhibit acceptable performance by virtue of the reliability experience data base.
- Protect against memory problems by using EDAC and software memory wash.
- Protect against processor setup table corruption by using hardware watchdog and/or fire code methods.
- Don't use more microprocessors than necessary.
- Ignore the issue of single event latchups.

The AMSAT Microsats, which include AO-16 described earlier, provide clear evidence that the AMSAT philosophy with respect to radiation issues is valid for low-cost LEO spacecraft. Each Microsat flight computer contains 453 integrated circuits and none are radiation-hardened parts. Only the boot ROM is Mil-Std-883. The net result is a total of over 1,800 ICs spread among four flight computers with a total of over 20 orbit-years (five years per satellite) of operation and no identifiable radiation-induced failures. Perhaps one of the few software crashes of unknown origin that have occurred were radiation-induced, but such software failures have been so infrequent they have been hard to characterize. Single-event upsets have been observed in the various computer memories but they have been handled by hardware EDAC and software memory wash as already described.

Apart from the radiation tolerance experience with ICs, AMSAT has found that solar arrays have degraded more slowly than predicted by industry-standard models.

Cooperation with Educational Institutions

AMSAT-NA has sought to establish partnerships with educational institutions to assist in some of its satellite projects. In this regard, a most productive relationship has evolved with the Center for AeroSpace Technology at Weber State University in Ogden, Utah (7).

The concept of building low-cost satellites is not new at Weber State (17). In April 1985, Nusat I was launched from a get-away-special (GAS) canister on the NASA orbiter Challenger. Nusat I operated nominally for 20 months until it burned up upon reentry. The cash outlay for Nusat I was less than $20,000 (1). In 1988, Weber State agreed to manufacture the major mechanical components for the AMSAT-NA Microsat project. One of the four satellites built as part of the Microsat project (WO-18) is owned and operated by Weber State and includes an earth imaging experiment designed and built by a Weber State team.

About the same time the Microsat project was under way, AMSAT-NA was investigating the feasibility of building a geostationary spacecraft called Phase IV. The help of Weber State was enlisted with this project also and a prototype structure was completed in June 1990. Additional work on antenna structures and deployment techniques was completed by spring 1991. Even though work on the Phase IV project was terminated due to lack of sufficient funding within the amateur radio community, the work on the Microsat and Phase IV projects has served to refine the management interfaces and procedures between Weber and AMSAT-NA.

Weber State is making a very significant contribution to the AMSAT Phase 3-D satellite now under construction, by building the entire flight model spacecraft structure, the electronics module boxes, and the cylindrical section that will enclose and support the satellite on the launch vehicle (14).

Current Trends

While AMSAT has developed philosophies and procedures that have resulted in many successful missions, similar mixtures of fiscal, project, and personnel management procedures are becoming more sought after. In a recent article (2), Robert F. Crabbs has the following to say:

> *As it was at the outset, the future of the U.S. space program—civil, military, and commercial—lies in the hands and minds of the current generation of under-graduate, graduate and post doctoral students. If these people are not trained correctly, do not have appropriate role models, and do not develop a passion for doing space research, the United States' program will fall in decline and we will become a second-rate space nation...*
>
> *Launching 20 small satellites a year at a total cost of $100 million, with four or five total failures, will still provide a huge science return for our money, and maybe even greater than if we had built one large spacecraft for the same $100 million. We will have trained more students, employed more people and generated a lot more ideas while solving a lot of problems...*
>
> *Passion is what makes it all work. Without passion, thousands of people merely go through the motions on a daily basis. With passion, real solutions to problems are developed, innovation is generated, excitement builds, fears are overcome and visions develop.*

Without a doubt, the passion Crabbs talks about is a huge factor in the amateur radio space program.

It is interesting to note that until the past five years or so, there have been relatively few university-based satellite projects, but this is rapidly changing. Some of the projects currently underway are: SEDSAT at the University of Alabama at Huntsville (18, 19, 20); ASUSat at Arizona State University (6, 15); and the SQuiRT microsatellite program at Stanford (11, 12, 13). Other projects are in progress abroad. The origins of some of these projects can be traced very directly to the amateur radio satellite program either by virtue of their leadership or through study of principles and practices already developed by AMSAT organizations throughout the world. It would appear that the value of small satellite projects in the training of future engineers and scientists is becoming more widely recognized.

This paper has shown the evolution in complexity of amateur radio satellites from those able to operate for just a few weeks on battery power to the AO-16 Microsat that has been discussed in detail. Readers should pause to contemplate the significance of a project like AO-16, which has been providing routine store-and-forward communications service for several years, while remembering that a parallel commercial service has not been developed in spite of many would-be service providers. Furthermore, it is important to note that the Microsats were developed from initial concept to launch in 25 months.

More important than any single cost-reduction strategy, what AMSAT hopes to offer is the encouragement to further develop and apply some of the AMSAT philosophy. Multiple-satellite systems, by virtue of their redundancy, can afford to implement different design philosophies than have been used in "all things for all people" single satellites. If the time has not been right for the adoption of new ideas before, perhaps the time for new ideas is closer. As the history, case study, and project management techniques are reviewed, it should be remembered that the goal of AMSAT's satellite projects is the enhancement of amateur radio communications through facilities provided in the Amateur Satellite Service. The volunteer nature of the service and the participating organizations and personnel dictate from the start that radically different procedures and techniques be employed. Clearly, the procedures and techniques that have been developed have resulted in many successful missions.

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