THE IN-ORBIT OPERATION
OF FOUR MICROSAT SPACECRAFT--FOUR YEARS LATER

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Abstract

More than four and one half years have passed since the launch of four Microsat spacecraft developed by the Radio Amateur Satellite Corporation of North America (AMSAT-NA) and other cooperating AMSAT groups. This paper documents the current status of the four Microsats with particular emphasis on AO-16 and DO-17. The software supporting the store-and-forward message system of AO-16 and LO-19 has changed significantly since launch, starting out as a real-time digital repeater, progressing to a connected-mode file server, and finally evolving to a broadcast-mode file server. A concise description of this software evolution is included along with long-term satellite usage data for AO-16. Statistics such as average bytes of directory and file data transmitted per day and the average time a user spends waiting for directory and file data requests to be serviced are included. In 1993, DO-17 was returned to service in the 2 m band after having been off the air for over 18 months. The temporary lapse in operations was caused by difficulties loading software after the failure of its 13 cm downlink transmitter modulator. Details of the recovery are summarized as an example of how operational problems have been addressed by an all-volunteer software development, command, and control team.

I. Introduction

More than four and one half years have passed since the launch of four Microsat spacecraft developed by the Radio Amateur Satellite Corporation of North America (AMSAT-NA) and other cooperating AMSAT groups. The four satellites and their primary missions are: AMSAT-OSCAR-16 (AO-16 or Pacsat), store-and-forward file server system; DOVE-OSCAR-17 (DO-17 or DOVE), space science education and promotion of international peace; WEBER-OSCAR-18 (WO-18 or Webersat), space science education; and LUSAT-OSCAR-19 (LO-19 or LUsat), store-and-forward file server system.

In a previous paper [5], King et. al. provided a review of the design criteria and the first months of operation of the four Microsats. This paper documents the current status of the satellites with particular emphasis on AO-16 and DO-17. The topics to be discussed are drawn from three categories: (1) Reliability of onboard systems--Which subsystems continue to operate as expected and which ones have failed? (2) Application software evolution and user activity--What communications facilities are available and what is the level of user activity? (3) Command and control--Have the satellites been available to the users for their intended purposes and how have operational problems been handled? A system reliability report will be given for all four Microsats. Application software evolution is focused on the store-and-forward file server satellites AO-16 and LO-19. DO-17 is the subject of a detailed description of how command and control difficulties have been handled by an all-volunteer command and software development team.

II. System Reliability

There is no doubt that the AMSAT Microsats have compiled an enviable performance record. 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 have caused the loss of a mission. This section focuses more on the current status of spacecraft hardware while the next section describes the application software in use on AO-16 and LO-19. Readers who may be interested in a more complete description of the Microsat systems are directed to [5].

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.

Fig. 1 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 Fig. 1 it can be seen that Pacsat and Weber have uptimes of 642 days and 541 days respectively. In contrast to the long uptimes of Pacsat and Weber, DOVE and Lusat show relatively short uptimes of 43 days and 52 days. The 43-day uptime of DOVE corresponds to the time since a new operating system kernel was uploaded in preparation for speech synthesizer tests. More about DOVE operations is given later in this paper. Lusat suffered a failure of unknown origin in mid-May 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 Fig. 1 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. Fig. 2 shows a recent whole-orbit survey of available power. 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 1990 survey [5] yielded an orbit average power of 5.8 W and the average for the sunlit portion was 8.1 W. The more recent values are slightly higher probably due to the fact that there was no attempt to match seasonal eclipse conditions between the older and newer surveys. The reason that the plot does not drop to zero during eclipse is that the power system design is such that during eclipse, the sensor is showing power required by all spacecraft systems except the downlink transmitter. Fig. 3 gives a whole-orbit plot of the +Y facet array current and Fig. 4 contains plots of the battery and +Z facet temperatures. Figs. 2, 3, and 4 were constructed to match Figs. 3, 6(c), and 2 in [5] as closely as possible. In Fig. 4, the plot that peaks nearest the X-axis origin is the +Z facet temperature.

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. There is also an 8 Mb non-EDAC-protected static RAM consisting of a 2 Mb bank-switched section and a 6 Mb I/O-mapped section. On AO-16 and LO-19, the two sections are used together as the message storage for the broadcast file server. On WO-18, the 2 Mb section is used for CCD image storage. Neither section has yet been utilized on DO-17, but they will eventually be used for storage of digitized messages for the DOVE speech module.

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 memory "wash" procedure. One 1024-byte RAM disk cluster at a time is read, corrected (if necessary), and re-written. 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 communicate 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 DO-17 speech module to the computer module. More than one trillion

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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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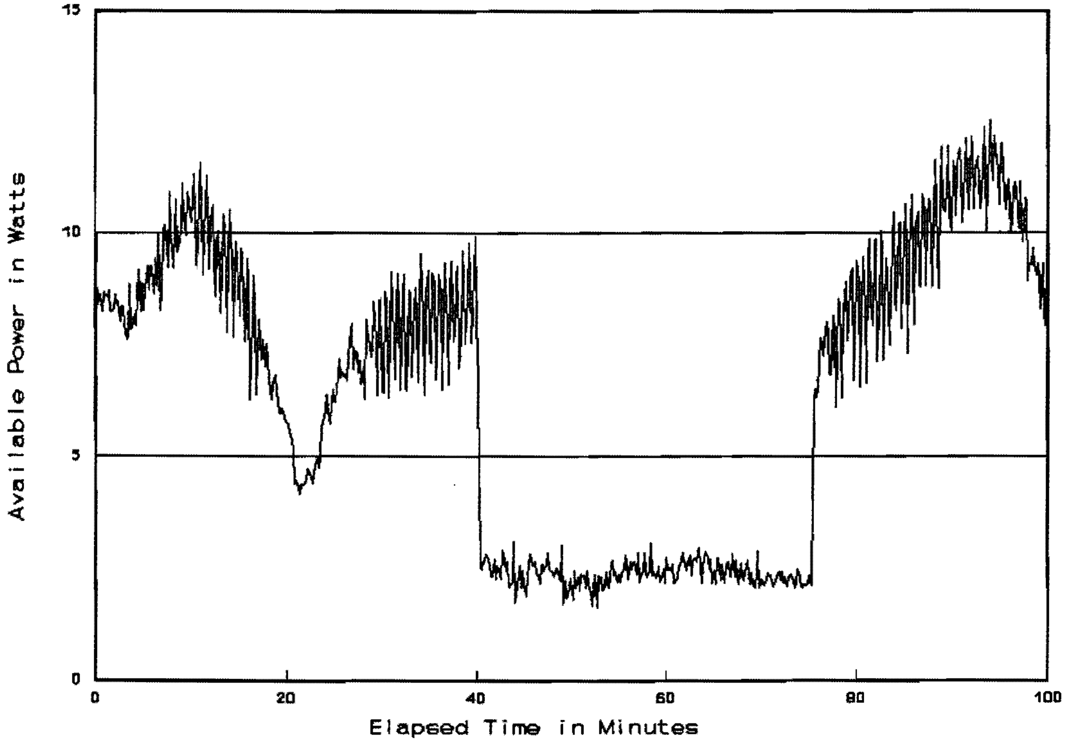
Figure 1. Date/Time/Uptime frames from each of the four Microsats.



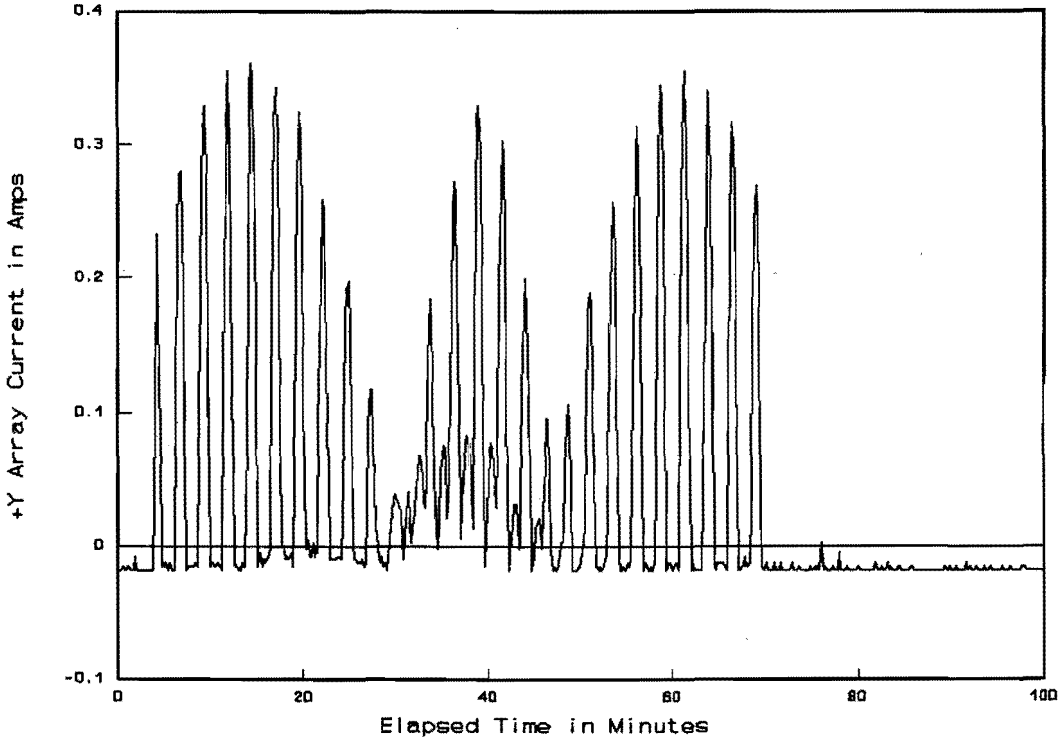
Start Date/Time: 07/22/94 @ 17:08:29 UTC

Figure 2. AO-16 whole-orbit data survey of available power.

AART commands have been issued successfully by the flight computers and acted upon by the receiving modules--none have been lost or interpreted incorrectly.

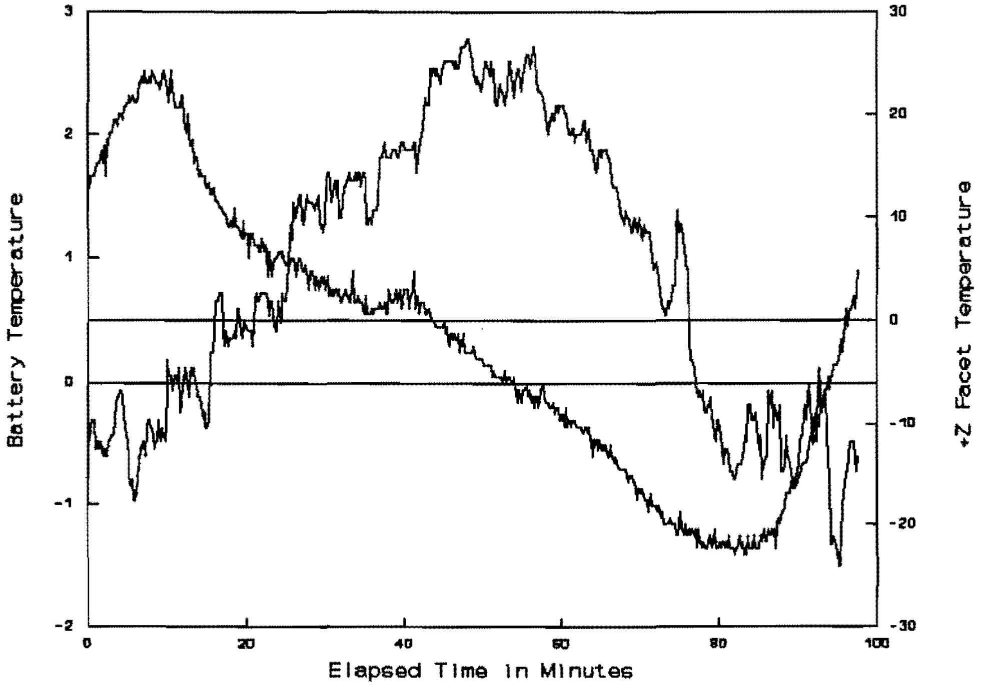
AO-16, WO-18, and LO-19 each have a pair of transmitters in the 70 cm band. In each pair, one of the transmitters utilizes a standard PSK modulator and the other has a raised-cosine PSK modulator. LO-19 has an additional CW transmitter in the 70 cm band and AO-16 has a third transmitter in the 13 cm (S) band. DO-17 has two AFSK FM transmitters in the 2 m band and a PSK transmitter in the 13 cm band. Three separate modulator failures have occurred among these 11 transmitters. The 70 cm PSK modulator on WO-18 was defective at launch. The carrier suppression on the AO-16 70 cm PSK transmitter gradually deteriorated over a period of two years after launch. The DO-17 13 cm transmitter carrier suppression also failed either at or shortly after launch.

None of the transmitter failures have had a permanent impact on the respective missions. For WO-18 and AO-16, operations were switched to the RC PSK transmitters. The failure of the



Start date/time: 07/08/94 @ 04:16:39 UTC

Figure 3. AO-16 whole-orbit data survey of +Y array current.



Start Date/Time: 07/13/94 @ 18:27:40 UTC

Figure 4. AO-16 whole-orbit survey of battery and +Z facet temperatures.

DO-17 13 cm transmitter had a significant impact on software uploading capability. Other aspects of the mission have not been affected, however, because one of the 2 m transmitters is used during normal operations. Details of how the impact of 13 cm transmitter failure has been minimized are given in a following section on command and control.

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

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

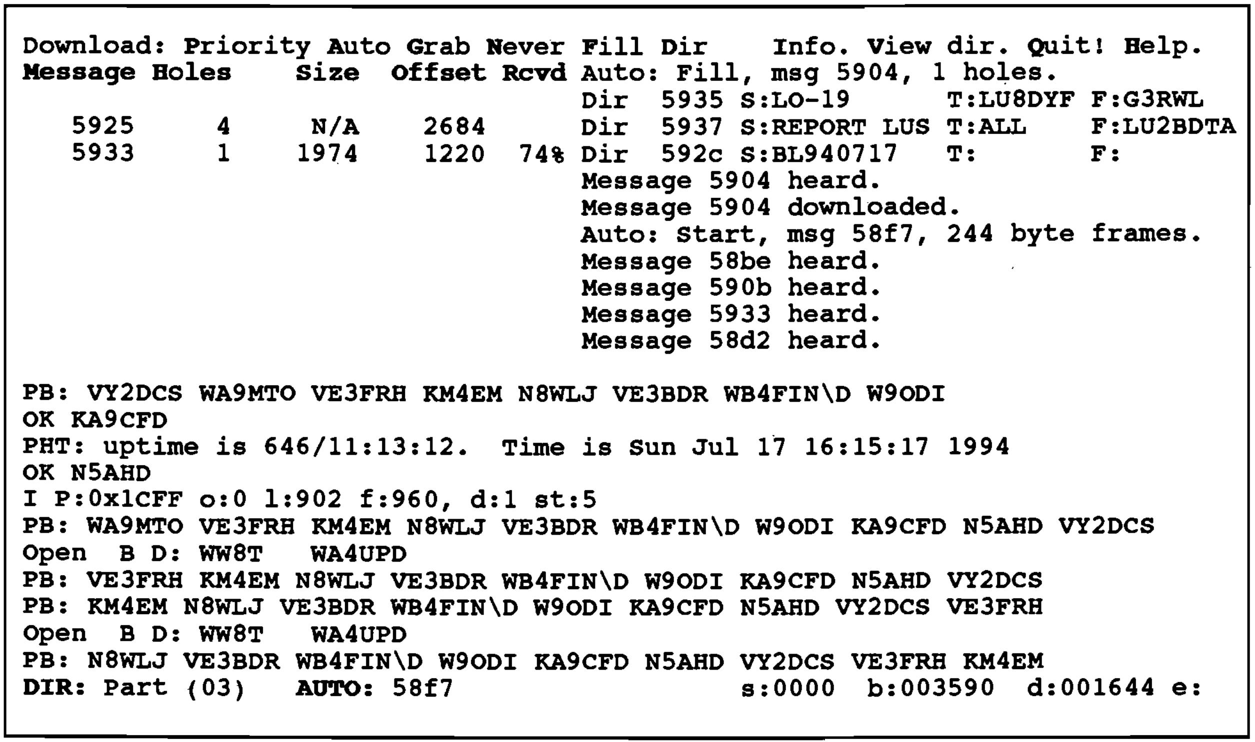
The important difference in the two modes is that with connected mode, data transmitted on the downlink can only be used by the station establishing the connection, even though the downlink data is being heard by all stations in the satellite's footprint. On the other hand, downlink data resulting from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

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

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

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

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 to automatically fill holes in broadcast files and directories. The software implementing the new broadcast mode facilities has been in continuous operation since it was started in October 1992. With the exception of file uploading, almost all access to the store-and-forward facilities is by the broadcast mode. Although the timeline has been slightly different, a similar progression of software installation has occurred on LO-19.



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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 l: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:
```

Figure 5. Ground station computer display while receiving data from the satellite downlink.

Details of typical ground station equipment configurations used to access AO-16 and LO-19 have been published in several other papers [3] [4] and thus have not been included. Similarly, descriptions of the software required to access the satellite's file system have also been published [1] [2]. However, Fig. 5 has been included as an example of a typical ground station computer display seen while utilizing AO-16.

The screen shown in Fig. 5 consists of three parts. The lower half contains certain informatory messages as they appear on the downlink. For example, the "PB:" lines show the callsigns of stations that have made broadcast requests. Station callsigns followed by "\D" have made requests for directory entries while the others have made file requests. Stations whose callsigns appear in the "Open" message are uploading files. The upper half of the screen is split in the middle vertically. The left side gives information about the files being downloaded and the right side tells what type of broadcast information is being received. In this example, files 0x5925 and 0x5933 are being downloaded. The size of file 0x5925 is unknown but its most-recently received record belongs at offset 0x2684 and the copy in the ground station computer currently has four holes. File 0x5933 is known to be 0x1974 bytes in length and the captured file is now 74 percent complete with only one hole remaining to be filled.

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. The AO-16 activity log data presented here was collected over a three-year period and clearly shows the effects of progressing from the connected mode of operation to the broadcast mode of operation.

Table 1 gives AO-16 connected mode statistics for September 1991 thru July 25, 1992--the time of the software crash. The averages for September 1991 thru February 1992 are computed from data sets containing about 15 days worth of data per month. From March 1992 to the present date, the data sets are virtually complete with only about three or four days worth of logs missing for the 2 1/2-year period. Note the amount of directory and download activity for 1992 and recall that in connected mode operation, none of this downlink traffic

Table 1
Connected Mode Statistics for AO-16 While Running the Initial Version of the File Server System

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

Table 2
Connected Mode Statistics for AO-16 After Installation of the New Version of the File Server System

	1992 from 10-17	1993 complete	1994 thru 05-31
Average Byte Count/Day			
Downloads	14,170	2,387	459
Uploads	26,932	18,232	17,124
Directories	2,811	1,003	818
Average Byte Count/Month			
Downloads	372,647	72,594	13,874
Uploads	682,287	554,559	517,146
Directories	71,211	30,497	24,707
Total Byte Count[1]			
Downloads	1,117,940	871,127	69,369
Uploads	2,046,861	6,654,712	2,585,731
Directories	213,633	365,965	123,533

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

could be used by any station other than the one establishing the connection. Table 2 shows connected mode statistics after the installation of the enhanced broadcast mode support. Notice that file and directory downloading is decreasing while file uploading now constitutes the majority of connected mode traffic as desired.

Table 3 gives the broadcast mode statistics starting at the time of the new software installation. Note that the total transmitted byte count for 1993 is about 650 Mbytes. At 1200 bps, about 4.75 Gbytes could be transmitted in a year. Consequently, 650 Mbytes represents about 15 percent downlink utilization excluding HDLC overhead, telemetry transmissions, and other types

Table 3
Broadcast Mode Statistics for AO-16 After Installation of the New Version of the File Server System

	1992 from 10-17	1993 complete	1994 thru 05-31
Average Transactions/Day			
Start+Fill Requests	794	646	727
Directory Requests	259	268	380
Average Byte Count/Day			
File Bytes	1,860,244	1,260,069	1,154,442
Directory Bytes	419,080	501,573	653,423
Average Transactions/Month			
Start+Fill Requests	20,104	19,649	21,942
Directory Requests	6,551	8,142	11,463
Average Byte Count/Month			
File Bytes	47,126,172	38,327,111	34,864,153
Directory Bytes	10,616,681	15,256,183	19,733,372
Total Transactions[1]			
Start+Fill Requests	60,313	235,792	109,709
Directory Requests	19,653	97,698	57,313
Total Byte Count[1]			
File Bytes	141,378,516	459,925,333	174,320,760
Directory Bytes	31,850,043	183,074,192	98,666,858

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

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 utilizing the broadcast mode data as a result of another station's request for a needed file or directory. If the monthly averages for the first five months of 1994 are used to project a yearly total, the total byte count would be about the same as 1993. This will be interesting to watch because it will mean that the usage of AO-16 has remained fairly level in spite of several new digital store-and-forward amateur radio satellites being launched since 1992.

Tables 4 and 5 have been included to better characterize operations when the spacecraft footprint encompasses the continental U.S. Both of these tables contain statistics from two downlink data samples taken at different times--February 1993 and June 1994. The only criteria for data collection was to try to include about the same amount of downlink time in both samples. There was no attempt to try to have the same number of ascending node (local evening) passes and/or descending node (local noontime) passes in each sample. Similarly, there was no attempt to match the number of weekday versus weekend passes in each sample.

In Table 4 it can be seen that for a roughly equal amount of downlink time, the broadcast mode byte count, number of file broadcast requests, and number of directory broadcast requests are about the same. The average time a given station spends waiting in the broadcast queue is more even for file versus directory requests in the June 1994 sample than it was for the February 1993

Table 4
Summary of Typical PACSAT-1 Downlink Data Samples

	February 1993	June 1994
Data taken from file:	AO16STAT.001	AO16STAT.002
Number of passes logged:	25	27
Lowest orbit number:	15,886	22,617
Highest orbit number:	16,194	23,274
Earliest date/time in logs:	02/07/93 @ 04:40:41	05/24/94 @ 05:02:22
Latest date/time in logs:	02/28/93 @ 18:57:54	07/09/94 @ 04:40:44
Total downlink time:	05:44:42	05:48:59
Total broadcast bytes:	2,510,858	2,385,490
File requests:	691	682
Directory requests:	228	366
Total number of requests:	919	1,048
Total time in queue for file requests:	18:04:02	12:19:45
Total time in queue for DIR requests:	09:59:38	08:37:09
Average wait/station for file request:	01:34	01:05
Average wait/station for DIR request:	02:38	01:25

Table 5
Typical Broadcast Queue Utilization for PACSAT-1

	February 1993			June 1994		
No. of Stations	No. of Times	Elapsed Time		No. of Times	Elapsed Time	
Empty	265	00:40:59	11.3%	616	01:42:18	26.2%
1	241	00:34:57	9.6%	423	00:44:31	11.4%
2	228	00:40:07	11.0%	270	00:43:45	11.2%
3	188	00:32:35	8.9%	240	00:37:34	9.6%
4	176	00:29:38	8.1%	205	00:29:24	7.5%
5	146	00:24:41	6.8%	182	00:26:30	6.7%
6	185	00:30:14	8.3%	191	00:29:01	7.4%
7	216	00:34:03	9.3%	187	00:29:58	7.6%
8	196	00:31:00	8.5%	121	00:20:10	5.1%
9	202	00:32:49	9.0%	91	00:14:55	3.8%
Full	157	00:31:13	8.6%	61	00:12:11	3.1%
Total		06:02:16			06:30:17	

sample. Table 5 shows the distribution of the number of users in the broadcast queue. The February 1993 sample is much more uniform than the June 1994 sample. Although this phenomenon has not been investigated, it could be due to a bias cause by more daytime passes and/or more weekday passes in the more recent

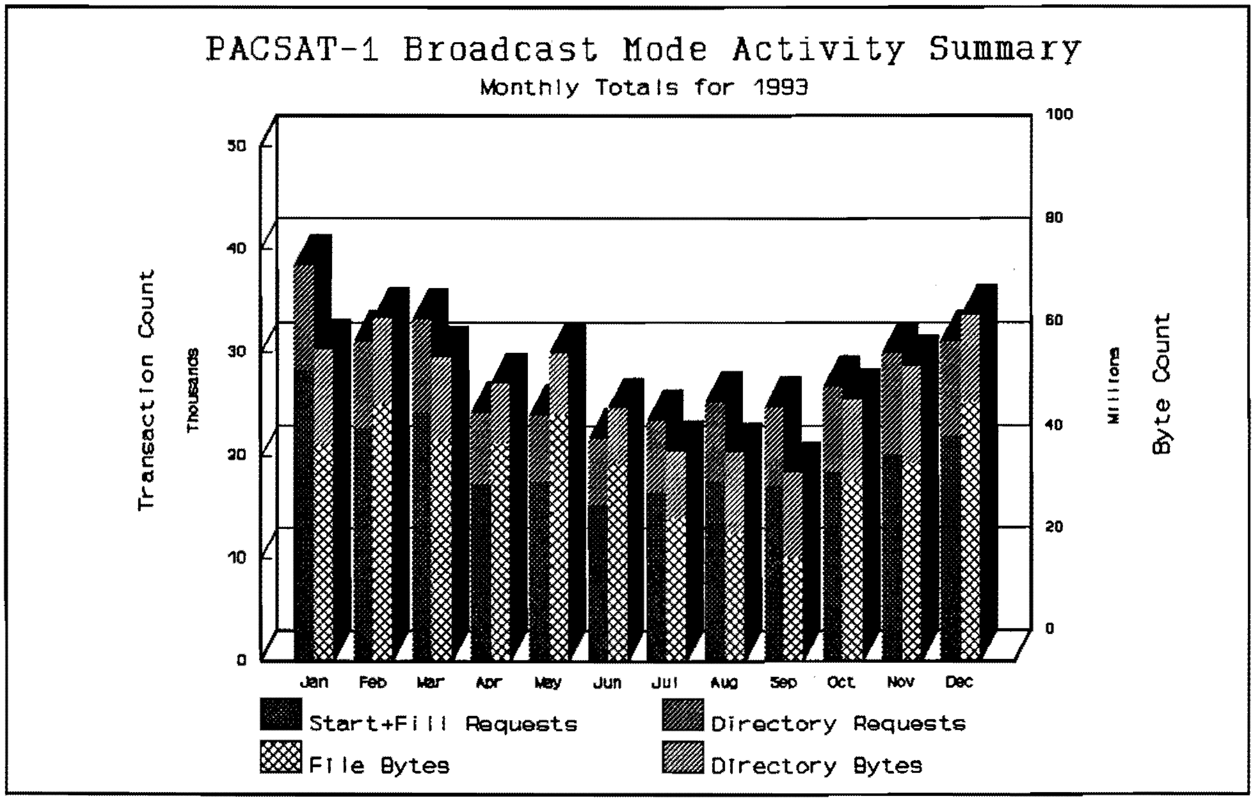

Figure 6. Month-by-month broadcast mode activity summary for AO-16.

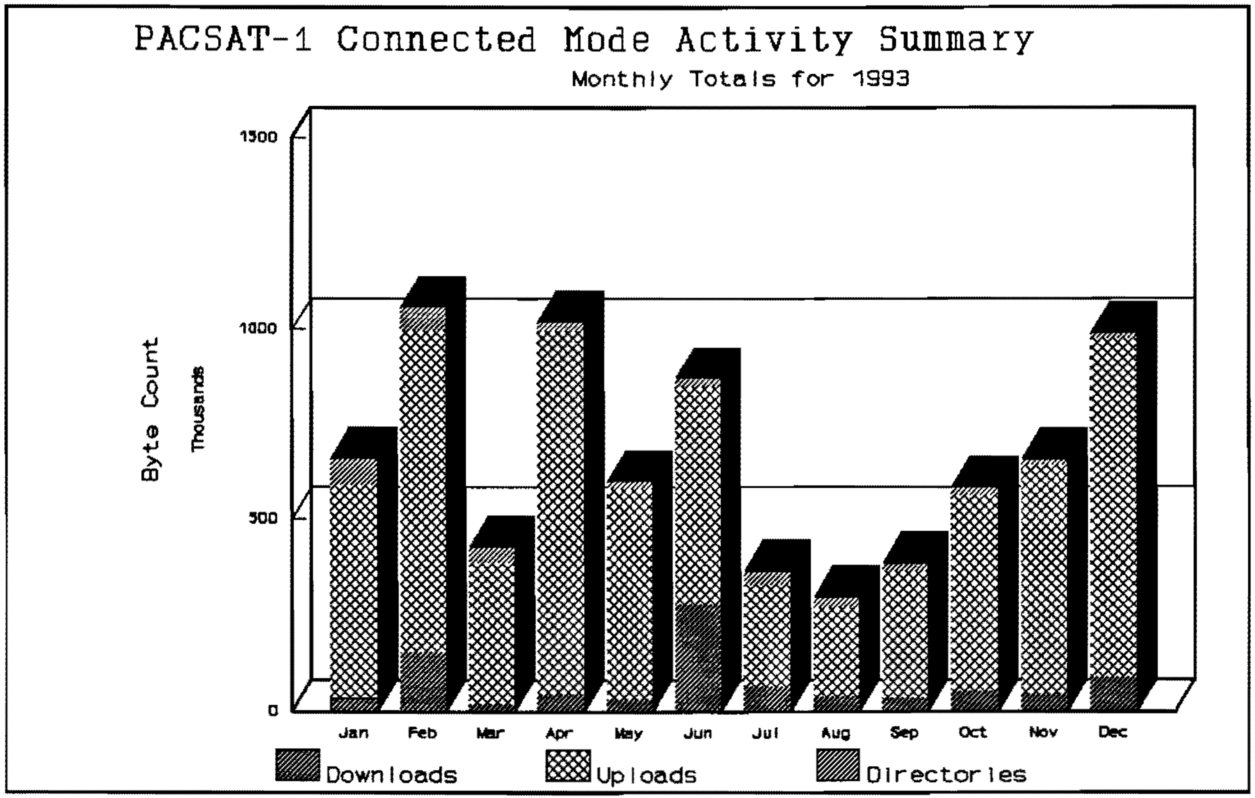

Figure 7. Month-by-month connected mode activity summary for AO-16.

sample. Daily work schedules tend to make user activity lower during these times. There could also be a time-of-year bias becuase users spend more time operating during the winter months than in the summer.

Finally, Figs. 6 and 7 give a month-by-month account of AO-16 usage for 1993. In Fig. 6, the left-hand bar of the pair is the transaction count and is read on the left-hand Y axis while the right-hand bar is the byte count and is read on the right-hand Y axis. Fig. 6 clearly shows a decrease in activity in the summer months. Fig. 7 shows that almost all connected-mode activity results from file uploading which is exactly what is desired.

IV. Command and Control

Of the four AMSAT Microsats, DO-17 or DOVE has been plagued with the most operational problems. Fortunately, during the past year, procedures and software have been developed to circumvent the problems and allow the original mission of DOVE to be realized.

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

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

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

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

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

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

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

For a multiplicity of reasons, most of which are related to the unpaid, volunteer nature of the Amateur Satellite Service, DOVE remained out of service until November 1993. What is important are the procedures that returned it to service and what has been accomplished since then to realize DOVE's planned mission. During the time DOVE was out of service, work was being done in parallel on three different software components. First, a simplified RAM-based boot loader was being developed as an intermediate step to loading the operating system kernel. The motivation was to load the smallest amount of software possible to get into a half-duplex load mode and thus minimize contending with the failed S-band modulator. Second, it was clear that a more efficient way of developing phoneme strings for the speech synthesizer was needed. Moreover, improvements were needed in the 68HC11 software controlling the voice module. Finally, modifications were required in the operating system task used to communicate with and control the voice module.

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

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

The last step toward returning DOVE to service was the completion of the RAM-based loader to allow half-duplex loading of the operating system kernel. This minimal-function loader required only 13 frames to be uplinked while listening for responses on S-band. For the most part, it would be unknown whether the responses were positive or negative acknowledgements. Therefore, the procedure was to be, load the RAM-based loader, then execute it and see if any telemetry was heard on the downlink. After testing on the simulator, the new

Table 6
DOVE Recovery Team Members, Locations, and Functions

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

loader was uploaded on October 31, 1993 (November 1 UTC) during an evening pass. The execute command was given and no telemetry was heard on the 2 m downlink. The assumption was that the code did not work as planned. However, on the evening of November 1 the U.S. east coast command station reported that telemetry was being transmitted on the 2 m downlink. What had happened was that the telemetry interval had been set fairly long and there had not been enough time to hear the telemetry before LOS on the previous evening.

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

During the period between May 24 and June 12, 1994 new operating system tasks were loaded in preparation for resuming the speech synthesizer tests and DOVE was intermittently out of service. After one unsuccessful test (garbled speech) and one unsatisfactory test (low transmitted audio level), a satisfactory test was initiated on June 11, 1994 with the satellite repeating the phrase, "Hi, this is DOVE in space" for one minute followed by transmission of digital packet telemetry. As this paper was being prepared, tests of audio production using the digital-to-analog converter were about to begin.

Having given a fairly detailed discussion of the process of returning the DOVE satellite to service, there are some important points to be made. One of them is that DOVE represents both the best and worst aspects of amateur radio satellite projects. Many readers already know that participants in projects like DOVE receive no monetary compensation for their work. Consequently, as personal priorities, family priorities, job situations, and related aspects change, the level of volunteer participation will also change. There is no doubt that such factors contributed to the lapse in operations of DOVE between summer 1992 and fall 1993.

At the same time, though, the recovery of DOVE has demonstrated some of the best aspects of the amateur satellite program. It would have been easy enough to sit back and be content that three of the original four Microsats were working and not try to return DOVE to an operational state. After all, it does represent six-year-old technology, and besides, who is interested in a satellite that you only listen to? But instead, a widely geographically distributed team of interested people, with the right mix of skills came together, and accomplished the job. The actual team members, their locations, and primary contributions to the project are given in Table 6. This is another example of highly-motivated people performing high-quality work.

For those interested in space science education there are some other points to be considered. First, in the opinion of this author, those involved in the recovery operations were motivated by the opportunity to expand their technical skills and the prospect of bringing an educational tool back in service. Second, bringing DOVE back in service has reminded us again that space science education is stimulated by a satellite that is available every day using readily-available equipment.

V. Summary

The current status of the AMSAT Microsats launched in January 1990 has been documented from three different viewpoints. Overall system reliability has proven to be excellent. There have been few subsystem failures with the most serious being transmitter modulators. However, due to the availability of redundant transmitters, these failures have not caused the loss of a mission. Power generation and storage systems, onboard computer and memory systems, and the inter-module local area network continue to operate reliably.

The evolution of the most complex of the Microsat onboard application software, the AO-16 and LO-19 broadcast file server, has been described. Long-term usage statistics show that AO-16 responds to an average of about 27,000 requests per month resulting in the transmission of an average of more than 50,000,000 bytes of user data per month. Analysis of two downlink data samples showed that users spend between 1.0 and 2.5 minutes in the satellite's broadcast queue waiting for their requests to be serviced.

Finally, a detailed description of the recovery of the DOVE mission was included. This description serves to show how a serious operational problem can be addressed by an organization with an all-volunteer command, control, and software development team. The recovery of the DOVE mission is especially significant because it is what makes the 1990 AMSAT Microsat mission 100 percent successful.

Acknowledgements

Several people deserve recognition for their assistance in preparing this paper. Thanks go to Jim White and Harold Price who provided many pieces of information and reviewed parts of the manuscript and to Russ Platt who collected and processed the whole-orbit telemetry data.

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