THE IN-ORBIT PERFORMANCE OF FOUR MICROSAT SPACECRAFT

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On January 22, 1990, Ariane V-35 placed four Microsat spacecraft into orbit. The orbit achieved is nearly perfectly sun-synchronous at 800 km altitude. The satellites, cubic structures measuring only 23 cm per side, were developed by the Radio Amateur Satellite Corporation of North America (AMSAT-NA). The time required to complete the project, from conception to delivery of the four satellites to Kourou, was exactly two years. Each satellite in orbit has a different mission and is performing in accordance with its intended design, although additional software is still being written to enhance the operating characteristics for each mission.

This paper reviews the design objectives of the four spacecraft and summarizes their in-orbit performance against these pre-launch technical objectives. The level of technology employed by the Microsat spacecraft is briefly discussed and the software approach taken in implementing a real-time, multitasking operating system is summarized. The paper reviews the AMSAT experience as the first payload user group of the Ariane ASAP structure. Some of the findings regarding the current technology and how it may be expanded to fulfill other mission needs has been touched upon.

INTRODUCTION

The term "microsat" is rapidly becoming the **Kleenex** of the aerospace community. Everyone has a concept; the term is in wide usage and attempts have been made to define the meaning of the word. The European Space Agency (ESA), for instance, refers to any spacecraft weighing less than 50 Kg as a micro-satellite.

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While it is not particularly important, it's still worth noting that after creating the name, someone had to be the first to put one in orbit. As far as we are aware, the Radio Amateur Satellite Corp. of North America (AMSAT-NA), working with several other national and international groups, launched the first four true Micosats on January 22, 1990. At least, they are the first four that can be discussed in the open literature. This paper describes the design of the four spacecraft and compares the in-orbit results to the intended design. The four Microsats are all healthy and doing fine after seven months in orbit. All of the major design aspects of the satellites have been validated in-orbit, however, flight software continues to evolve for all satellites and this activity will probably continue for many years. No doubt, having created a flexible tool: It will be flexed.

TRUE MICRO-SATELLITES - WHY?

With all due respect, a micro-satellite should not be thought of as a 50 Kg object! To those in the amateur satellite world who originally coined the term and who have been building and flying small satellites for three decades - it's just not what we had in mind at all. Rather, a micro-satellite is a spacecraft approximately **one order of magnitude** lighter than a GAS CAN spacecraft. If these shuttle-launched satellites are intended to be in the 100-200 lbm class, then a micro-satellite is a 10-20 lbm spacecraft. Why is such a spacecraft even interesting?

In fact, the reason is a very practical one: **Cost.** For AMSAT, launch costs while admittedly still subsidized, increased by a factor of four between 1985 and 1989. The reason for this, in turn is straight-forward: Supply and demand. The **lightsat** era was born in this same time frame. While the international amateur satellite community was working on their 25th - 31st spacecraft, the rest of the world realized the value of the small satellite and at the same time, the shortage of launch supply for secondary payloads. It's worth noting that since 1988 and after AMSAT secured a contract with Arianespace for four launch positions on ASAP, the price has again quadrupled, making the current price to AMSAT 16 times that which we paid for launch capacity in 1985.

This set of economics, having gotten the undivided attention of the austere but industrious AMSAT organization, allowed us to conclude, without difficulty, that if the cost per kilogram was going up a lot, we had better get a lot more from every kilogram. Further, it was reasoned, if a very small spacecraft with significant capability could be created, volume and mass might be found for its inclusion on nearly any launch vehicle.

Three technology factors have significantly changed in the past decade and make micro-satellites possible. To wit:

1) Extreme micro-miniaturization of electronic components.

2) Significant improvements in photo-voltaic power generation.

3) Significant improvements in the efficiency of RF power production in the VHF/UHF portion of the radio spectrum (used by our spacecraft).

To put numbers to these factors, after both trade-off studies and design & development of the Microsat system, we were able to achieve:

1) A baseline flight computer using 1.3 micron SMT device technology. The computer power consumption averages 0.45 W and contains 8,783,872 bytes of total memory. The computer is contained in a module 23 cm X 23 cm X 4 cm.

2) Solar arrays capable of 16.5% efficiency using back surface field reflector (BSFR) cell technology. GaAs cells could have been used with an efficiency of 18%, however, cost was a factor.

3) Flight transmitters at VHF with DC/RF efficiencies as high as 76% and UHF transmitters with efficiencies of 63%. Devices employed are low cost, readily available and incredibly rugged.

As can be seen, a significant capability can be packed into a **true micro-satellite** - a "blue cube" measuring only 23 cm (9 inches) on a side!

THE AMSAT-NA MICROSAT DESIGN OBJECTIVES

The intended application of our micro-satellites are as digital store-and-forward communications systems. All of the first "batch" of Microsats have this capability, although only two of the four have packet data communications as their primary mission. The other two spacecraft are intended as classroom educational tools. A spacecraft of this type is necessarily a flying computer with a few other appendages. Flight software becomes the most important aspect of the mission.

An objective of the new Microsats was to correct design and human engineering difficulties that had occurred in AMSAT-NA's previous eight spacecraft fabricated and launched since 1970. Other objectives are related to the store-and-forward communications requirements of the first missions. By way of example:

1) Eliminate, to the extent possible, wiring harnesses in spacecraft. They are time consuming to fabricate, significant sources of failure and definitely **not fun.**

2) Create a mechanical structure that could be completely assembled and disassembled ("racked and stacked") in less than 30 minutes.

3) Create a solar array design that minimizes the possibility of damage during handling and yet can be rapidly installed on the spacecraft body.

4) Use a load-side power management technique that dynamically adjusts the transmitter power output in order to maintain an orbit-average power balance. This technique should be modifiable in orbit and should deliver every possible mW of RF power to the system user downlink transmitter.

5) Create a micro-satellite design that is capable of serving data user terminals employing only omni-directional antennas.

6) Develop a suitable multi-channel serial data communications computer that has a minimum data storage capacity of 4 Megabytes and requires less than 1.0 watts of average power.

7) Target for a total spacecraft mass of 10 Kg (22 lbs).

All of these objectives, established at the beginning of the Microsat program in late 1987, have been achieved.

ORBIT ACHIEVED

The first four Microsat spacecraft were carried on Ariane V-35, launched January 22, 1990. The orbit achieved was in excellent agreement with the pre-launch predictions. The nominal orbital elements for the four spacecraft are:

$$a = 7161.2 \text{ km}$$

$$e = 0.0013$$

$$i = 98.713 \text{ deg.}$$

These Keplarian elements yield a nominal apogee height of 792.3 km and a nominal perigee height of 773.7 km. The orbital period is 100.5 minutes/orbit. The orbit is very nearly sun-synchronous with approximately a 10:30 AM ascending node. Prior to releasing the four Microsats the Ariane 40 executed a 180 degree maneuver that placed the forward end of the vehicle pointing exactly against the velocity vector of the orbit. Microsats A through D were all released within a 1 second time window, however, each with a different spring velocity in order to avoid collisions and to assure that the satellites separated from one another. Springs were selected such that each satellite (A - D), in turn had a higher separation velocity. Since the spring velocity subtracted from the orbital velocity, it was expected that Microsat-D would have the shortest period (shortest semi-major axis) and would move out ahead of the other spacecraft. Similarly, Microsat-A was expected to have the longest period and drop behind the others. This is exactly what is observed as the four satellites pass over an individual ground station. In the sequence, Microsat-D is followed in succession by -C, -B and finally -A. The difference in periods are such that Microsat-D will "lap" Microsat-A, and be one orbit ahead, approximately one year after launch.

STRUCTURAL AND THERMAL DESIGN

One of the most exciting aspects of the Microsat program at AMSAT was how well the structures for the satellites worked in practice to save time during the integration and test phase of the project. This was exactly what had been hoped for, since the bolting and unbolting of modules or boxes to and from space structures had long been one of the major consumers of time. The overall structure, known as the **Frame Stack Assembly** is simply a stack of modules (machined boxes) each containing a major element of the spacecraft electronics. Five modules comprise the stack, however, this stack can be extended as is the case for Microsat-B (Webersat). The Weber State University (WSU) stack is equivalent to seven modules. Four solar panels mount in recessed areas formed by the module stack on each side of the spacecraft. These honeycomb panels provide significant shear load support once installed on the structure. Quick and safe electrical connection is provided by a single standard electrical tip jack centered on each panel. Ground return is accomplished via the frame itself. The modules interconnect electrically via a 25 wire bus fabricated using standard printed circuit material. This constitutes the entire wiring harness for the spacecraft and can be installed or removed from a satellite in 5 minutes (including the locking hardware required for flight). The top panel contains another solar panel and the VHF receive antenna for the spacecraft. On two of the satellites à small S-Band bifilar helix antenna also shares this real estate. The most complex surface of the spacecraft is the bottom surface. It contains another four solar array segments (producing 1/2 the power of the other faces), the separation system, a microswitch for turning on the spacecraft transmitters, and the transmitting turnstile antenna. This surface is a major load carrying surface and is fabricated as a single piece of machined Aluminum. It is fastened in the corners by four gusset plates to the bottom module frame which contains the transmitting equipment for each satellite. Figures 1A and 1B show the two different configurations of the first four Microsats. The larger configuration is for WSU who required the additional space as an experiment module. The standard configuration mass at launch was 10 Kg while the Webersat version weighed in at approximately 12 Kg. Figure 1C show an exploded view of a standard configuration.

Module Frames

Each module frame has a useful volume of 200 mm X 184 mm X 40 mm. The center module, intended for the power subsystem, has a slightly larger useful height of 42.8 mm. Each module has a recessed area in the front of the module to allow a volume in the Frame Stack Assembly for electrical interconnections. Circuit boards may be mounted within the module with small plastic Delrin blocks designed for this purpose. Other means are also possible.

Separation System

A single compression spring is used to separate the spacecraft from its launcher plate. Concentric to the compression spring is a bolt which passes through the spring and then through the launcher plate and finally through a bolt cutter. Four locator pins on the spacecraft side of the interface mate to four locator pads on the launcher plate. These devices also counteract shear loads from the spacecraft. The bolt is tensioned from the underside of the launcher plate. The spacecraft has been qualified to separate using both NASA and ESA standard initiators. Full static and dynamic testing of the separation system has been conducted using both ordnance types.

Spacecraft Resonant Modes and Vibration Performance

One of the obvious, yet very nice features of a micro-satellite structure is that the natural resonant frequencies of the tiny structure can be expected to be very high. Since launcher resonant modes are usually quite low (5 to 25 Hz) there is no resonant coupling between the spacecraft and launch vehicle. Both versions of Microsat were formally tested at qualification and acceptance levels in accordance with Arianespace documentation. The highest random level achieved during qualification level testing was 14.6 g rms for a duration of 90 seconds. It was exciting to learn that no resonances of the spacecraft exist below 100 Hz. Primary spacecraft resonances are in the 200 to 400 Hz range. The test structure was

AMSAT-NA
MICROSAT CONFIGURATIONS

Fig. 1A

Standard Microsat (Microsat-A)

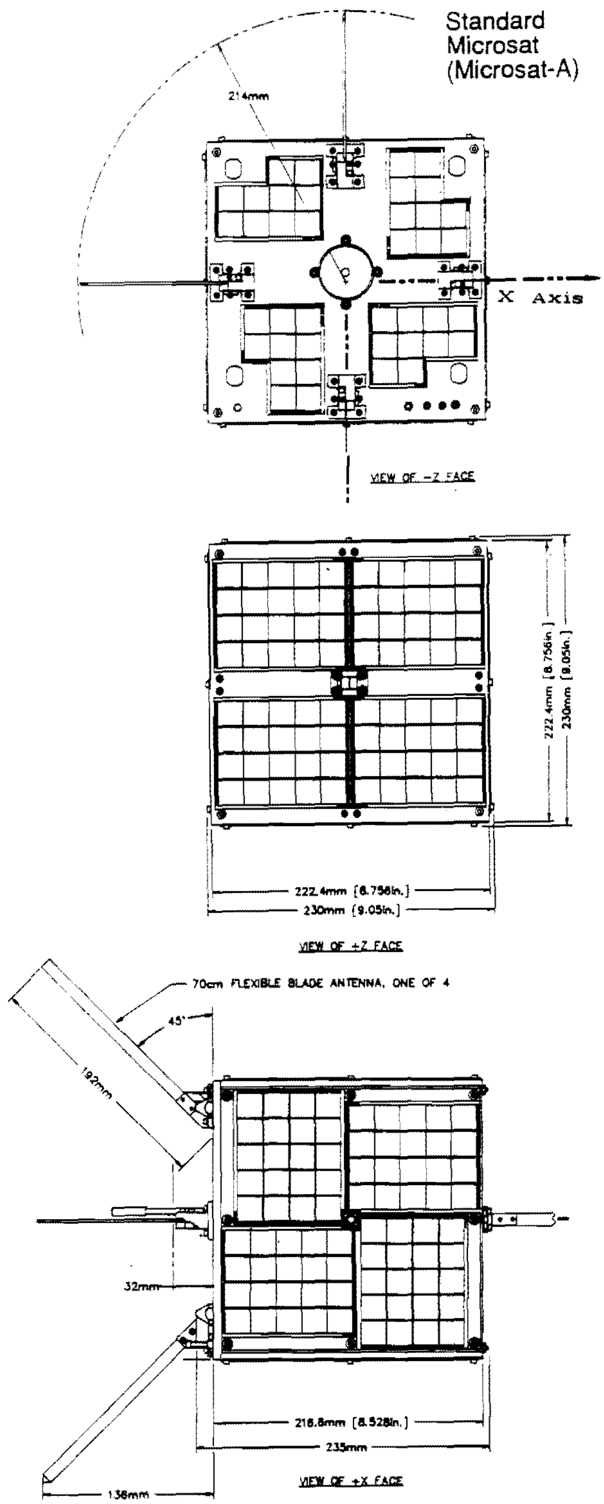
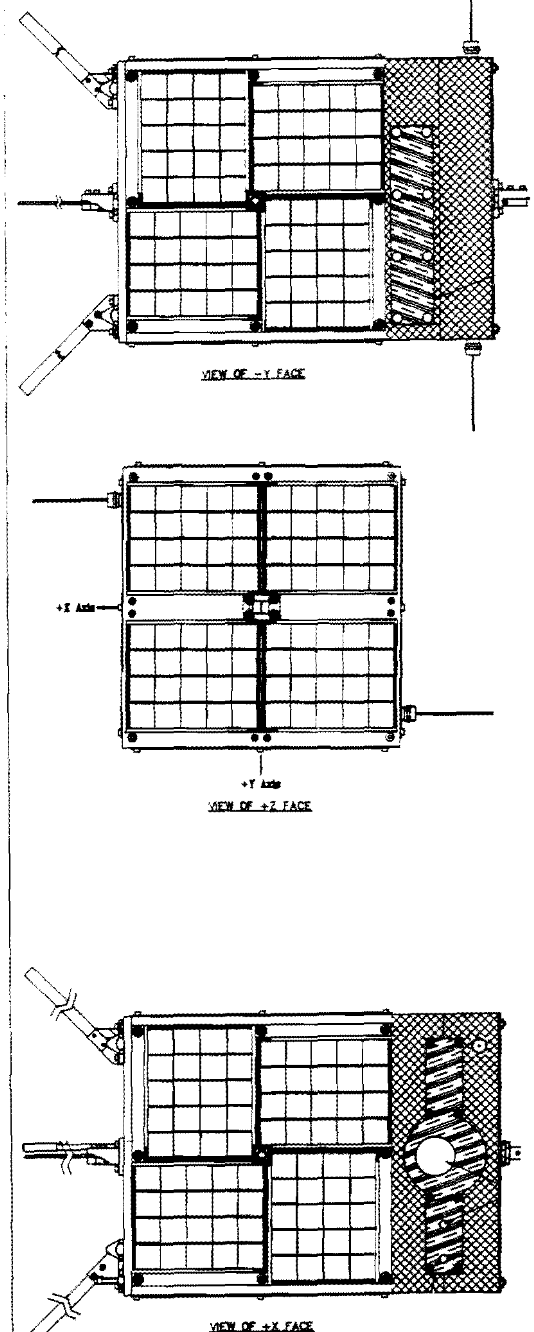


Fig. 1B
Extended Microsat (Microsat-C)



sufficiently well behaved at 14.6 g rms random that it is quite likely that at least 20 g rms could have been sustained by the structure.

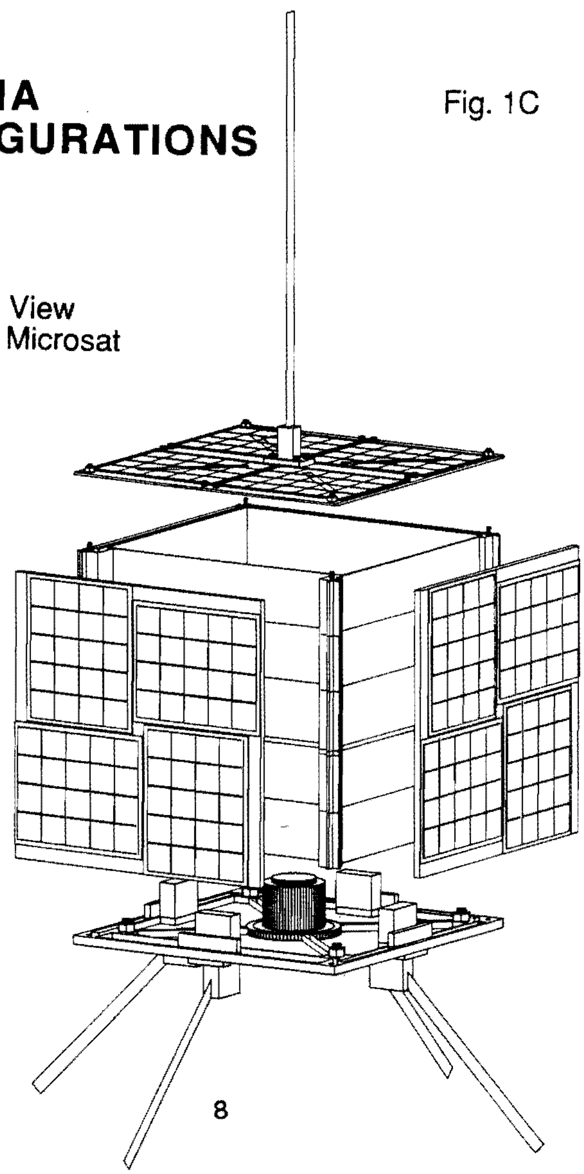
Spacecraft Thermal Design and Performance

The thermal design of small spacecraft of this type is straight- forward. To begin with, the intended orbit for the first four Microsats is sun synchronous with an ascending node time near noon. Eclipse variations over time are very minimal. For a simple rectangular solid structure with no booms or appendages a thermal model with only a few nodes is adequate to describe the performance of the system. Such a model was constructed and incorporates the two components of the rotation of the spacecraft (see section on attitude control) as well as the fluxes from the sun, earth IR and earth albedo. Significant spacecraft internal radiators were also included in the model although their contribution to the overall temperature balance is small.

AMSAT-NA
MICROSAT CONFIGURATIONS

Fig. 1C

Exploded View
Standard Microsat



A completely passive thermal design was implemented. The thermal balance is dominated by the external absorptivity to emissivity ratio (a/e) properties of the solar arrays. This value, which is near unity, is a given factor in the design. There is simply no flexibility in the design to reduce the solar cell area, rather, in a micro-satellite design this quantity is to be absolutely maximized. This results in a limited remaining surface area that can be used to bias the overall temperature. Of the total spacecraft surface area of 2916 cm^2 only 591 cm^2 is available for thermal control. Taking into consideration satellite motion, eclipse and variations in solar array efficiency over the orbit (which occurs as a result of the power system control approach) the predicted bulk temperature of the spacecraft, prior to launch, was estimated to be:

	Minimum	Maximum
Temperature:	-8.4 deg. C	+2.6 deg. C

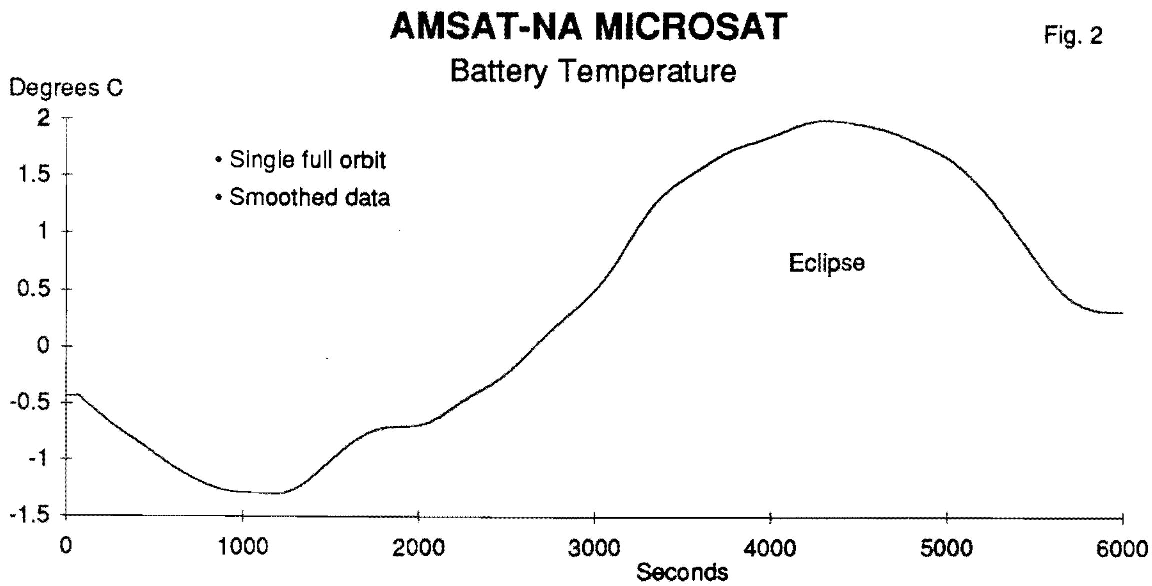
Measurements taken over a whole orbit at ten second intervals and then dumped at a single ground station show the following in-orbit results for Microsat-A:

Temperature Point:	Minimum:	Maximum:
Battery	-1.3 deg. C	+2.0 deg. C
+Z (Top) Array	-19.0 deg. C	+21.0 deg. C
Rcvr Module	-7.0 deg. C	+11.0 deg. C

The colder temperature range designed for and achieved is both good for long term battery lifetime and increases the power output from the solar arrays. It can be concluded that the thermal performance of the satellite is in good agreement with the design temperature range. The temperature differences observed between satellites, including Webersat, are very small. Figure 2 shows a Microsat-A whole orbit plot of the battery temperature. Note that the total temperature swing of the particular battery cell monitored is small and that the maximum temperature actually occurs during the middle of the eclipse period (1/2 orbit thermal lag). Both of these conditions point to a high battery thermal inertia which was better than expected and is most desirable.

POWER SUB-SYSTEM DESIGN

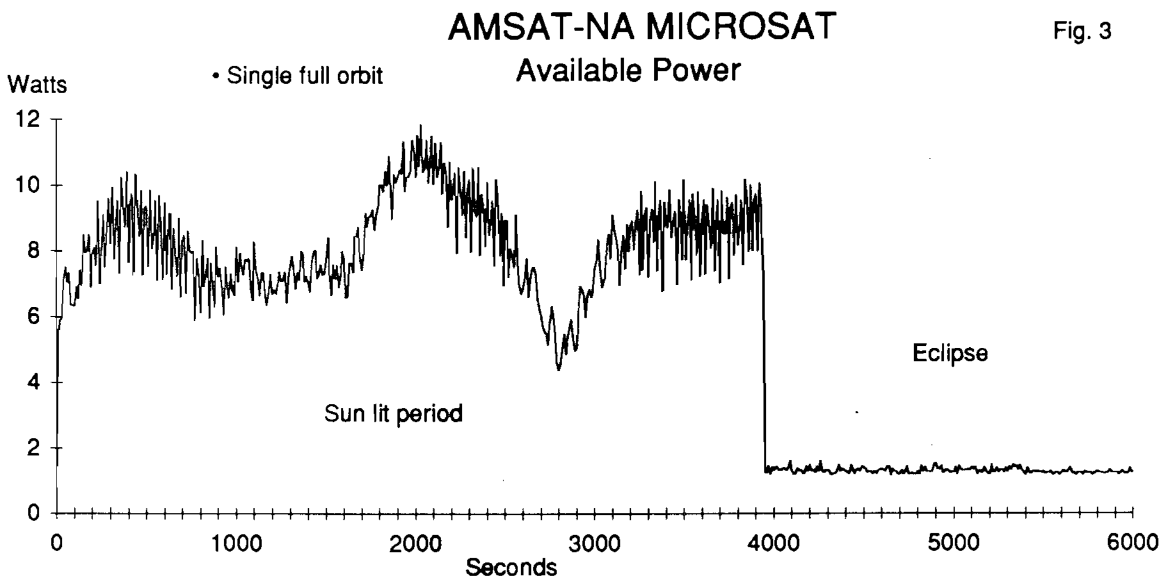
Certainly, one of the most difficult challenges in the design of a micro-satellite is the maximization of useful power and a strategy for not wasting that which is



generated. The efficiencies of power regulators and RF generating equipment is critical to the design. Micro-power consumption of computers and receivers is also a major challenge.

Solar Arrays

It is quite helpful that newer solar cell technologies are becoming available with efficiencies as high as 18% (GaAs) to 23% (hybrid cells). Cost and availability, however, drove this particular design to the use of back surface field reflector (BSFR) cells. These cells have an individual cell efficiency of 15.0% at 28 degrees C and nearly 16.5% at the temperatures achieved by the Microsat spacecraft. The particular cells selected are 2 X 2 cm and are manufactured by Solarex Corp. in Rockville, MD. The fundamental unit of power selected for Microsat is referred to as a solar cell **clip.** A clip is a small module containing 20 series connected cells. The clips were also manufactured by Solarex to AMSAT specifications and then assembled on the honeycomb panels by AMSAT. On each of the side panels (X and Y faces) and on the top (+Z face) two clips are wired in series and two are in parallel yielding a maximum per panel current of about .35 Amps at a knee voltage of 20.5 volts when the panels are cold. The bottom surface (-Z face) contains four "half-clips" wired in series to produce a single 40 cell string. This surface gives less than half of the power of the other surfaces since some shadowing also results from the four canted turnstile antenna blades. Figure 3 shows a scan of the total power generated by the arrays over one entire orbit for Microsat-A. The average power generated by the arrays over the sunlit portion of the orbit is 8.1 watts, however, the orbit average power must consider the eclipse period as well. This particular orbit generated 5.8 watts orbit average. Peak powers as high as 14 watts and orbit average powers as high as 6.5 watts have been observed.



Power Regulation

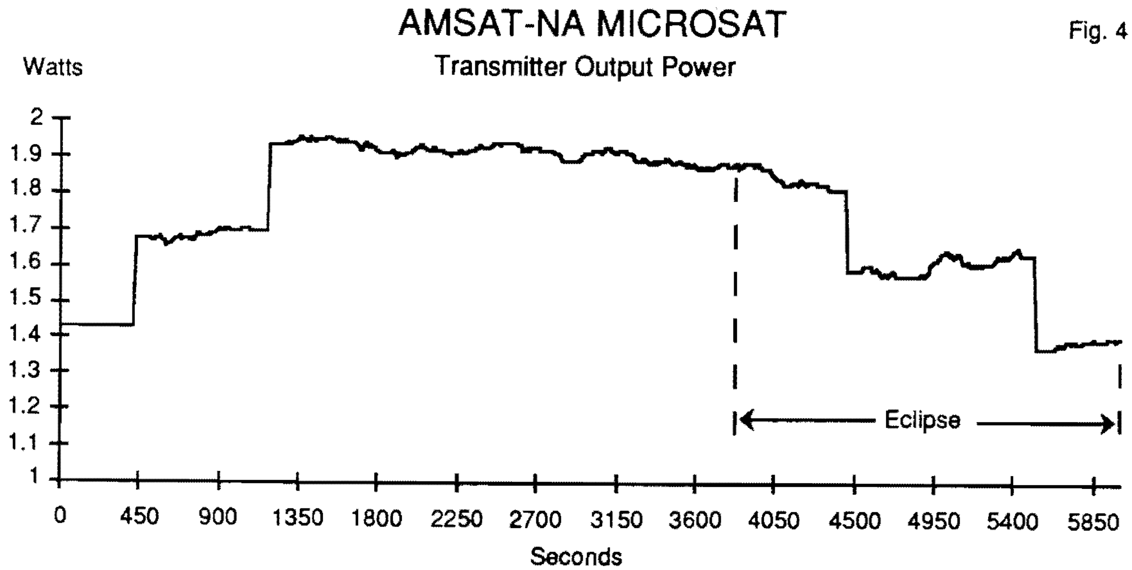
During the eclipse portion of the orbit it can be observed from Figure 3 that approximately 1.5 watts of power is flowing through this particular current sensor. The power is provided from the battery and is fed forward via a Schottky diode to the array summing point in order to power the regulated busses of the spacecraft. Power is fed forward in this manner so that during the sunlit portion of the orbit, the regulators do not need to take power from the battery. Rather, it is taken directly from the arrays. Power arriving at the battery has already been through one stage of regulation. The battery charge regulator (BCR) down-converts the 20 V array bus to the battery voltage of approximately 11 V. By having secondary regulators take power from the arrays when it is available, a double regulation loss is avoided. The 1.5 watts seen by the sensor is a measure of the power required for all of the spacecraft **except** the downlink transmitter. The transmitter power is taken directly from the main battery bus so that additional regulator losses do not occur on the main bus either.

Battery charge regulation is accomplished by a two step process. Maximum array power is always transferred to the battery by manipulation of the solar array operating point. The load impedance of the BCR is dynamically adjusted to keep the voltage point of the array always at the knee of the I vs. V curve. This is accomplished by a duty factor switch operated under control of the flight computer. The overall efficiency of this switch is approximately 90%. Corrections to the operating point are made based on the measured temperature of the array. Bias adjustments may also be made as changes in the knee voltage occur resulting from radiation damage or other effects. In principle, it could occur that the battery becomes over-charged if spacecraft loads do not demand all of the power produced by the solar arrays. While this situation is not likely to do serious damage to the batteries in such a small spacecraft, it does suggest that power is being wasted. The second step in the power regulation of Microsat is to use a load-side management scheme. The power output of the spacecraft primary transmitter is continuously variable, under computer control, from a few milliwatts to a full 4.0 watts (as much as 5 watts of output is achieved at the lower temperatures of the spacecraft). When excess DC power is available and the battery is fully charged, the active transmitter power increases, under software control, until a break-even power condition is obtained. If, after some time, it is determined by the computer that the power budget is slightly negative, the transmitter power can be decreased until the power is once again balanced. While this approach to power management would not be appropriate for a large spacecraft, in the case of the Microsat design, it assures that every single available milliwatt of RF power that can be afforded is generated for the user on the downlink. Figure 4 shows a whole orbit scan of the power output of the active transmitter of Microsat-C. Note that the power output drops during the eclipse portion of the orbit in response to the loss of array power. The average power output over the orbit is 1.75 watts. This value is lower for Microsat-C (Webersat) because other spacecraft experiments consume power continuously. The two packet communications satellites (Microsats A and D) which do not always have auxiliary experiments operating normally produce orbit average transmitter powers in excess of 2.0 watts. Microsat-B (DOVE) has VHF transmitters that are particularly efficient and as a consequence, the active transmitter averages closer to 3 watts over the orbit.

Two regulated voltages are provided by the spacecraft power system. Both +5.0 V and +8.5 V are available from regulators operating at efficiencies above 90 %. All power conditioning equipment on all four spacecraft has operated flawlessly since launch.

NiCd Battery

A single 8 cell NiCd battery is used in each Microsat spacecraft. The specified capacity of the cells is 6 AH, however, the measured capacity approaches 7 AH at ambient temperature. At the operating temperature of the spacecraft, the capacity is once again back to approximately 6 AH. The cells used are standard GE goldtop series, size F and are rated to perform at temperatures as high as 70 degrees C. In order to match cells for capacity and voltage from commercial



manufacturing lots and in order to select out poorly manufactured cells AMSAT has developed a proprietary cell selection and test program that has been very successful in producing flight quality cells at a fraction of the cost of cells specifically manufactured for space usage.

NiCd cells have a negative temperature coefficient of approximately 3 mV per cell per degree C. Since the Microsat cells are operating near 0 deg C, the typical operating voltage is slightly above 11.0 V during the sunlit portion of the orbit and decreases to approximately 10.4 V by the end of eclipse. Typical depth-of-drain for each satellite during eclipse is between 4 and 6 % which, in combination with the temperature, should allow the batteries to last nearly indefinitely.

The batteries and the power regulation equipment are all contained in the third module frame of the Microsat frame stack assembly. Given the weight of the batteries (220 g per cell) a 3 mm thick Aluminum plate in the bottom of the module frame is used to mount the cells.

RF SUB-SYSTEM DESIGN

The Microsat RF sub-system consists of two redundant data transmitters and a five channel receiver system. A quarter wave linearly polarized antenna is used in conjunction with the receiver and a 45 degree canted turnstile antenna is used on the downlink. The latter is circularly polarized.

Data Receiver

The packet communications system used by the spacecraft employs data standards in current and common use in the Amateur Radio and Amateur Satellite Services. Packet communications techniques developed by these communities use the ALOHA form of Carrier Sense Multiple Access (CSMA). While the throughput of this technique is not high (18.4% maximum) it is simple to implement and ground station equipment is readily available. Each spacecraft has a single UHF downlink with a data rate selectable between 1200 and 4800 bits per second. With a maximum throughput approaching only 20% it is evident that the uplink total offered traffic should be approximately 5 times that of the downlink data rate. This has been accomplished by implementing a 5 channel VHF receiver system where each uplink channel can be adjusted by ground command between 1200 and 4800 bits per second. Uplink modulation is FSK.

A common receiver front end serves all five receiver channels. Unlike most space applications, receiver G/T performance is not important in this application. User uplink signals have EIRPs in the range from 20 to 40 dBW. At these uplink power levels and also due to the level of carriers in adjacent frequency bands, it is more important that the receiver have excellent overload characteristics than a good noise figure. In this particular design the LNA was not preceeded by a high-Q filter but rather a GaAs FET transistor was used in the LNA which has a particularly high (i.e. large amplitude) front end overload characteristic. In fact, the third order intercept of the device used is above 0 dBm. Following the LNA is a helical resonator band pass filter. The input signal at 145.9 MHz is down-converted to approximately 50 MHz and is amplified and split into 5 separate channels. Each channel makes use of a Motorola 3362 FM receiver chip and the signal within each channel is down converted two more times. The final IF at 1.8 MHz is passed to a discriminator and then to a slicer and data filter. Prior to passing raw data from the receiver to the flight computer any DC component resulting from doppler offset or user uplink frequency error is removed. The value of the DC component, however, is measured and provided to the telemetry system so that users can choose to Doppler compensate their uplink signal. A very steep-skirted band pass filter (15 kHz wide) is placed after the second IF. This filter allows for a user transmitting 1200 bps Manchester data on the nominal uplink frequency to pass through the filter even at maximum Doppler shift without distortion. When 4800 bps data is used, however, the user must compensate for Doppler so that his modulation spectrum will properly pass through the filter. All five receiver data channels are routed to the flight computer. The receiver monitors the signal strength and frequency offset of each channel. These 10 values are available as telemetry. Receiver sensitivity varies slightly between channels and ranges from -110 dBm to -117 dBm for a 10E-5 bit error rate. The total power consumed by the receiver is less than 0.25 watts. The receiver runs from +5V except the GaAs FET LNA stage which requires 8.5V.

The receiver occupies a single module frame and is usually located in the top module position. A short coax cable connects the receiver to the top 1/4 wave VHF antenna. It should be noted that while the antenna is configured as a quarter wave antenna, in actual practice the spacecraft structure is so small that it will not properly image the active element at this VHF frequency. Instead the 1/4 wave element acts as one half of a dipole antenna; the spacecraft structure acting as the other half (the fat half) of the dipole. In matching the antenna this fact has to be taken into consideration.

Data Transmitters

The bottom module of each spacecraft contains two transmitters. For Microsats -A, -C and -D these are UHF (437 MHz) transmitters capable of producing up to 4.0 watts of RF power and employ PSK modulation. Microsat -B uses two identical VHF (145 MHz) transmitters also capable of 4.0 watts of RF power output. All are power agile. Power is adjusted in 16 equal voltage steps by controlling the voltage delivered to the final two RF stages. The power output is approximately proportional to the square of the selected step. Higher power steps are larger than lower power steps. It's worth noting that the 4.0 W setting was made at a supply voltage of 10.0 volts. At the cooler spacecraft temperatures achieved the battery voltage is frequently above 11.0 V. The transmitters produce a maximum power of 5 W RF output at this higher supply voltage. As described above, the power setting is under computer control and is used in closed-loop fashion to manage the overall spacecraft power budget.

The two UHF transmitters in three of the satellites are not identical. It was import for us to experiment with variant forms of PSK. Signals from Microsat are sufficiently strong when received on standard OSCAR ground station equipment that the PSK demodulator carrier recovery loop can become confused by receiving one of the PSK sidebands instead of the carrier recovered from the center of the modulation spectrum. It was considered important to determine how difficult this situation would become in an automated ground terminal environment. For this reason, one transmitter transmits standard (+/- 90 degree phase shift) PSK while the second transmitter emits Raised Cosine PSK. This technique "shapes" the data as it is passed to the modulator in such a manner that the higher order sidebands of the signal are greatly reduced in amplitude. This technique has the added advantage that it reduces the overall occupied spectrum required to transmit a given information rate. Figure 5A shows the normal PSK spectrum measured from Microsat-A before launch while Figure 5B shows the Raised Cosine Spectrum under similar conditions. It is hard not to notice the spectral improvement. The price for this nice spectral characteristic, however, is not zero. The Raised Cosine modulator produces a non-constant envelope. That is, the signal is both amplitude and phase modulated. In order to prevent the signal

Fig. 5A

Normal PSK Transmitter Spectrum

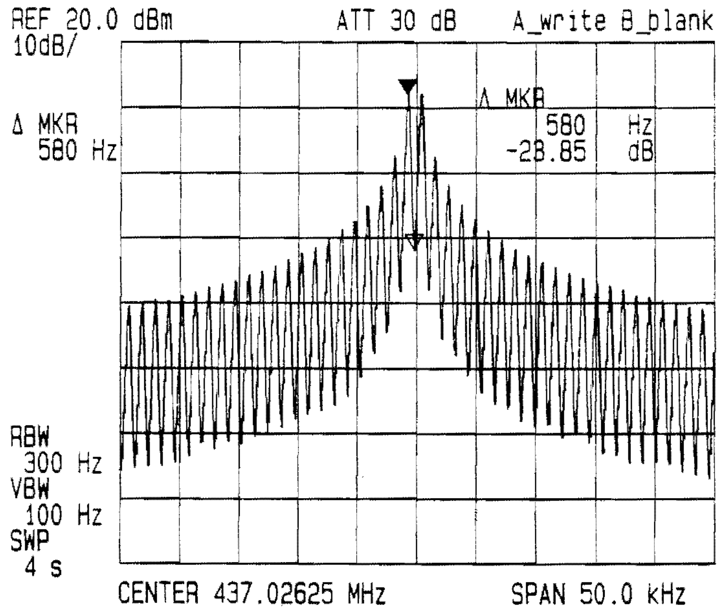
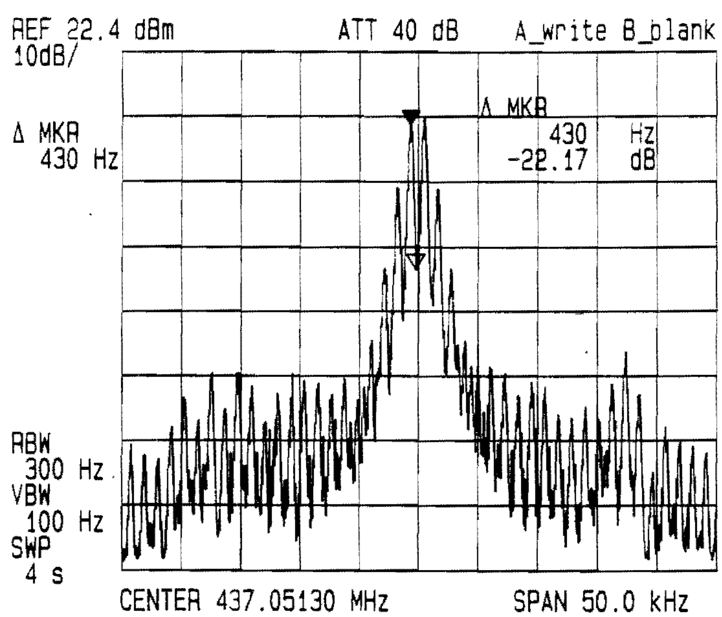


Fig. 5B

Raised COSINE Transmitter Spectrum



from spreading out again when it is passed through the final amplifier of the transmitter (due to AM-PM conversion), that amplifier must be linear. Normally, liner amplifiers are not very efficient. Since AMSAT has been designing high efficiency linear amplifiers for space since 1972 this is simply one more application. In this case, we chose to use a variation of the technique known as Envelope Elimination and Restoration developed by L. Kahn (1). The loss of efficiency of the overall transmitter caused by using the "linear" amplifier is about 8% (from 63% for the PSK transmitters to approximately 55% for the Raised Cosine transmitters). It is also more complex than the simple PSK transmitter and consequently, somewhat less reliable.

Since they are intended for both voice and AFSK data communications, the two VHF transmitters in Microsat-B use simple NBFM modulators. The most exciting aspect of their performance is their DC/RF efficiency. The breadboard unit achieved an overall efficiency of 84% at 4.0 W output. The flight units dropped to 76% efficiency when they were installed in their modules. Some detuning necessarily occurs because of the close proximity of the box lid to the air wound coils. Note that at these efficiencies, the dissipation of the transmitters into the rest of the spacecraft can be virtually ignored. The power transistors are not even warm to the touch.

In all spacecraft the two transmitter outputs are fed to the two isolation ports of a 90 degree hybrid. The two remaining hybrid ports feed a turnstile antenna to produce circular polarization. Each antenna element contains a small "matching box" at its base to allow for the inclusion of lumped constant networks that facilitate antenna matching. When one transmitter is used, RHCP is produced. Similarly, LHCP is generated when the other transmitter is used. Users are instructed to use linear polarization so the circular polarization sense of the downlink is unimportant. Counting the 3 dB polarization loss, the link is designed so that a user at maximum slant range with an omni-directional antenna will have a 10 dB margin at 1200 bps data rate and assuming the transmitter is at 4.0 watts output. Transmitter power output is more typically 2.0 watts for a break-even power condition so the link margin is usually 3 dB less.

It is possible to operate both UHF transmitters simultaneously. The straight PSK transmitter contains a source multiplexer that may be switched either to the data output generated by the computer or to any one of the five receiver raw data outputs, thus bypassing the computer. This latter mode was considered for straight data relay or to allow for a ranging function. This mode has not yet been used in orbit. It would be possible to operate both transmitters simultaneously with one connected to a receiver output directly while the other is connected to the normal computer data line.

ATTITUDE CONTROL SUB-SYSTEM DESIGN

AMSAT has been using a particular type of passive magnetic attitude stabilization in small LEO polar spacecraft since 1974. The technique has been demonstrated to work well and there was no particular reason to increase the complexity of the Microsats by using an active system therefore, the same set of techniques was again employed.

To begin with, assuming that a particular spacecraft has good omni-directional antennas and link margins are large (both of which are valid for Microsat) the need for an attitude control system is minimal. It is, however, desirable to minimize polarization and "tip null" fades that would result in some data loss, particularly on the downlink. Also in order to avoid thermal gradients, a slow rotation of the satellite is important.

The method employed uses four ALNICO-5 bar magnets mounted to the outside of the spacecraft. They are physically located at the four edges of the cube parallel to the Z axis. Seven hysteresis rods oriented in the X-Y plane of the satellite are normal to the magnets. They are embedded in the battery support plate and run parallel to the X-axis of the spacecraft. Their location is near the center-of-gravity of the satellite. Finally, the four antenna blades that make up the transmit canted turnstile act as solar photon vanes. They are approximately 10 mm wide and are painted white on one side and black on the other. Since they are mounted in succession, the sun always "sees" at least one black surface and one white surface.

The bar magnets have a very strong dipole moment. While this value was not measured on this particular mission it is estimated to be in the vicinity of 50,000 to 100,000 pole-cm. The effect of using permanent magnets and hysteresis rods should be to quickly align the spacecraft Z-axis with the local earth field vector at any point around the planet. The hysteresis rods quickly damp any motion about the field lines. The spacecraft were expected to be randomly tumbling when they left the launch vehicle. This, in fact, proved to be true. The spacecraft achieved magnetic lock within 7 days and major oscillations of the Z-axis were damped within approximately 14 days. The four solar vanes impart a torque about the Z-axis and reduce the thermal gradient across the spacecraft body. The solar torque is counter-balanced by both the hysteresis rod damping and eddy current damping that cannot be eliminated in various components of the spacecraft. In order for the hysteresis rods to be effective dampers of this rotation, attitude deviations of the Z-axis from the local magnetic field vector on the order of ten degrees will be required. The two damping torques place an upper bound on the rotation rate about Z in response to solar torque. The net effect of the stabilization system is to cause a rotation of twice per orbit of the Z-axis in response to the earth's dipole and then a rotation about Z. The target value of the rotation period about

Z was set by thermal considerations to be 2.5 minutes per rotation. A large tolerance on this value is quite acceptable. Rotation rates from .25 minutes per rotation to perhaps as much as 20 minutes per rotation will still allow magnetic "lock" and acceptable thermal gradient behavior. In fact, the interior thermal time constant of the spacecraft is much longer than originally anticipated, given such a small object.

The lines of force at LEO orbit altitudes are quite nearly perpendicular to the surface of the earth, except between about plus and minus 30 degrees of the magnetic equator. Certainly, the difference angles are small enough to assure acceptable communications system performance even when a hemispherical coverage antenna is used on the spacecraft. A simplified equation for determining the tilt of the field lines with respect to a **perpendicular** to the earth's surface and at approximately the altitude of the Microsat orbit is given by:

$$\mathbf{b = 90 - atan[2*tan(g)]}$$

where:

b = angle of the field line to a line drawn from the center of the earth through the surface at mag. latitude g.

g = the geomagnetic latitude value

Table 1 gives values of **b** for a number of magnetic latitudes:

TABLE 1

g (deg.):	b (deg.):
90 (pole)	0
75	7.6
60	16.1
45	26.6
30	40.9
15	61.8
0 (equator)	90.0

Figure 6A shows schematically, the attitude of the spacecraft relative to the earth for one full rotation of the Z-axis of the spacecraft in accordance with the above equation. Figures 6B and 6C show orbit scans of the two Z-axis array currents and the +Y-axis array current during an entire sun-lit orbit segment (which is somewhat more than one full rotation of the Z-axis of the spacecraft). The data is for Microsat-A and was taken on April 14 starting at about 16:27 UTC. The graph axes are solar panel current and relative time (seconds). The sun in Figure 6A is about 11 degrees north of the geographic equator and 22.5 degrees out of the orbit plane (the plane of the paper). The pass proceeded up over the central Soviet Union in shadow and then over the northern Soviet Union, Greenland and then Canada and the United States in sunlight. In the vicinity of the descending node at approximately 100 deg. W, the magnetic equator is slightly south of the geographic equator (-7 degrees). As the spacecraft first comes into sunlight, according to Figure 6A, the -Z surface should be partially illuminated. As time passes neither Z surface sees the sun and then shortly thereafter, the +Z surface current should begin to increase as the top of the satellite rotates toward the sun. As the spacecraft begins to approach the magnetic equator the rate of rotation of the Z-axis increases and the +Z array current goes past its maximum value and then falls to zero. The opposite situation occurs in the southern hemisphere as the -Z surface produces the mirror image of +Z (there is a scaling factor involved because the -Z surface has only 1/2 of the solar array area of the other panels). Just before the spacecraft goes into eclipse the +Z array begins to see sunlight again as it goes beyond the south geographic pole. Figure 6C shows the behavior of one of the side solar panels (in this case, +Y). Recall that the solar vanes should cause a rotation about the Z-axis. This effect is clearly evident and the rotation period given by the data is 2.35 minutes per rotation (in excellent agreement with the target period of 2.5 minutes per rotation). As the satellite comes out of eclipse the side panels of the spacecraft should be near maximum output current. Then as the top of the spacecraft pitches toward the sun the side panel currents should decrease. Note that the minimum +Y current corresponds exactly to the maximum current from +Z as it should. The side panel currents should not go to zero because the sun does not lie precisely in the orbit plane. This is also evident in the data. The current from the side panels then rises very quickly as the satellite approaches the magnetic equator. In the southern hemisphere the same behavior is evident in mirror image. Also visible in the data is a small contribution to the array current from earth albedo. As much as 50 mA of current are produced near the sub-solar point by the side solar panels.

In summary, the attitude control system performance, as is evidenced by the above data, is working extremely well and very close to design expectations. Both the rotation of the Z-axis and the rotation about the Z-axis are as predicted. Further, the rotation of the Z-axis due to the earth's magnetic field appears to be very nearly in the orbit plane. Signals received from the spacecraft are stable and attest to the usefulness of the stabilization system.

AMSAT-NA MICROSAT

STABILIZATION AND ARRAY CURRENT EXAMPLES

- Array current plots are sun-lit portion of orbit, s/c chart is one half orbit
- Angles are to scale in Fig. 6a
- Letters a - e refer to same points in orbit on the three charts
- +Z is 'top' surface, -Z is 'bottom' surface, +Y is a side surface
- Data is from 14 April, 1990

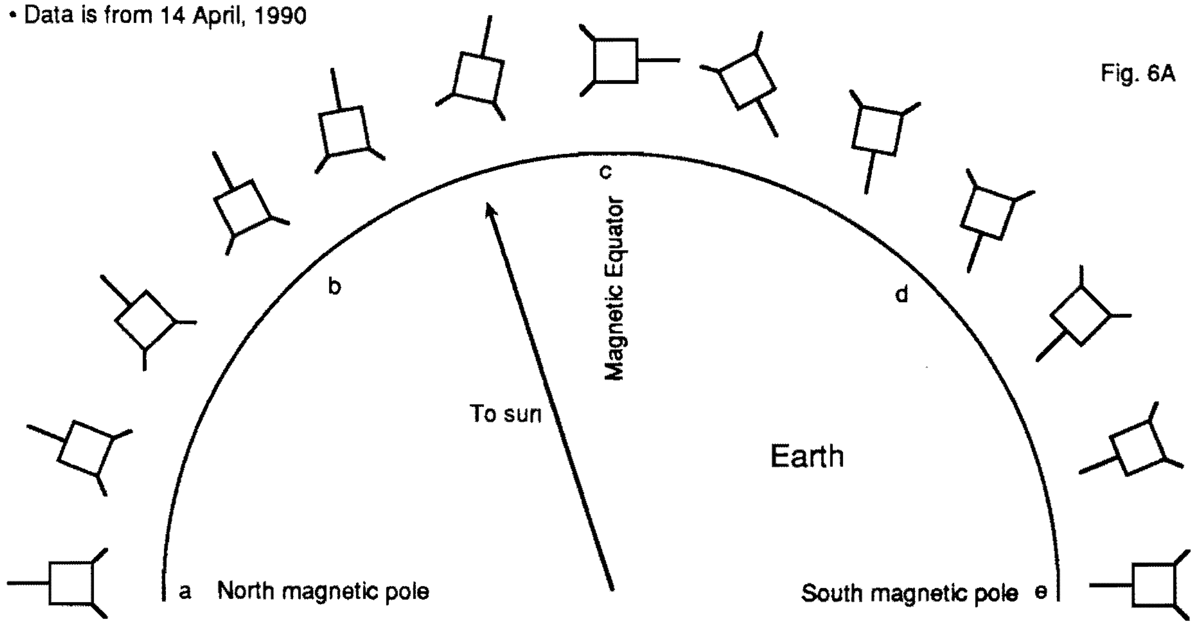


Fig. 6A

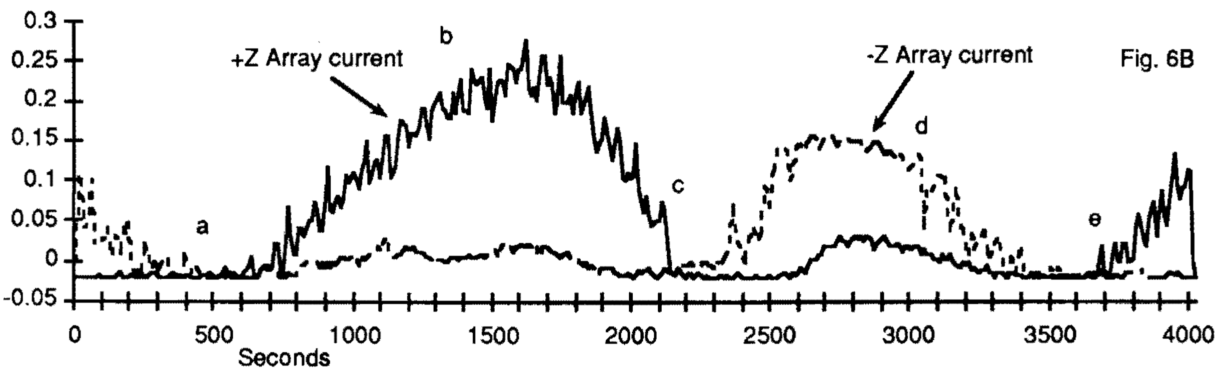


Fig. 6B

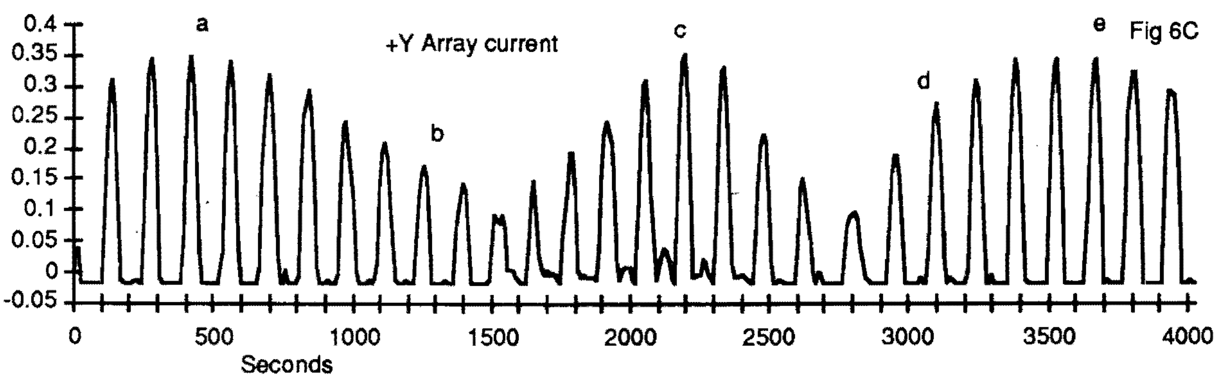


Fig 6C

Considerable fine structure of the motion of the Z-axis can be observed to take place from orbit-to-orbit. Nutation of the Z-axis is frequently observed on Microsats -A, -B, and -D, however, this motion also seems to damp out from one orbit to the next. The nutation amplitude can be as large as 20 degrees. This may be a result of perturbing effects when the spacecraft passes its northern or southern most point but is farthest from the magnetic pole. The ratio of inertias (Izz/Ixx or Izz/Iyy) are known to be very close to 1.0 and may even be slightly less than unity for some of the spacecraft. The nutations of Webersat are typically larger than the other satellites and the motions of the spacecraft are quite complex. In this particular case the ratio of inertias is considerably less than 1.0. More analytical work is necessary before the details of the motion of the four spacecraft can be fully explained. It has been suggested that a 6 DOF simulation of the attitude control system be implemented. Interested volunteers are currently involved in this analysis.

FLIGHT COMPUTER AND DATA HANDLING SUB-SYSTEM DESIGN

Considerable reference has already been made to the flight computer. Like most other AMSAT spacecraft, the computer plays a very central role in the performance of the satellite, only in this case even more so. It is used in a multi-tasking, real time environment and, as such, it is a component of all of the other electronic sub-systems of the spacecraft. Data to and from the receiver and transmitter are handled via fairly high speed serial links (designed for up to 100 kbps) using formal serial data control. Data carried between other sub-systems in the spacecraft and the Flight Computer use a serial interface with a single line providing data to the subsystems from the computer and a single line return. A specialized board known as an Addressable Asynchronous Receiver/Transmitter (AART) is used within each hardware module to provide serial communications with the flight computer. Telemetry signals are also handled via the AARTs and multiplexed analog signals are routed to a single A/D Converter within the computer via the 25 pin bus. Two wires forming a differential pair are employed for this function.

Flight Computer Design

The flight computer design in Microsat is state-of-the-art in terms of its weight, size, fabrication technology and performance. Weighing in at 1025 grams and consuming an average power of 0.45 W the computer is optimized for serial communications. The clock speed is not outstanding, at 9.830 MHz, however, by making use of the computers DMA functions, the computer will support 6 simultaneous serial inputs at as high as 100 kbps each. The first four Microsats use only a fraction of this capability, loafing along at 4800 bits per second per serial input (maximum). Three serial controller devices (NEC type 72001) handle the incoming data which is HDLC formatted and compatible with a variant of CCITT X.25. The variant, which allows for an extended address field and routing functions, is known as AX.25. The 72001s also provide up to six transmit outputs although the current design only provides for a single line to the common transmitter modulation inputs. Data from and to the 72001s is 8 bit parallel. The microprocessor used is the NEC V40 which is equivalent to an 80C186 with a slightly modified instruction set. A serial input/output pair directly from the V40 are used to communicate with four AART boards distributed on the 25 pin bus. In addition to the A/D converter mentioned above the computer provides a utility latched port and headers are provided for direct access to the address and data lines of the processor for experiments that may require maximum speed. This feature was used, for example, to facilitate the Webersat Camera on Microsat-C.

Memory is, perhaps, the most impressive part of the computer. Four classes of memory are used by the Microsat Flight Computer. 2k bytes of ROM contain the boot loader. Main program memory uses 256 k bytes of error detecting and correcting (EDAC) RAM. Memory devices are the Harris HM6207. This memory is configured as 12 bits per byte and is capable of detecting two and correcting one bit error per byte (caused typically by a single event upset) anywhere in memory. If a single output data bus line were to fail out of the 12, then the memory would also carry on without a problem, however, with a degraded error protection capability. Any single event error is counted by the computer and software incorporates this value into each telemetry data packet. 2M bytes of bank switched RAM provides for high speed general purpose RAM, segmented in 512k byte blocks. Each block can be enabled or disabled as required. This memory can be used as general purpose RAM and may be accessed in 90 nS. The Webersat camera experiment uses this memory as a video storage area. Bank switched RAM has no hardware error protection, however, software error protection may be employed. In addition, 6M bytes of memory are configured as RAM disk. Access to this memory is slow but, more than fast enough for packet data communications requirements. This RAM may also be switched ON or OFF in 512k blocks to save power. Bank switched RAM and RAM disk is implemented using Hitachi 62256L surface mount RAM chips. The configuration of this device is 32,768 X 8 bits. A total of 256 RAM chips make up these two classes of memory.

The computer is constructed on three mulit-layer boards. The CPU board and the Mass Memory board (which contains the RAM disk) are eight layer printed circuit cards while the Bank Switched RAM board is six layer technology. The Mass Memory board is populated on both sides with surface mount components. Most integrated circuits in the Flight Computer are, in fact, surface mount ICs. RAM chips have 0.021" lead spacing while the other surface mount devices are 0.050 " between traces. Board interconnects use Kapton ribbon lead cables. All boards were conformally coated after final check-out. The total flight computer contains 453 integrated circuits. With the exception of the boot ROMs, none of the components used were high-rel. or rad-hard. The HM6617 ROMs used were qualified to MIL-STD-883B. This project was of sufficient technological complexity that it was contracted out to two surface mount technology firms who completed board layout and fabrication and then, component population of the boards. This is the first time in our history of 22 years and 12 spacecraft that AMSAT has allowed an outside organization to fabricate flight hardware. AMSAT assembled the boards into the module frames and debugged the computers as required. We are indebted to a small group of volunteers who worked tirelessly for a single week, nearly 24 hours a day to bring the four flight units to life for the first time. Given the complexity of this particular part of the project, we were very fortunate to have such a great engineering team on "hot standby" and some very good luck with the hardware.

Since the flight units have been brought on line there have been no hardware failures and computer "crashes" can all be identified with specific software errors. The computers have been amazingly reliable given their level of complexity. Their performance in space to date has been outstanding. No known failures have occurred to any of the units. There are also no known bad bits among the 281,083,904 total bits of memory distributed between the four spacecraft. Soft errors do occur regularly but, have been measured only in the 256k bytes of EDAC memory. The error rate in EDAC is approximately two per orbit when that orbit flies through the area of the South Atlantic Anomaly. Otherwise there is only an infrequent single even upset. Estimated cumulative dosage to date, referenced to outside of the computer module, is about 600 Rads Si. This data is provided from our sister UoSAT spacecraft flying in the same orbit. That spacecraft is equipped with a radiation dosimeter.

AART Design

A unique identifying feature of Microsat is its use of serial communications to handle all data flow between modules within the spacecraft. The AART board within each module of Microsat, except the Flight Computer, uses an MC14469 addressable asynchronous receiver/transmitter. The device receives 4800 bps data on a data line common to all units. Each AART has a unique single byte address that must first be recognized by that particular AART unit. The addressed AART unit then takes the next serial byte as data. Depending on the value of the data the unit will either latch as many as three data bits in a field of 24 available bits or, alternatively, will set two different analog multiplexers on the AART board to place a particular analog value on the analog bus line which is then read by the A/D converter in the Flight Computer. By changing the most significant bit of the AART address byte the AART unit can also return an 8 bit value to the flight computer on a second serial line common to all AARTs. If this feature is used, the Flight Computer software must know to poll the particular

AART module periodically for the expected data. The AART unit has no means of signaling to the computer that it has data ready. Each AART board has signal conditioning for up to four thermistors and up to 32 telemetry voltages. The board also contains its own precision 2.55 V reference. This level of telemetry capability per module has proved to be more than adequate, although the power module in each of the Microsats does use most of it.

FLIGHT SOFTWARE DESIGN

The Microsat bus is a minimal architecture design. The single CPU is required to implement all software functions in the spacecraft including:

1) Telemetry generation. This requires commanding the AARTs in each module and sampling all analog telemetry points, then generating both the real-time telemetry and the stored "whole orbit" data, which is dumped on command by the ground.

2) Ground command. Includes adjusting targets for power management, switching on and off various hardware modules, etc.

3) On-board autonomous control. Includes the load-side power management routines, experiment scheduling, over and under voltage software fuses, etc.

4) Single Event Upset cleanup. Single bit errors are purged from memory with a process called "memory wash", described in detail later in this section.

5) Data communications protocol handling. The standard amateur radio service data protocol AX.25, is a variant of LAPB, the X.25 link layer protocol. This full duplex sliding window protocol is non-trivial.

6) Applications such as the Weber State experiment package, including image capture, compression, and transmission; the DOVE digital-to-analog voice mailbox, the PACSAT and LUSAT store-and-forward message system.

The software design for the Microsat CPU had goals which were similar to the hardware design goals. We wanted something based on standard, proven, cost effective components that could be integrated in interesting ways. We could then concentrate on the actual applications rather than the nuts and bolts of operating system and compiler design. These goals and the resulting design decisions are detailed below.

The main goal was:

1) Allow AMSAT to exploit a larger group of software engineers.

   Previous complex AMSAT missions used the 1802 CPU, developed before "user friendly" was first conceptualized. The 1802 was either programmed directly in assembler, or in a homegrown variant of FORTH. Implementation of all the spacecraft control, protocol handling, and several large data processing applications for a Microsat would require more software to be flown than all previous AMSAT missions combined. A Microsat would also be an ongoing experiment, requiring continuing software development over the many-year lifetime of the spacecraft. This meant a larger number of software developers would need to be brought in. Also, each sponsoring organization would be responsible for its own application software to control its mission-specific hardware module. The development system used would have to be accessible to a large number of people in several countries, and would, as always, need to be inexpensive. Most of the other goals followed from this.

Subsidiary goals:

1) Allow use of an industry standard development environment.

   This was a factor in the choice of the NEC V40 CPU for the Microsat computer. The V40 is an 80186, an Intel 808x style chip enhanced for embedded controller applications. As this chip is software compatible with the 8088 used in IBM PCs, this allows standard IBM PC development tools to be used. Additionally, since the instruction set is the "native" PC set, mainstream compilers could be used rather than cross compilers. The Microsoft C compiler was chosen.

2) Allow programs written at different times by different programmers in different locations to be brought together and run on the single Microsat computer at the same time.

   Since AMSAT cannot afford ether the time or money consumed by the vast amounts of procedures, meetings, documentation, CASE software, and other standard trappings to allow disparate software elements to be tightly bound, we elected to permit each major function to be a separate program running in a multi-tasking environment. Peaceful co-existence among tasks, enforced by an operating system which manages shared resources such as memory, the telemetry system, and the data protocols is relatively easier to obtain.

   This is the software equivalent of the fast "rack and stack" mechanical structure and of the 25 wire harness, and is desirable for the same reasons.

3) A program is no different than a regular IBM PC program. Since we're allowing separate tasks, allow each to be debugged using standard programs, such as Microsoft Codeview.

4) All C functions should be available, including floating point.

5) The operating system should provide a simple intertask communication scheme.

6) The operating system should be RAM, not ROM resident, so that it can be maintained and extended once in orbit. This is in keeping with the experimental nature of all AMSAT spacecraft. Only a small (though mission critical) bootload routine is kept in ROM.

The operating system chosen was "qCF", developed by Quadron Service Corporation of Santa Barbara, California. This is a system designed for 80186-based communications co-processor cards. The card plugs into the IBM PC bus and acts as a communications front end, using several 8030 SCC communications chips. qCF support both the IBM ARTIC card and the Emulex DCP286i card.

qCF support Microsoft C programs, and provides pre-emptive multi-tasking, timers, and inter-task communication. It also provides interrupt and DMA driven HDLC I/O handlers. Quadron, a company where three of the four rounders are radio amateurs, ported qCF to Microsat and supplied I/O drivers for the 72001 communications chips. As the software was then compatible with the Microsat CPU and with the IBM ARTIC card, the ARTIC card would be used as a spacecraft CPU simulator.

This reduced the cost of a full-up development system and spacecraft simulator to an IBM PC clone, a $1200 adapter card, Microsoft C, and the donated Quadron development software. The resulting off-the-shelf commercial quality components allow the software application developers to concentrate on the applications, and not on the development environment itself. The tools are widely available, including such separate locations as Argentina, Italy, and the UK.

It should be noted that the qCF system was also selected for use by the University of Surrey on one of its spacecraft launched on the V35 ASAP. Although its CPU is a very different design, the high level application programming interface is the same, allowing for some shared applications between AMSAT and UoSAT. AMSAT provided the AX.25 communications handler and the I/O driver, UoSAT in return provided the file system task and portions of the message and file server system.

A short summary of the various types of programs running on a Microsat are in order.

Operating System

The kernal supplies the basic multitasking services. It manages the hardware timers, sets up memory, loads and unloads tasks.

File Support

The 8M byte data storage area is managed as a RAM-based disk. The low level C read and write subroutines in the standard C library used by applications are replaced by routines that format an I/O request and send it an inter-task message stream to the file support task. Acting much like an IBM PC RAM disk driver, the file support task provides blocking and deblocking services as well as providing error correction for single bit errors.

Message File Server

This will be the most visible program to users on the ground. The major goal of the two PACSAT Microsats is to provide a bulletin board and file service. This interface is optimized for computer to computer transfers, the user's ground station software provides the human interface. The software and procedures are being developed now to integrate the Microsats into the amateur radio service's world-wide ad hoc packet network. More than 100,000 interface units, called terminal node controllers, have been sold worldwide since 1983; all are potential and many are current users of this network.

AX.25 Handler

The AX.25 handler implements the LAPB-style communications protocol. It permits point-to-point connects between the various tasks running on the Microsat and the many ground stations visible in the range circle.

HDLC Driver

The HDLC driver passes frames between the AX.25 handler and the uplinks and downlink. The driver is non-trivial. The hardware design supplies several DMA channels, but even so there are more I/O channels than DMA, so the drive must do both DMA and straight interrupt driven I/O. To get the most out of the available processor power, and to enable later Microsat missions to use even higher baud rates, the HDLC driver is written in assembler code.

Housekeeping

This task implements the spacecraft power management algorithms discussed above.

Telemetry

The telemetry software module periodically gathers telemetry data by using the AART driver to collect data from sensors throughout the spacecraft. The data is both sent to the downlink for real-time monitoring, and is also stored in a virtual disk file in memory. The "whole orbit data" format, where the values for telemetry channels are stored over several hours and are later downlinked is an invaluable tool for low orbit spacecraft.

Memory Wash

Some of the memory on the spacecraft is protected with hardware Error Detection and Correction (EDAC) circuitry. When an error is induced in memory by an energetic particle normally filtered out by the atmosphere, the EDAC will correct the error when a read occurs and place the correct data on the bus. The corrected byte is not written back into memory automatically by the hardware. If an error is allowed to linger, there is a chance that a second bit in in the same byte will get flipped. Since the hardware can only properly fix single bit errors, it is important to fix all single bit errors before they become multi-bit. In a process called "washing memory", a task periodically runs through the EDAC memory, reading and writing every byte, causing the corrected byte to be written back into memory over a damaged one.

Most of the memory is not protected by hardware. The reason is economics, 12 bits are used to store each 8 bit byte in hardware protected memory. Hardware EDAC is used for memory that programs run from, since a program byte in error will usually lead to no good. Software algorithms must be used to protect the remaining memory. This memory is used to store data files and messages. The RAM disk routines will use software EDAC to correct errors, but if a "disk sector" goes unread for too long, multiple bit errors may occur. To reduce this chance, the memory wash task periodically reads all "disk sectors" and writes them out.

<u>Camera Control</u>

In the Weber State Microsat, the primary mission is the CCD camera. Software written by WSU controls the camera, digitizes the image, compresses it, and formats it for transmission. Software is also under continuing development to run the other on-board experiments.

<u>Software Summary</u>

The onboard software environment has proven to be very reliable; Microsat-D (LUSAT) has gone 233 days at this writing without a reload of the qCF kernal. Applications have been reloaded several times, particularly on Microsat-C (Webersat), as improved camera control algorithms are produced.

OTHER MICROSAT EXPERIMENTS

Despite their very small size, it was possible to design all of the required electronics for a store-and-forward communications system into 4 of the 5 standard module frames. This leaves one frame available for experiments. All four Microsats made use of this capability, each in a somewhat different way.

Microsat-A (PACSAT): Carries a 1 watt S-Band (2400 MHz) transmitter that can be used to test the viability of packet communications via satellite at microwave frequencies. The transmitter was exceptional in that it achieved a DC/RF efficiency of 47% despite the low absolute output power level. This is very difficult to achieve and implies that the lower level stages of the transmitter are particularly efficient. In the achieved orbit this transmitter can be received with a simple helix antenna only 8 inches long. This transmitter has been used on several occasions as an augmentation to the UHF transmitter. It is working very well.

Microsat-B (DOVE): Carries another S-Band transmitter and a voice broadcast experiment. The transmitter is identical to that on Microsat-A, however, the carrier suppression on this transmitter has been lost, apparently due to a component failure in the modulator circuitry. The voice broadcast experiment allows two forms of digital voice data to be uplinked and stored in the flight computer memory and then downlinked at a specified time or repeated multiple times. Both digitized speech and a voice synthesizer may be used to produce voice outputs.

Microsat-C (Webersat): Uses its spare module plus the equivalent of two more to carry a variety of experiments that are of interest to the educational community. These experiments, developed by WSU, include:

- o A visible light CCD camera
- o A visible light spectrometer
- o A micrometeorite detector
- o A flash video image converter
- o Two 2-axis flux gate magnetometers

Microsat-D (LUSAT): Uses its spare module to provide a stand-alone telemetry system. It includes a sensor package, a small microcontroller, a 437 MHz transmitter transmitting data in a modified Morse Code format and a simplified command decoder to turn the experiment on and off from the ground, thus bypassing the other command and telemetry features of the spacecraft. This unit works like a "spacecraft within a spacecraft." It has performed flawlessly since launch and has been almost continuously turned ON. It was constructed by amateurs from Argentina and represents the first space flight hardware ever flown by that country.

The ability of the spacecraft to adapt easily to other uses and to be expandable to even wider usage, as was accomplished with Webersat, makes Microsat particularly valuable as a candidate spacecraft for many future small satellite missions.

USE OF THE ARIANESPACE ASAP PLATFORM

Being a secondary user of a large launcher has always had its advantages and disadvantages. There is a process, as old as space flight itself, that a "lightsater" must go through - a kind of hazing ritual. This is the process whereby the secondary payload project management convinces the primary payload management that:

1) Yes, we know what we're doing

and

2) No, we won't hurt your big beautiful spacecraft.

The first time through, this process its actually fun, particularly when you win. The tenth time through the process, it's not at all fun any more but, at least one knows the routine. There is hope that Pegasus and other launchers dedicated to small satellite services will remove this role of secondary payload/second class citizen.

To their great credit Arianespace, in creating the Ariane Structure for Auxiliary Payloads (ASAP) has almost completely buffered the secondary customer from the primary customer so as to solve these problems. Almost. There are still requirements for the secondary customer to communicate specific technical information to the primary payload project manager and there are still times when technical information delivered to said project manager is ignored and the will of said project manager is still the law of the land. Our great thanks to Arianespace for doing their best professional job to try to minimize our paperwork tasks and allow us to get our work finished at the launch site with minimum grief from the prime contractor.

The ASAP platform is a big improvement over previous means of launching small payloads on large rockets. To wit:

1) The ASAP structure is quite large and there is adequate space for all secondary users to work around its large flat mounting surface. The ASAP is placed in the integration clean room with the secondary spacecraft team(s). This allows the spacecraft workers continuous access to the ASAP hardware for quick fit checks of wiring harnesses, antennas, mounting adapters, etc. in a less formal environment then ever before. This reduces the overhead time and the length of the launch campaign.

2) The ASAP structure can be populated with small spacecraft at a pace that is more driven by the needs of the secondary user and is decoupled from the

demands of the primary payload customer because they no longer shares common facilities.

3) The completed ASAP structure and its secondary payloads are mated to the forward end of the launcher (VE structure) just prior to the mating of the primary payload(s). This minimizes the time from the beginning of the secondary payload launch campaign until the day of launch.

4) The Arianespace program office has now segregated the much needed daily meetings of the secondary users from those of the primary users. This was not the case in the "old days." The result is the secondary users do not have to sit through endless meeting agenda items that are of no real interest or concern to them. This reduces the staffing requirements of the secondary payload project. The Arianespace staff conducted these morning meetings in a most professional and supportive manner that helped greatly in giving "lightsaters" the feeling they're real customers.

5) The support of the Arianespace people throughout the launch campaign, and indeed throughout the entire program, was fantastic. All reasonable requests for technical support, including various specialized materials and services that we needed were quickly and accurately supplied. Problems, what few there were, were solved with a sense of team spirit. One becomes accustomed to the usual aerospace approach where, when a problem occurs a memo is never far behind. Then contractor A blames contractor B for the problem and vise-versa. During this activity, of course nothing is being accomplished. In fact, all one really cares about is for the problem to be fixed. This the Arianespace team did, and quickly.

There are a few recommendations we would make to future secondary users of ASAP:

1) Regardless of any previous projections to the contrary, be prepared to deliver you spacecraft to Kourou approximately 2.5 to 3 months prior to the **real** launch date. While it may appear that the process can be completed closer to the launch, experience shows that events conspire so as to cause secondary users to come early and work at a pace slower than that you would if you were working at your home facility.

2) If you intend to play in this game, be prepared to be smart enough to figure out the real launch date. It can be done. This is not a criticism of Arianespace but, a realization that **all** launcher schedules slip. You will be in serious trouble if you are late and you've wasted valuable time you could have been testing or improving your satellite if you are early. Life is tough!

3) Support the decisions of the primary payload when they effect you (even when painful). In the long run, the big guy will win anyway so you're wasting your time to fight it. If you fight it, they may pull you off the rocket. Remember, the primary customer paid about 200 times more than you did for your launch so he is always right.

4) Remember that the safety rules are for everyone's benefit so follow them carefully. Your life may depend upon it. We have found the CSG safety system to be sound and reasonable. The Arianespace paperwork requirements regarding safety submissions are very modest and their safety people do a great job. They are there to help you so we see no reason why safety submissions should not be done on time.

5) From the standpoint of your project's financial and schedule planning, be prepared for the real possibility of a launch slip that may likely occur even after the launch team has arrived in Kourou. This is a common occurrence in the aerospace world. It is frustrating but, even worse, it could be a disaster if you are on a very tight budget and you have not planned for this possibility. Money should actually be set aside for this eventuality.

AMSAT wishes to thank Arianespace for continuing to support the small satellite program. In turn, AMSAT has been a long supporter of the Ariane program, having been the very first of two passengers on Ariane LO2 in 1980 and one of the three passengers on Ariane 401, the first Ariane-4 launch. We have launched more satellites on Ariane today than any other user - a total of seven spacecraft on four different launches - and we are proud to have been a part of this exciting program. Our working relationship with Arianespace has been the best and we look forward to our next launch opportunity.

CONCLUSIONS

Table 2 summarizes the design values of the four Microsats and the performance obtained to date in space or the measured parameter just before launch (as appropriate). Attachment 1 gives a more complete summary of the design characteristics of Microsat.

In summary, the four spacecraft and the Microsat design exceeded, in almost every area, our expectations at the time the project was conceived. We have once again proven that sound design is more important than "high-rel." parts and that KISS is more important than redundancy. Most importantly, we have shown the way to a new wave in space technology. Microsat is the **army ant** adaptation to space as opposed to the **elephant** adaptation. Many microsats in a low earth orbiting network would provide an incredibly powerful communications network

TABLE 2

Standard Microsat
Design vs. In-Space Performance

Parameter	Design Value	Final Value or In-Space Performance
Mass	9.5 Kg	9.7 - 10.1 Kg
MoI		
Ixx=Iyy	.075 Kg m^2	.09 Kg m^2
Izz	.070 Kg m^2	.097 Kg m^2
Orbit Avg Power (800 Km Sun Sync)	6.0 W	5.8 - 6.5 W (Max 13W)
Orbit Avg Temp (Battery)	-8.4 to +2.6 ° C	-2 ° C to +2 ° C (Average +.2 ° C)
Break even TX power	2.0 W	1.7 - 2.7 W
Rotation rate of Z axis	2/orbit	2/orbit
Rotation rate about Z axis (solar pressure)		
Sat A, C, D	2.5 min/rot	1 - 2.3 min/rot
Sat B	.3 min/rot	.3 min/rot
Nutation cone angle	0 °	0 ° - 20 ° (depending on orbit)
Soft errors per orbit (256K EDAC RAM)	3 - 5 per day	2 - 6 per day
Packet receiver sensitivity (successful packet threshold)	-110 to -117 dBm	-110 to -117 dBm

and a catastrophic failure of one satellite means very little to the rest of the swarm which continue to carry out their duties. Mass production of anything makes the product more reliable and cheaper. Microsat lends itself perfectly to this concept. Finally, a nine inch cube can do an amazing amount of work in space. They even have the communications capacity to serve omni-directional and even hand held user terminals on the ground as AMSAT has demonstrated. Spacecraft of even a smaller size than ours, carrying out specialized function are entirely possible and practical today. They will be more so in the future. AMSAT has shown that small organizations can do significant work in space and that there is room for universities and non-profit organizations to participate directly in the development of their own spacecraft.

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It would be impossible here to thank individually the many volunteers who made the AMSAT Microsat program happen. These individuals know who they are and they have been recognized on other occasions. These volunteers and radio amateurs are located all over the world and the U.S. participants are from all areas of our country. Of the twelve satellites AMSAT has constructed and launched since 1970, these four were done in the shortest time and with the hardest work. None of our other projects have required so many 24 hour days and quite so much dedication on the part of our core team. The authors would particularly like to thank our sister organizations who helped finance this program: Brazil AMSAT (BRAMSAT), AMSAT Argentina and the Center for Aerospace Technology/ Weber State University. We hope that these organizations are having the time of their lives with their new satellites. We also hope we have helped each of these groups to influence the environment around themselves in a positive manner. Uniquely, the amateur radio community in Argentina can accurately state that their organization built, flew and now routinely operates the very first satellite ever from the country of Argentina. We want to thank Dr. Junior Torres de Castro of Brazil for his brief letter to us in 1987 suggesting that such a small satellite might be practical. From such simple seeds grander things sometimes grow. Finally, we wish to thank Arianespace for their significant financial investment in the ASAP platform which will greatly help the emerging small satellite world for many years to come.

BIBLIOGRAPHY

1. Kahn, L.R., Comparison of Linear Single-Sideband Transmitters with Envelope Elimination and Restoration single-Sideband Transmitters, Proceedings of the IRE, December, 1956, pp 1706-1712.

2. Microsat Launch System/Spacecraft Interface Control File, DCI 10/393 00, Arianspace, Issue 2, Rev. 1, November 1989.

3. Wertz, James R., Spacecraft Attitude Determination and Control, D. Reidel Publishing, London, 1980.

4. Tada, H.Y., Carter, J.R. Jr., Solar Cell Radiation Handbook, JPL Publication 77-56, Jet Propulsion Laboratory, Pasadena, CA, 1977.

5. White, J., Microsat Motion, Stabilization, and Telemetry, AMSAT Journal, Accepted for Future Publication, 1990.