Evolving Operations and Decommissioning of the Midcourse Space Experiment Spacecraft

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The objective of the Midcourse Space Experiment (MSX) mission was to collect data on midcourse target and background phenomena and to support space situational awareness. To accomplish these objectives, the MSX spacecraft was designed for a 5-year lifetime. Launched in 1996, the MSX spacecraft exceeded its design lifetime by 7 years. It collected the first comprehensive set of multispectral midcourse target data and more than 10 years of space surveillance data in support of our nation's space situational awareness objectives. In 2008 the MSX spacecraft was decommissioned, and with that event came the end of more than 12 years of successful operations. The decommissioning of MSX had to be planned and executed in a manner for which the spacecraft was not designed; however, this was not unusual for the MSX spacecraft: throughout the operational life of the MSX, much of what was accomplished was beyond its design. The operational life of MSX was one of adapting to challenges while maintaining a high level of productivity. That productivity lasted until decommissioning, and the operational challenges remained through the end of the decommissioning activities.

MSX BACKGROUND

The MSX spacecraft was launched on 24 April 1996, into an 898-km circular orbit with an inclination of 99.3° (Fig. 1). MSX was designed to collect data on multispectral target and background phenomena of ballistic missiles in the postboost phase of flight, or midcourse, to address the needs of the Ballistic Missile Defense Organization and, as a secondary objective, to support space situational awareness (SSA).[1] The midcourse objectives of the MSX mission were met through the successful implementation of a series of dedicated and cooperative target experiments. These target experiments included the Midcourse Dedicated Target experiment, which was launched on 31 August 1996, and was designed to acquire signature phenomena against a long-range target, as well

Figure 1. A drawing depicting the mission concept of the MSX.

as to acquire data in other target experiments against shorter-range targets. In addition, MSX acquired routine observations of stressing Earth-limb and celestial background scenes. During the time of these experiments, MSX deployed a cryogenically cooled infrared imaging telescope, a suite of UV and visible imagers, spectrographic imagers, and a visible spectrum camera. As planned, the cryogenically cooled telescope expended its cryogen, ending the infrared ballistic missile target phase of the MSX mission.

SSA became the primary mission of MSX after the cryogenic phase ended in February 1997. The SSA objective for MSX was to maintain and enhance a current space object catalog (including position, velocity, and time) of all objects orbiting Earth. The goal of the MSX SSA data collection was to acquire 100 satellite observations per day, a goal that was exceeded by a significant margin, with a peak of 400 satellite observations per day in 2001 (Fig. 2). MSX became the first successful Air Force Advanced Concept Technical Demonstration (ACTD), and ownership was transferred to Air Force Space Command. MSX was much better than the ground-based radars at detecting objects in high-Earth orbit and was heavily tasked to search the geosynchronous belt. One factor leading to the success of MSX in meeting the Air Force's SSA objective was that MSX, which had a 5-year design lifetime, lasted for 12 years and provided the Air Force's first operational space-based SSA sensor. Over its 12-year lifetime, MSX made long-term contributions to the maintenance of the space catalog and serves as a pathfinder for future Air Force systems.

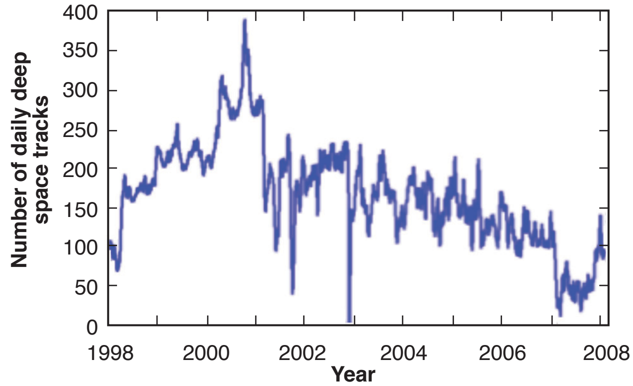

Figure 2. Objects detected per day by the MSX.

MSX was a large and complex spacecraft. It is the largest spacecraft ever built by APL. The operation of the spacecraft was very labor intensive because its mission and observations were highly varied.[2] Significant planning and mission-operations efforts were required to maintain the productivity of MSX.

The MSX spacecraft was an episodic spacecraft. It spent most of the time in a three-axis-stabilized, zenith-pointing-attitude mode (parked). The spacecraft would maneuver from parked attitude to conduct a task for data collection (track mode). If an anomaly occurred, MSX entered safe mode. To support the desired Ballistic Missile Defense Organization experiments, the MSX spacecraft was host to a suite of state-of-the-art instruments and had a large suite of pointing and tracking options.[3]

INSTRUMENT OVERVIEW

The Spatial Infrared Imaging Telescope III (SPIRIT III) was designed and built by the Space Dynamics Laboratory of Utah State University. It was a cryogenically cooled, midwave through longwave infrared instrument package used to support the primary remote sensing system for MSX. The SPIRIT III could detect infrared radiation ranging spectrally from 4.2 to 26.0 μm. The life of SPIRIT III was limited by the consumable solid hydrogen in the instrument's dewar.[4]

The Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) was a highly complex instrument suite designed and built by APL for the purpose of acquiring UV and visible target signatures and backgrounds. The UVISI instrument consisted of four imagers and five spectrographic imagers and a set of instrument electronics used for control and data processing. Together, these nine sensors were sensitive to wavelengths from 110 to 900 nm. This instrument also contained an onboard image processor that was used successfully to conduct closed-loop tracking of resident space objects.[5]

The Space-Based Visible (SBV) camera, designed and built by Massachusetts Institute of Technology Lincoln Laboratory, performed above-the-horizon surveillance experiments and acquired visible and near-infrared band data on targets and backgrounds. SBV was the sole instrument tasked for the space-surveillance portion of the MSX mission. The SBV sensor was used mainly to track spacecraft in the geosynchronous belt during the secondary mission.[6]

MSX also included a suite of spacecraft contamination instruments designed to monitor the contamination environment throughout the lifetime of the mission. This suite of instruments included five quartz crystal microbalance monitors, a total pressure sensor, an ion mass spectrometer, a neutral mass spectrometer, a water vapor monitor, and a xenon flash lamp to detect particulate contamination.[7]

BUS OVERVIEW

The payload instruments on MSX were able to perform because of a highly capable spacecraft bus. The importance of the mission necessitated a high degree of capability and reliability. The latter was achieved via the following redundant and cross-strapped subsystems on the spacecraft.

- **Electrical power subsystem (EPS):** The EPS consisted of two solar arrays with a maximum output of approximately 1200 W each. They were used to charge a 50-A·h nickel metal hydride battery. The battery charge was controlled by redundant power maintenance modules (PMMs).
- **Command and data handling:** The command and data handling system was made up of redundant command processors (CP1 and CP2) and redundant data handling systems. Communication was provided by S-band uplink with a 16-Kbit/s housekeeping downlink, 1-Mbit/s S-band downlink, and 25-Mbit/s X-band downlink.
- **Tape recorders:** MSX carried two analog reel-to-reel tape recorders, with a 54-Gbit capacity on each to allow for storage of vital mission data.
- **Attitude-determination subsystem:** The attitude-determination subsystem (Fig. 3) provided a stable platform and accurate target pointing. Two redundant attitude processors and five types of attitude sensors were on the MSX spacecraft. The five sensors consisted of a three-axis magnetometer, two horizon sensors (HSA1 and HSA2), a five-head digital Sun-angle detector, a star tracker, and two ring-laser gyroscopes (RLG1 and RLG2). Control was provided by four large reaction wheels and three internally redundant magnetic torque rods.

EVOLVING OPERATIONS

During the life of the mission, various spacecraft systems degraded, some gradually and others suddenly. The mission control team (MCT) was able to mitigate those degradations and maintain the productivity of the spacecraft. The MSX spacecraft occasionally went into a safe mode that limited data collection, but for the most part MSX was reliable.

The mode of operation changed when the secondary mission began. During the primary mission, the spacecraft conducted brief data-collection events, during which it would slew to the target and turn on the instruments. The results of these experiments were stored on the two analog tape recorders for later X-band downlink over APL. The spacecraft was inactive (parked) approximately 90% of the time. During the secondary, or extended, space-surveillance mission, the spacecraft became increasingly busy, with a duty cycle approach-

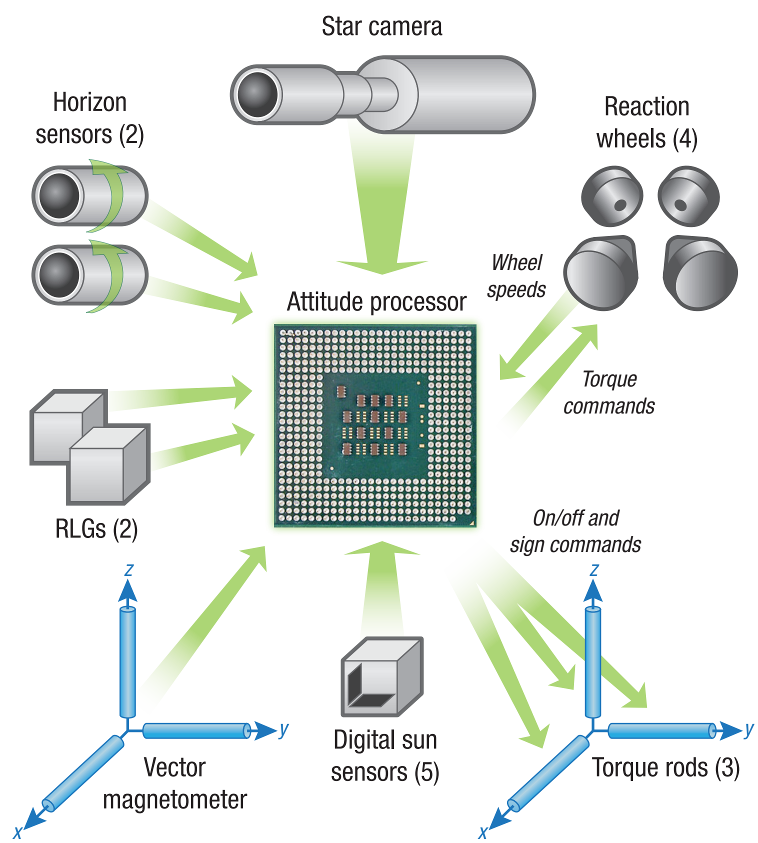

Figure 3. MSX attitude-determination subsystem components.

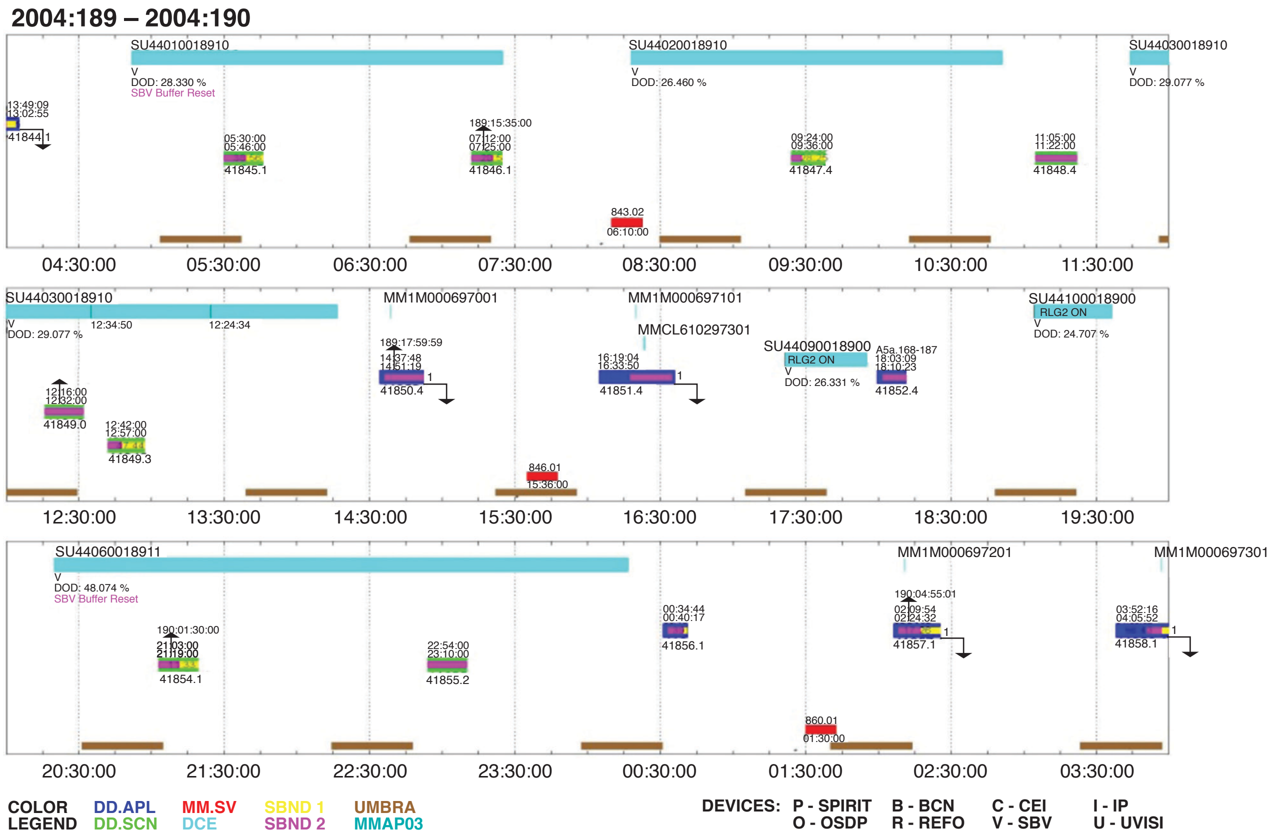

Figure 4. Graphical timeline showing a day in the life of MSX. The light blue bars represent data-collection events, while the shorter bars represent ground contacts with the spacecraft.

ing 50% (Fig. 4). This produced significant additional stresses to the aging spacecraft.

The intensity of the lasers in the RLGs began to noticeably degrade soon after launch but became a critical issue after the spacecraft's prime phase was completed. The gradual degradation did not affect performance of the RLGs; however, if the laser intensity would have fallen below a certain threshold, the RLG would have become inoperative. The degradation was determined to be a function of the amount of time the RLGs were turned on, so the attitude-control software was modified to allow the gyros to be turned off in park mode and used only for data-collection events. This periodic use of gyros significantly extended the life of the mission.

Eventually both RLGs showed significant degradation of laser intensity, and the attitude system was changed again to allow operations to proceed without the gyros and to use only the other attitude sensors. This change, although vital, introduced significant operational difficulties. The onboard system was not designed to be used without the gyros, especially in the track mode, when the spacecraft was dynamic and the view of sensors was changing rapidly. Gyros provided a continuous knowledge of the MSX pointing direction, and without them the onboard system had to rely on the other sensors. Reliance on only the other sensors was not ideal because during rapid spacecraft maneuvers the star trackers lost track of stars. In addition, the Sun sensors were not available during eclipse on every orbit. Depending on spacecraft pointing, occasionally neither horizon sensor was pointed at the horizon, and this resulted in availability of only the magnetometer data. However, it is not possible to determine attitude with only a single vector, and safe mode would result. During safe mode, data collection ceased, the spacecraft slewed to zenith-pointing attitude, and the solar arrays were rotated to track the Sun. The MCT largely mitigated these problems by reducing slew rates and redesigning data-collection events to keep one horizon sensor on the horizon.

The MCT efforts were largely successful, but to maximize data to the customer, the spacecraft attitude-control system was again modified to allow the spacecraft to autonomously promote from the safe mode without ground intervention (provided very specific conditions were met).

Other subsystems degraded sporadically over the duration of the mission. Fortunately, the MCT and attitude-control system engineers largely mitigated these degradations as well. Other degradations included

- **X-band antenna:** A gimbaled X-band dish antenna, mounted at the aft end of the spacecraft, pivoted to point the dish at APL during data downlinks. Because of repeated cable flexure during passes, the connection to the dish became intermittent. In response, the MCT made operational changes that kept the dish in a fixed orientation, pointing directly aft of the spacecraft, and instead pointed the entire spacecraft such that the dish would point at APL during a pass over APL. This was made possible by using the attitude-control system much like it would be used for a data-collection event.
- **HSAs:** HSA1 experienced periods of erratic behavior that caused the spacecraft to enter safe mode on many occasions. Operations were again changed by restructuring data-collection events so that they would attempt to keep HSA2 on the horizon during the maneuver. HSA1 ultimately failed.
- **Star camera:** There was a gradual decline in the sensitivity of the star camera. This had some effect on tracking success and likely contributed to the gradual decline in productivity shown in Fig. 3. Some changes to the parameters were made to the flight software late in the mission to mitigate tracker issues, but insufficient time remained to see their effect clearly.
- **Digital Sun-angle detectors:** An electronics problem in one of the five heads occasionally flipped the Sun-angle vector most significant bit in the sensor telemetry. This caused the spacecraft to enter safe mode occasionally.
- **Tape recorders:** The tape guidance motors failed on both recorders. Both recorders were tested over the entire range of tape, and the tape counts where the data were reliably good were mapped. In the secondary mission, the tape recorders were not used heavily and it was possible to use the small remaining good stretches of tape to record the science data.
- **Battery:** As the battery aged, its energy capacity decreased. PMM parameters were tweaked to increase the current flow to the battery during charging. Autonomy rules were also developed to conservatively manage the battery (minimizing battery discharge). These rules would terminate data-collection events when battery drain became excessive.

2007 AND 2008 DEGRADED OPERATIONS

In January 2007 the MSX spacecraft was operating without the use of the RLGs or HSA1 for routine attitude determination in parked and track modes. However, late in the month the spacecraft experienced a serious degradation to the attitude system that greatly limited the ability of MSX to collect data. An intermittent problem with HSA2 caused the spacecraft to experience safe modes on nearly every orbit. The remainder of 2007 was spent working to mitigate the HSA2 issue. A variety of operational approaches were taken to counter the HSA2 problem. HSA2 data was cycled in and out of the attitude solution, alternative maneuvering techniques were tried, and the safe mode timeout limit was increased. MSX productivity continued at a reduced level through 2007.

In January of 2008 the MSX spacecraft experienced failures of an attitude processor and hard failure of HSA2. Attitude determination was switched to the redundant processor (attitude processor 1), but the HSA2 failure left MSX with significantly degraded attitude determination capability. It was decided that continuing the MSX program would be impractical and too costly. A decision was made to decommission the spacecraft, but not before another several months' worth of additional data were collected by MSX by using the remaining, limited life of the RLGs.

DECOMMISSIONING AND DISPOSAL

MSX was decommissioned in July 2008. Decommissioning the MSX spacecraft did not consist of a series of deorbit maneuvers, as is the practice for some satellites, because it had no propellant. Nor was it as simple as just powering down the spacecraft components and walking away because the design of the spacecraft included a level of autonomous survival methods that were hard-coded into the flight software. Any decommissioning plan needed to account for the flight software design and to defeat those survival actions.

The decommissioning goal was to place MSX in a state such that it would not generate any RF signature and would minimize any chances of debris. Because there was no propellant or other expendables on the spacecraft, the decommissioning planning revolved around depleting the MSX power subsystem to a level at which there would be insufficient energy to support any subsystem operation and insufficient energy for the spacecraft to autonomously reconfigure itself for survival.[8]

Planning Phase

The technical aspects of the MSX decommissioning plan originally were outlined in 2005 at the request of the sponsor. The plan developed some strategies for disposing of the MSX spacecraft in a manner consistent with the decommissioning goal, but many details remained to be determined. Once the decision was made to decommission the MSX, the 2005 disposal plan was used as the foundation of the decommissioning operations.

The decommissioning plan targeted the EPS that supplied power to the spacecraft from the solar arrays and battery. A strategy was developed to place the spacecraft in a power-negative state in which the needs of the spacecraft exceeded the ability of the EPS to provide power.

One portion of the power strategy was to reconfigure the PMMs. The PMMs were designed to command the battery to maximum, reduced, or trickle charge rates on the basis of sensor inputs that measured voltage, temperature, and pressure. The PMMs also calculated the battery's state of charge (SOC). The SOC is the percentage of the battery's charge compared with its capacity. The PMMs linked the SOC to the battery's charge rate, so that as the battery reached a particular SOC threshold, the battery's charge rate changed from the maximum rate to the reduced rate and then to the trickle rate. Fortunately, this relation was configurable. For decommissioning, the plan was to configure the PMMs to the least advantageous state for maintaining the battery's power (Table 1).

In addition to changing PMM set points, the battery's SOC was a major tool for disposal operations. The PMM-calculated battery SOC would be commanded to 100% before the battery actually reached a full SOC. This would redefine 100% SOC at a lower level each time the command was executed. Essentially, the EPS was fooled into thinking that the battery was fully charged when it was not. PMM logic dictated that once the SOC reached 100%, the battery would charge at the trickle charge rate, which for disposal was set to 0.0 A. Execution of those SOC commands was done both in real time and by using the spacecraft's autonomy. A new autonomy rule was created exclusively for this purpose.[8]

The solar arrays were the source of power for MSX. By design, the arrays would normally track the Sun to maximize the supply of power. For decommissioning, the plan was to determine a solar array position for a particular time and duration to minimize the amount of energy output by the arrays and lock the arrays into that position. The solar array positions were determined both by modeling software and during testing before disposal. Those positions deemed best for minimal power output relied on a stable parked attitude of the spacecraft.

With a plan in place to configure the power storage and production by MSX, attention was then focused on another portion of the plan: to increase the power load on the spacecraft. The increased power load would increase the rate at which the battery would be depleted. The method for increasing the power load on the spacecraft was simple: all components that would not be detrimental to the decommissioning effort would be powered on. A list of components that could be safely powered on was compiled before the decommissioning effort and was carefully evaluated.

The MSX spacecraft was designed with low voltage sensing switch (LVSS) capabilities. The LVSS logic was hard-coded into the command processors (CP1 and CP2) and would have been detrimental to the decommissioning efforts. The LVSS logic was designed to execute commands that would place the solar arrays back to Sun-track mode and would begin to shed the load by powering off nonessential components once the main bus voltage of the MSX spacecraft fell below 24 V. The LVSS commands were executed from both CP1 and CP2 independently and the commands could not be changed; however, they could be disabled or masked. Masking of the LVSS logic allowed the battery to continue to drain, and the main bus voltage to continue to fall, without any intervening autonomous actions trying to save the spacecraft.[8]

The configuration of the spacecraft for decommissioning required heavy uplink commanding and near-continuous monitoring to verify and assess the decommissioning configurations. The nominal MSX contact schedule, consisting of a single 10- to 15-min contact between the ground and spacecraft approximately every 90 min, was insufficient. Therefore, some logistical planning was needed as well. The support assets, in this case the coverage of the orbit from ground antenna, needed to be increased. Nominal scheduling of ground antenna would be insufficient for both the execution and the monitoring of the decommissioning plan. The decommissioning plan called for the maximum antenna coverage from both the APL 10-m dish and the sponsor's ground network. Although the orbit of MSX made it impossible for continuous coverage, the increased antenna time allowed for sufficient time both to execute the decommissioning plan and to monitor MSX downlink telemetry to gain understanding of the spacecraft's health.

Table 1. PMM settings for MSX disposal operations.

PMM Function	Nominal Setting	Disposal Setting
Over voltage limit 1 and 2	33.91 V	32.57 V
Over temperature limit 1 and 2	24.66°C	21.4°C
Pressure limit 1	1158 psi	979.83 psi
Pressure limit 2	1120 psi	947.70 psi
Maximum charge rate 1 and 2	41.86 A	18.1 A
Trickle charge rate 1 and 2	0.38 A	0.0 A
Charge control reduction point 1 and 2	96% SOC	88.07% SOC

Derived from Ref. 8.

Execution Phase

When the MSX decommissioning activities began, the MCT executed the various uplink command scripts and configured the spacecraft for decommissioning. The spacecraft was completely configured for decommissioning within four spacecraft contacts. Once configured, the MCT needed to monitor key spacecraft data to ensure that the decommissioning plan was on track and to determine how close MSX was to the end of its life.

To ensure that the decommissioning activities proceeded as planned, the MCT monitored the attitude, command processor, and component power on the spacecraft. Because the solar array offset was based on a nominal parked attitude and the solar arrays would resume Sun pointing if the spacecraft were to enter a safe mode, it was vital to ensure that the spacecraft attitude remained stable. The MCT had safe mode mitigation plans ready to be used if needed. The MCT monitored the command processors for resets. Resets to those processors would unmask the LVSS, thus allowing for the spacecraft to autonomously shed electrical loads, and would have placed the solar arrays into Sun-track mode. To verify maximum power loading, the MCT also monitored the various components that had been powered on.

The main bus voltage was the key parameter for determining the remaining life of MSX, and, thus, final end-of-life activities were triggered on the main bus voltage reading. The battery's SOC percentage could not be used to assess battery charge because of its commanded redefinition of 100% SOC. The spacecraft was believed to be inoperable after the main bus voltage fell below 22 V.[8] When that criteria was met the MCT sent commands to power off the reaction wheels. Additionally, the MCT powered off the RF communications system on MSX; this guarded against any stray RF transmission in the event that the battery regained sufficient capacity to operate. These were the final actions performed on the spacecraft, in accordance with the MSX decommissioning plan.

Verification Phase

At the start of the next contact, attempts were made, as planned, to power on the RF communications system. When those attempts failed, the active portion of the decommissioning plan ended, and the start of the verification stage began. The verification portion of the decommissioning plan consisted of repeated attempts to contact MSX and enable the RF system, carried out periodically for the next 7 days. None of the attempts to contact the MSX spacecraft was successful, and the MSX program had come to an end.

CONCLUSIONS

The decommissioning of MSX marked the end of one of the most successful satellite programs ever undertaken by APL. The MSX spacecraft had fulfilled not only an ambitious primary mission, but it had also provided an abundance of useful data for a time well beyond its designed lifetime. The 12 years of active operations that followed years of development and testing at APL were filled with frequent adaptation to changing spacecraft capabilities as well as to sponsor needs. These changes presented challenges to the operations teams throughout the program, including during the decommissioning process.

ACKNOWLEDGMENTS: We acknowledge the hard work and dedication of the people who worked on the MSX program, especially the dedicated MCT and mission planning team members. Additional thanks are owed to the engineering and testing support from Rick Reinders as well as to Tom Strikwerda and his attitude-control team, which enabled the last 2 years of the MSX program to be a success. The ground system maintenance expertise of Steve Lundfeldt and Jay Haslup ensured that the aging ground system hardware and software remained operable throughout the MSX mission, and none of the productivity would have been possible without their dedication to the program. Special thanks go to Glen Baer for years of coordination and the extra effort necessary to extract every bit of life out of the spacecraft. The ability to maintain any level of success in the final years of the MSX program was because of the guidance received from past team members; in particular, Dan Ossing made himself available to the MSX team, helping the team to gain much insight. Finally, a great deal of gratitude is owed to all who worked on the development, design, integration, and testing of MSX throughout the entire program. The success realized on MSX operationally was built on the solid foundation established early in the program.

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