



## MSX Ground Operations

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**T**he multidisciplinary nature of ground operations necessitates careful planning from the start of any space program. For the Midcourse Space Experiment, ground operations began at APL with integration and test and continued at the NASA Goddard Space Flight Center with environmental and system-level electrical testing. Mission operations simulations were conducted at every opportunity. The spacecraft and its ground support equipment were then flown to Vandenberg Air Force Base, where additional testing and simulations were conducted and the spacecraft was prepared for launch.

### INTRODUCTION

The Midcourse Space Experiment (MSX) ground operations began with the installation of the spacecraft electrical harness on the payload adapter in mid-December 1991 and will end when the command to initiate first-stage ignition is sent from Vandenberg Air Force Base (VAFB), California. This article discusses the numerous steps required to get MSX integrated, tested, transported, and processed for launch during the final phase of spacecraft development known as ground operations.

The assembly of the MSX structural system began on 20 April 1992 in the APL Spacecraft Integration and Test Area—a clean room in compliance with MSX requirements. The structure provided a foundation for the installation, over 2 years, of the electronics and

instruments to be flown on MSX. During integration, the electrical ground support equipment (GSE), to be used for testing and spacecraft operation, was transferred from the laboratories where it was developed to the Payload Control Center at APL, where it was consolidated into a fully integrated operational system called the Ground Support System. In parallel, software engineers continued to fine-tune the ground and flight test software as well as the mission operations software.

Environmental testing was conducted at the NASA Goddard Space Flight Center (GSFC). MSX resided at the GSFC Environmental Test Facility from 22 June through 19 September 1994. There, it was demonstrated that MSX could withstand the acoustic and

pyro-shock environments of the launch phase and the thermal-vacuum environment in orbit.

Transporting MSX and its GSE from APL to GSFC and then to VAFB involved moving many large pieces of equipment over land and by air under tight constraints of temperature and daylight time. Finding a place to process MSX at VAFB was difficult because it had few facilities certified for hazardous operations available to meet the needs of MSX. An early attempt to alleviate this problem was the construction of a Payload Processing Facility (PPF) by Astrotech Space Operations near the Delta II launch pad. The VAFB Payload Control Center, where the Ground Support System was located, and the MSX Program Office were set up in a NASA facility much farther away.

NASA/Kennedy Space Center/Vandenberg Launch Site, representing NASA interests at VAFB, and the U.S. Air Force 30th Space Wing communications squadron played major roles in setting up the communications system to support MSX operations at VAFB. In addition, APL engineers were involved in setting up the communication links between the Payload Control Center and the PPF and other nerve centers vital to MSX operations.

The goal of MSX ground operations was to launch a completely tested, operable spacecraft into an Earth orbit defined by the MSX mission. The primary objectives were to demonstrate that spacecraft performance and design requirements were consistent with one another, to show that the software designed to operate MSX in orbit was compatible with the requirements of the mission, and to give the mission operations team ample opportunity to develop the skills needed to operate MSX properly.

Ground operations for MSX addressed concerns about contamination, security, safety, and performance. Hazardous operations, particularly those involving the handling and transfer of substantial quantities of cryogenic substances for the Spatial Infrared Imaging Telescope III (SPIRIT III), were of the most serious nature of any space program managed by APL. The requirement for 2000 L of liquid H<sub>2</sub> made cryogenic operations a highly scrutinized activity at VAFB.

## CONTAMINATION CONTROL

Most of the instruments aboard MSX are optical sensors extremely sensitive to contamination. For example, 17 items were continuously purged with the boil-off from 440-L dewars of liquid N<sub>2</sub>. The quantity of liquid N<sub>2</sub> consumed increased daily, peaking at 205 L/day, as the instruments and special packages that required purging were added to the spacecraft. Controlling contamination at the system level was handled in the conventional manner: a Class 10,000<sup>1</sup> (no greater than 10,000 airborne particles/ft<sup>3</sup>, 0.5 μm or larger in

size) or better clean room; complete clean room attire including face masks, boots, latex gloves, and taped wrists; frequent wipe-downs of the spacecraft; weekly wipe-downs of the clean room walls; daily floor mopping; double-bagging of the spacecraft when the threat of contamination increased; and constant monitoring of air quality and surface contamination with particle counters, tape lifts, and blacklight inspections.

The diverse sensor complement of MSX made contamination control quite challenging. Since sensor performance is sensitive to scatter and stray light, it would be degraded by particulate contamination. The Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instrument was also sensitive to hydrocarbon contamination. Because of these sensitivities, contamination control requirements for the entire payload were set at the most sensitive levels: less than 10.76 mg/m<sup>2</sup> hydrocarbon level and Level 100 particulate contamination for internal optical surfaces (see Table 1). To maintain the Level 100 or better on orbit, exterior surfaces could be no worse than Level 500 on orbit after launch fallout from the launch vehicle fairing (particulate that shakes free from the interior surfaces of the launch fairing). Allowing for this fallout, the flight hardware was maintained at no greater than Level 300 during integration. When qualitative observation from tape-lift samples indicated contamination in excess of this level, operations in progress were interrupted for cleaning. This process was repeated until the specified cleanliness level was demonstrated.

The same clean room practices were employed wherever the spacecraft was processed. The launch pad was to be the most difficult area to manage. There, the garment dressing room is located on level 3, two levels beneath the spacecraft white room on level 5, and an elevator—a notorious particulate carrier—is used to get to the working levels. The local wind conditions range from high velocity—sustained to extremely gusty, and the space for personnel to work around the spacecraft is extremely limited because of all of the equipment located on level 5 to support SPIRIT III cryogenic servicing.

## CRYOGENICS

Cryogenics played a leading role during MSX ground operations because of the special needs of SPIRIT III, the primary instrument. Since SPIRIT III is an infrared sensor, many of the optical and electro-optical elements inside the telescope had to be cooled to cryogenic temperatures—nominally 10 K—to function properly and to prevent self-contamination. This cooling was accomplished with a variety of cryogenic liquids: N<sub>2</sub>, Ar, and He, as well as Ar and H<sub>2</sub> for flight, which were frozen solid with liquid He during prelaunch processing. Furthermore, this ultracold condition had to be main-

**Table 1. Surface particulate cleanliness levels (particles/0.093 m<sup>2</sup>).**

Particulate size ( $\mu\text{m}$ )	Level 100	Level 300	Level 500
$\geq 15$	265	NA	NA
$\geq 25$	78	7450	NA
$\geq 50$	11	1020	11,800
$\geq 100$	1	95	1100
$\geq 250$	NA	2	26
$\geq 500$	NA	NA	1

Note: Data are from Ref. 2.

tained without interruption from the moment SPIRIT III was installed in the spacecraft until launch. This feat took a large quantity of specialized equipment, skilled personnel working three shifts, and copious amounts of cryogenics drawn from 500-L dewar storage containers, not to mention countless industrial-sized containers of compressed He and N<sub>2</sub>. Liquid He was always in great demand and was the most difficult to obtain in the large quantities that SPIRIT III required.

Venting the boil-off of all cryogenics harmlessly required large amounts of cryohose interface hardware that had to be designed, fabricated, installed, and checked out in time to support spacecraft operations. This requirement applied to operations at APL, GSFC, and VAFB, as well as those aboard the military aircraft that transported the spacecraft from the East Coast to VAFB.

## LOGISTICS

Transporting the entire MSX cargo, including the spacecraft and its shipping container, as well as the GSE, required five 12.2-m Flexivan trailers and a sixth trailer used to transport noncritical hardware overland to VAFB. Two C-5 air cargo carriers provided by the U.S. Air Force Air Mobility Command were needed for the flight to VAFB. Travel by air was complicated by the liquid He required to keep the SPIRIT III telescope at cryogenic temperatures and the liquid N<sub>2</sub> needed for purging the contamination-sensitive instruments with N<sub>2</sub> gas. For safety, boiled-off He was externally vented, whereas the N<sub>2</sub> was vented into the aircraft's cargo bay, where the accumulation was constantly monitored. Representatives of APL, Wright-Patterson AFB, Andrews AFB, Dover AFB, and VAFB met often to resolve numerous issues before the MSX cargo was transported to VAFB.<sup>3</sup>

## SAFETY

Safety issues required constant attention because of the numerous hazardous items on MSX, including

lasers, RF transmitters and radiators, pyrotechnics, high-voltage circuits, cryogenics (especially H<sub>2</sub>), radioactive coatings, pressure vessels, and reference object ejectors. These items were involved in various hazardous activities such as spacecraft handling, large package installations, cryogenic operations, liquid H<sub>2</sub> transfer, pyrotechnic checkout, and spacecraft functional/electrical testing.

MSX operational safety documents described the requirements for all locations, taking into account the unique operations of each site. There was the *MSX Emergency Action Plan for APL*,<sup>4</sup> *MSX Ground Safety Plan* for operations at GSFC<sup>5</sup> and VAFB,<sup>6</sup> and *SPIRIT III Operational Review for Payload Processing Facility and SLC-2W*.<sup>7</sup>

Since the hazards of H<sub>2</sub> operations were of constant concern, they were performed only at VAFB. A major issue was how to detect a dangerous accumulation of leaked H<sub>2</sub> in time to evacuate personnel and prevent damage to the spacecraft and facility. To address this problem, two H<sub>2</sub> sensors were mounted between the roof and the clean room ceiling of the PPF. These sensors were augmented by seven others positioned at strategic locations along the liquid H<sub>2</sub> transfer line and near MSX. The seven sensors were selected from a nine-sensor H<sub>2</sub> monitoring system developed by McDonnell Douglas for the launch pad. This system included provisions for remotely monitoring and recording the sensor output in the event of an evacuation.

Since VAFB mandated the remote monitoring of some H<sub>2</sub> sensors, a video camera was set up so that the readout of the two ceiling sensors could be monitored from the Payload Control Center. An end-to-end test of the detection system demonstrated automatic activation and power shutdown, the actuation of a roof-level exhaust louver and alarm lights (the louver opens automatically to allow leaked H<sub>2</sub> trapped under the roof to escape harmlessly into the atmosphere), and the notification of the fire department.

When the SPIRIT III cryostat suffered its first internal failure, the portion of the warning system downstream of the hydrogen detection system performed successfully following manual actuation. The failure resulted in the total boil-off of all of the hydrogen (64 kg), which exited safely and without incident through the emergency vent stack. Since no hydrogen escaped into the clean room, the hydrogen sensors were not activated.

Safety training was compulsory for all personnel requiring access to the various spacecraft sites. For the APL clean room, the GSFC space environment simulator, and the PPF, access was granted through a card-reader badge system upon completion of safety training. Furthermore, adherence to approved, written procedures was mandatory for all operations at GSFC and VAFB involving the flight hardware.

## COMMUNICATIONS

Communications associated with ground operations encompassed a variety of networks that connected the spacecraft to the Payload Control Center at a specific test site; to the Command Center at the Air Materiel Command's Detachment 2/Space and Missile Center, Onizuka AFB, California; or to the Mission Control Center at APL. Communication links to support MSX operations while the spacecraft was at APL or GSFC were relatively simple. The networks at VAFB (Fig. 1), however, were quite intricate and required considerable time to implement.

Both land-line and RF links were established for MSX operations. The land lines, consisting of both fiber-optic and copper conductors, were set up to support baseband testing. Frequent use of open-loop testing at VAFB is discouraged in the S-band frequency domain, in particular, because S-band frequencies are in great demand daily. RF communications are allowed but have time-of-day usage restrictions and require permission to use. Occasional RF testing is necessary to verify that MSX can communicate successfully through the entire RF system, including the antennas. This requirement is particularly important during the hours just before liftoff during a last-chance confirmation that the communications are viable.

Communication links at VAFB were complicated by the fact that while MSX would be located at either the PPF or a few kilometers further north at the Delta II

launch pad, the Payload Control Center was located a considerable distance away at NASA Building 836. The only existing links to the PPF were several pairs of 40-year-old copper conductors of dubious quality. To support MSX testing, multiple digital (up to 5 Mbps) and analog channels were needed, as was a set of point-to-point RF links (L-, S-, and X-band) from the PPF to the Payload Control Center.

The existing copper conductor pairs were capable of providing the necessary voice networks, telephone lines, and two low-rate data modem links to the PPF. In addition, the PPF was practically in-line with the Payload Control Center and NASA Building 1610, which already had point-to-point RF links between them. To satisfy MSX RF requirements, Astrotech Space Operations installed the appropriate antennas and cabling at the PPF. Antenna alignments and system performance tests were conducted by NASA RF engineers.

Many high-quality, high-data-rate, baseband (non-RF) channels were needed between the PPF and the Payload Control Center. Since VAFB could not guarantee when the fiber-optic backbone would reach the PPF, a direct hookup to the existing VAFB communications network was made via a small switching building (Hut 1) about 8 km from the PPF. Since this was considered MSX-unique, cost became a driving factor, so an 8-km armored fiber-optic cable was laid over the ground from the PPF to Hut 1. With 10 fibers in the

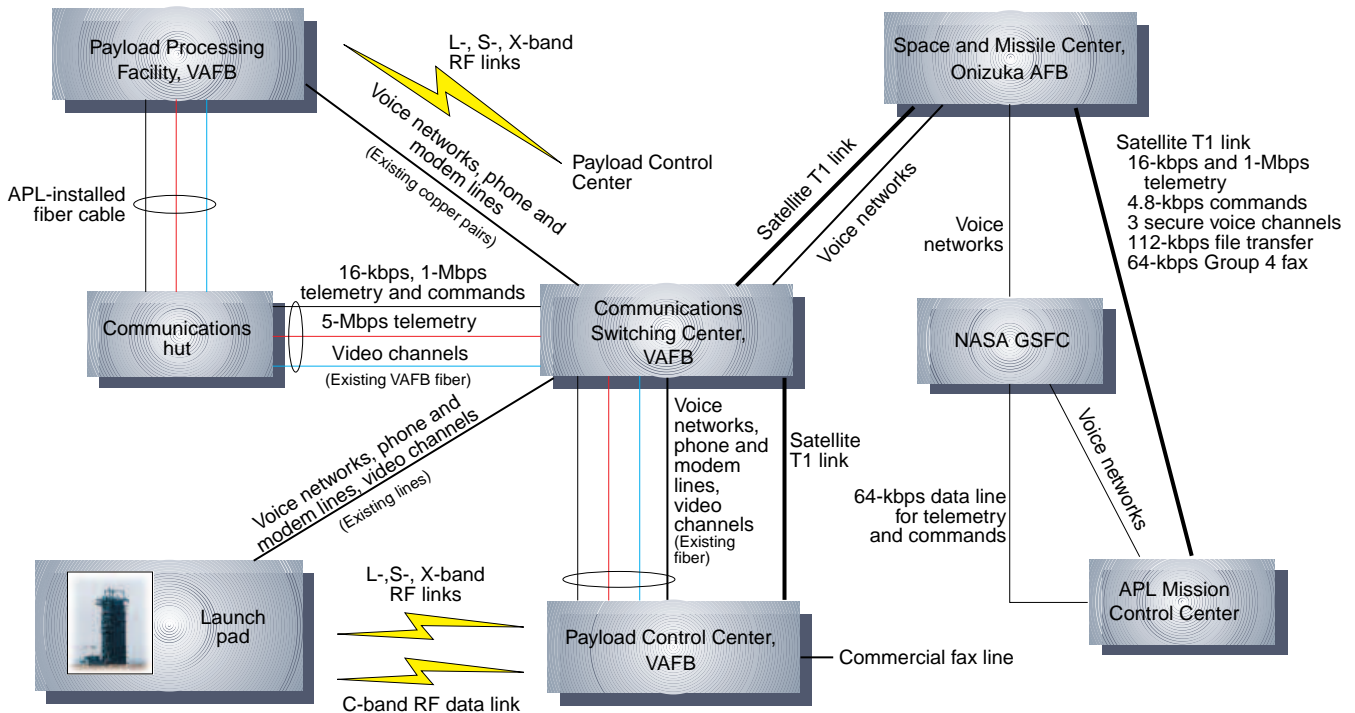


Figure 1. MSX communications networks for ground operations.

cable, all of the analog, digital, and video links could then be sent via Hut 1 to the main VAFB Data Transfer Center and from there over the many available fibers and copper lines running to the Payload Control Center. With approval from VAFB, the fiber-cable end equipment was installed, and the completed links were tested and verified as operational in August 1994—about a month before MSX arrived. Links to other facilities, such as the launch pad, Onizuka AFB, and APL, used existing communication lines.

Once the communications system was installed, a significant effort was expended to make it fault-free. Persistent power outages at VAFB demanded that uninterruptible power supplies be placed at each point in the baseband system (Hut 1 and the Data Transfer Center). In addition, despite labeling, an occasional disconnection in the Data Transfer Center interconnection patches would occur, breaking the link. On one occasion, landscapers accidentally damaged the land-laid fiber cable in two places with powered weed trimmers. Field splices had to be made to re-establish the link.

More serious problems surfaced with the T1 data links between VAFB and the Mission Control Center at APL. A T1 link is a 1.544-Mbps full duplex data link that uses time-division multiplexing to relay any number of lower-rate data streams between sites, provided the combined data rates, including overhead, do not exceed 1.544 Mbps. MSX used T1 links to transfer the 1-Mbps compressed science, 16-kbps telemetry, and 4.8-kbps command data streams. At one point during testing, four T1 links were needed to communicate digital data between VAFB and the Mission Control Center. Jitter introduced in each T1 link multiplexer contributed to frequent clock slips (analogous to bit errors, where a bit is dropped from the data stream entirely instead of being misdetected). This problem was particularly evident in the 1-Mbps science data link, where the jitter from the multiplexer was a larger fraction of the clock cycle and led to unacceptably high bit-error rates. For this channel, it was possible to bypass the two T1 links at VAFB by transmitting the data over video lines and regenerating a clean clock with a bit synchronizer. This change removed half of the jitter contribution from the total T1 link, and the error rate improved.

The initial performance verification and debugging (shakedown) of the MSX communication system at VAFB included the linking of the Vandenberg Tracking Station east of the PPF as well as the Space and Missile Center at Onizuka AFB. At one point during the processing, a fully equipped, portable ground station called the Transportable Space Test Resource, provided by the Space and Missile Center, was parked alongside the PPF to communicate with the MSX inside to demonstrate

that the Space and Missile Center would be able to communicate with the orbiting MSX successfully.

Much later, after the second cryostat failure, the Payload Control Center had to be moved to a triple-wide trailer near the PPF. Although the closer proximity to the PPF provided many advantages, the connectivity between the original Payload Control Center and the MSX communications network already in place at VAFB had to be shifted to the new Payload Control Center. This matter was further aggravated by the uncertainty of the extension of the VAFB fiber-optic backbone to the PPF. Overall, however, the MSX communications networks at VAFB worked extremely well.

## SECURITY

APL was responsible for MSX security planning, coordination, and oversight at all APL locations, GSFC, and VAFB. The Laboratory was also responsible for protecting the integrity of the MSX spacecraft, GSE, and mission operations, which included the Mission Control Center, Mission Processing Center, and Operations Planning Center, as well as the data management at all of these centers.

To protect MSX and its sensitive mission objectives, the *MSX Program Protection Plan*<sup>8,9</sup> was developed. A card-reader system, an armed guard, or both, were used at every facility in which MSX or its GSE were resident to prevent unauthorized entry into either the spacecraft room or the control center(s). Alarms or warning lights were installed in strategic places to alert the guards of illegal entries. For the off-hours, door-mounted combination locks were added for extra protection. Lock combinations were revealed to only a few people. Video surveillance was provided at the entry points to all security-sensitive areas at APL. Communications security equipment mounted on MSX and in GSE racks was kept secure with metal cage locks and visual or video monitoring.

## PERFORMANCE ASSURANCE

Performance assurance concerns itself with the disciplines of reliability engineering, quality assurance, and systems safety. Its role during spacecraft processing was governed by the *MSX Product Assurance Plan*.<sup>10</sup> Other performance assurance documents are listed as follows:

- *Integrated Test Specification for Space Payload Equipment*<sup>11</sup>
- *Technical Services Department Hardware Configuration Management Manual*<sup>12</sup>
- *MSX Program Test Plan*<sup>13</sup>
- Various acceptance test procedures
- Automated computer test scripts (runstates)

The performance assurance engineer is responsible for controlling and documenting all of the variables affecting reliability, quality, and safety once integration begins. This job at the system level is largely a continuation of the earlier package-level (individual electronic module) effort but with a significant adjustment in perspective. Concern over package quality and performance carries over to the system level, broadening to consider the interdependency of all packages and their performances as parts of a much larger and more complex system.

For the integration and test phase of MSX, the main tasks of the performance assurance engineer included the verification that the subsystem was ready to integrate; maintenance of the problem/failure reporting system as well as tracking the corrective actions; monitoring conformance with the program test plan; and preparing monthly reports to the MSX Program Office on the condition of the spacecraft and operations associated with its processing.

Performance assurance received close attention on MSX. The spacecraft is extremely complex and the operating system consists of numerous electronics packages, many of which are populated with large quantities of densely packed electrical connectors. The total connector count for MSX, not including internal package connectors, is 1547; more than half of these are in the primary, redundantly wired electrical harness that weighs 163 kg.

Numbers and types of connectors became an important aspect of integration and test since many packages were integrated more than once. Connections and disconnections became so numerous in some cases that connector pin wear and damage had to be closely monitored.

## INSTRUMENT PURGING

A purge system was integrated into MSX to continuously provide the contamination-sensitive instruments with research-grade (99.9995% pure)  $N_2$  gas from the time of installation until liftoff. Instrument internal pressure was maintained at more than 0.266 kPa (2 torr) above atmospheric, with a design goal of 0.665 kPa, to prevent the entrance of contaminants. Once the system was in full use, it was discovered that some of the instrument housings were not as leak-tight as expected. To compensate for excessive leakage, the purge-gas flow rate was elevated from the 77 L/min design criterion to 99 L/min to maintain the minimum pressure differential of 0.266 kPa in the instrument housings with the largest leaks.

Purge gas was distributed to the instruments via a U-shaped stainless steel manifold wrapped around the bottom of the instrument section. The lines that connected each instrument to the manifold were provided

with flow restrictors to meter the gas. Pressure in the manifold was set at 99.98 kPa, so the flow through the restrictor was sonic (choke flow), which provided a constant-volume gas flow to each instrument, regardless of other users of the manifold.

The purge manifold had a primary inlet used for routine ground purging and an inlet with a flyaway fitting that disconnected when the umbilical tower retracted. The flyaway feature allowed the purge to continue right up to liftoff. Check valves in all hose connections sealed disconnected lines to stop purge-gas backflow and prevent contaminants from entering the manifold.

The MSX purge-gas monitor suitcase contained gas regulation, analysis, and filtration equipment. Inlet gas in the 689.5- to 861.8-kPa pressure range was regulated down to the 99.98- to 110.3-kPa range to feed the connecting hoses and spacecraft manifold. An electronic hygrometer in the suitcase was programmed to constantly monitor the  $N_2$  purge-gas pressure, temperature, and  $H_2O$  and  $O_2$  content to verify its purity. An out-of-range indication of any of these parameters would activate a flashing amber alarm light and a telephone auto-dialer that would alert service personnel.

The need for continuous purging required a portable liquid  $N_2$  supply any time MSX had to be moved from one facility to another. Three leased, pristine dewar storage containers, equipped with built-in pressure building and evaporator coils and filled with liquid  $N_2$ , were shipped along with the spacecraft when it was transported between facilities. Two of them were 440-L containers, each providing a 52-h supply; together, they were adequate for all planned trips, including the one to VAFB on the C-5 air cargo carrier. A 160-L dewar provided an 18-h reserve of liquid  $N_2$  in case of an emergency and for use on the McDonnell Douglas handling cart for transporting MSX from the PPF to the launch pad.

For air transport, provisions were included to dump  $N_2$  overboard through a special bulkhead attached to the C-5's fuselage to avoid filling the cargo bay with oxygen-depleting nitrogen in the event of a catastrophic release from either dewar.

## INTERFACING WITH CRYOGENIC SYSTEMS

Cryogenic interfaces were required between the SPIRIT III GSE and the various test/processing facilities. They were also required between MSX and its support hardware such as the shipping container/transporter and C-5 air cargo carrier. All SPIRIT III cryogenic servicing equipment, with interfaces liberally distributed throughout, was strategically positioned around MSX. Much of it was connected to SPIRIT III with vacuum-jacketed hoses. To minimize the loss of

cryogen through boil-off during transfer operations, the hoses were kept as short as possible. Typical lengths fell in the range of 4.6 to 7.6 m.

In addition, the shipping container was equipped with cryogenic bulkhead fittings for the emergency vent as well as the cryostat, aperture door, and orbit vent. Also, two ports in the GSFC space environment simulator were modified to accept bayonet bulkhead fittings so that SPIRIT III and the other instruments could be serviced in the chamber by cryogenic GSE located outside the chamber. A pressure-relief system was installed in the C-5 aircraft to protect SPIRIT III's internal burst disk system from sizable pressure differentials that would be experienced at high altitude.

At the PPF, SPIRIT III was loaded with liquid H<sub>2</sub> from a 1000-L dewar located outdoors for safety reasons. An identical dewar, also filled with liquid H<sub>2</sub> for the gas top-off, and a 440-L dewar of liquid N<sub>2</sub> for the instrument purge were located on a concrete pad along with the primary dewar about 7.6 m away from the building. A custom-made cryogenic bulkhead fitting was mounted to the wall of the PPF about 4.9 m above ground level—the height of SPIRIT III's hydrogen inlet. This fitting helped support the 7.6-m-long inside and outside cryogenic hoses that connected SPIRIT III to the supply dewar outside. A specially designed, environmentally sealed panel was mounted on the wall of the PPF, to which a He vent hose and the N<sub>2</sub> purge line were attached. The panel also provided sealed passages through the wall for the H<sub>2</sub> and emergency vent hoses. These two hoses were connected to custom interfaces on the emergency vent stack, which was attached to the outside wall of the PPF and exhausted about 1.8 m above the roof top. (The PPF roof is 12.2 m above ground level). A portable vent stack also was attached to the wall of the shipping container and connected to the SPIRIT III emergency vent port with a short piece of vacuum-jacketed hose and fitting.

Cryogenic interfaces on the launch pad are basically the same as those at the PPF, except for the liquid H<sub>2</sub> transfer hose. For safety reasons, H<sub>2</sub> transfer on the pad is prohibited.

## SPACECRAFT AND INSTRUMENT ALIGNMENTS

The SPIRIT III, UVISI, and Space-Based Visible (SBV) instruments were to be coaligned within 0.1°, including uncertainties due to mapping errors, thermal distortion, and stress-induced distortion and hysteresis. Also, their lines of sight were to be mapped into the MSX coordinate system for boresight pointing knowledge. To meet these requirements, alignment error budgets partitioned the 0.1° between thermal distortions, mechanical distortions due to ground-to-orbit transitions, stress-induced distortions, and alignment

errors. Mapping and shimming alignment errors had to be kept to less than 0.03° to meet the coalignment specification.

To satisfy the instrument coalignment criteria, the following plan was implemented: A calibrated optical cube was mounted on each instrument or sensor (UVISI consists of nine independent sensors), and then the line-of-sight vector of each one was mapped into its optical cube. After each instrument was mounted on the spacecraft, its optical cube orientation was mapped with respect to the MSX coordinate system. The SPIRIT III mounting surface—the support ring around the cryostat—was used to define the coordinate system. Minimizing the coalignment errors of SPIRIT III, UVISI, and SBV to this interface allows the instruments to keep the observable targets in their respective fields of view simultaneously.

After the initial assembly and alignment at APL, all instruments and attitude control devices were remapped before and after environmental testing at GSFC and after shipment to VAFB. During the mappings at APL and GSFC, all of the high-resolution instruments had an average misalignment of less than 7 arcsec (0.002°). However, during the transit of MSX to VAFB, all of the instruments shifted 0.014° with respect to spacecraft coordinate axes.<sup>14</sup> This shifting was attributed to a settling of the instrument section at its interface with the graphite-epoxy truss. All instruments except SPIRIT III, however, maintained their relative coalignments, and the small offset relative to SPIRIT III was within tolerance.

## ELECTROMAGNETIC ENVIRONMENTS

To avoid damaging MSX electronic components sensitive to electromagnetic radiation and to establish what effect the ambient RF environment might have on electrical testing, electromagnetic surveys in and around the PPF and level 5 of the launch pad were conducted in September 1994.<sup>15</sup> RF frequencies from 10 kHz to 10 GHz were monitored to determine potential field strengths during spacecraft processing. Previous radiated susceptibility tests on the transponder system, for example, showed that direct radiations could disturb this system's operation in the 200- to 1000-MHz range at field strengths of 1 to 2 V/m. Other radiated susceptibility tests involving the integrated spacecraft at APL demonstrated that MSX could withstand field strengths as high as 10 V/m at specific frequencies that occur at VAFB at certain times. Nevertheless, other signal frequencies that could cause disruptions at lower field strengths might be present.

Previous RF surveys conducted during the fall of 1993 and summer of 1994 at the launch pad and the PPF showed that known tracking radars as well as

surveillance radars could impinge on these locations with high levels ( $>10$  V/m) of RF interference. Special controls were instituted to keep this from happening while MSX resided at VAFB.

The electromagnetic survey indicated a slight chance that MSX would encounter a radiated susceptibility problem at VAFB. It showed that MSX had immunity of up to 1 or 2 V/m across the entire spectrum. Although the survey was comprehensive, it covered only the common types of electromagnetic interference emissions at VAFB. It did not guarantee that something disruptive would not occur.

## VITAL SUPPORT FUNCTIONS

The daily spacecraft maintenance routines included flight battery conditioning and instrument purging (discussed earlier). Documentation consisted of 80 electrical, mechanical, environmental, and mission-related plans generated to meet the requirements of the *MSX Program Test Plan*.<sup>13</sup> In addition, numerous documents covered contamination control, communications, safety, security, and logistics support operations.

Photo-documentation provided a visual and chronological record of all spacecraft activities from the beginning of integration until liftoff. These photographs were archived in the APL MSX Program Office and were invaluable to MSX engineers during reintegration.

## SUBSYSTEM INTEGRATION: EVOLUTION OF MSX

The object of subsystem integration is to verify that the subsystem being integrated is compatible, both mechanically and electrically, with the previously integrated subsystems and to check the subsystem for functional performance. Integration is a prelude to the more comprehensive system-level tests discussed later in this article.

Before integration, all subsystems had to meet the applicable pre-integration flight acceptance requirements. The performance assurance engineer documented departures from requirements and alerted the APL MSX Program Office. If a problem could not be resolved quickly, a "workaround" was devised to prevent delay of integration. The final step before subsystem integration was the integration readiness review, where the subsystem's lead engineer demonstrated the subsystem's readiness to other APL MSX engineers.

Subsystem integration began with the delivery of the package(s) to MSX for pre-installation resistance measurements. Next, the delivered unit or units were installed at the proper locations on MSX, power and signal connectors were mated, units were powered up, and signal interfaces were checked. The final check was an "aliveness test": a relatively simple functional test

that verifies whether or not the circuitry within the package is working properly at nominal voltage under ambient conditions.

Throughout integration, functional test procedures and computer test scripts called "runstates" enabled the test conductor and test team to verify quickly whether the subsystem being integrated was functioning properly and was compatible with the other subsystems already on MSX. Interface compatibility between the subsystem GSE and the Ground Support System was established earlier.

## SOFTWARE TESTING

While MSX was under development and well into the integration and test phase, the complex software needed to operate MSX during ground testing and in orbit was being developed. The effort was segmented into 16 areas covering the various spacecraft subsystems and mission operations.

Software testing<sup>16</sup> was done in four phases: (1) unit testing, (2) module integration testing, (3) verification testing, and (4) acceptance testing. Unit testing verified that the program unit performed as specified in the design documents. Module integration testing followed successful unit testing and integration of the units into a subsystem. This process continued until the entire package of units was integrated into a system (module) and was ready for verification. After module integration testing indicated that the software performed as specified in the design documents, verification testing was conducted.

Verification testing was done in accordance with the software requirements documents and involved target computers and attendant hardware on MSX. The software was verified by the APL-developed attitude processor/tracking processor (AP/TP) testbed simulator whenever spacecraft instruments were not available. The AP/TP testbed simulator played a central role during the integration of the various flight processors.

Acceptance testing was conducted throughout integration and test. Mission profiles were run in conjunction with specific tests to verify that the latest hardware or software modification did not somehow "break" the software. All software testing was documented in the software engineering logbook, kept in the AP/TP testbed simulator as an electronic record, or was recorded chronologically in handwritten notes. The AP/TP testbed simulator was a frequent stand-in for missing hardware during this phase. Stress testing was performed on the AP/TP testbed simulator, in parallel with continued spacecraft testing, to verify the robustness of the software. Throughout acceptance testing, operator handbooks were compiled so that mission operations personnel could have documents based on "real-life" experience to refer to when operating MSX.



## PRELIMINARY HARDWARE/ SOFTWARE TESTING

The attitude, tracking, and image processors were subjected to initialization, data handling system, memory dump, and real-time commanding tests during the initial phases of spacecraft integration. In addition, the tracking processor, in conjunction with UVISI, SBV, the beacon receiver, and the attitude processor, participated in pointing verification tests.

Attitude processor pointing verification included tests to demonstrate magnetic and gravity gradient momentum dumping. Real-time commanding by the attitude processor involved the X-band antenna gimbal, the solar array drive, and magnetic torque rods. The UVISI image processor was tested to verify the tracking message, image input, and image processing control.

Systems tests consisted of simulated track scenarios using data from the beacon receiver and UVISI. Errors were introduced deliberately to demonstrate how well the software would deal with spurious out-of-range and conflicting data as well as data dropouts. Systems tests of this nature were performed on the AP/TP testbed simulator to verify, once again, that the software was robust.

## INTEGRATION AND TEST

For a large and complex spacecraft, integration and test is a process that, by its very nature, threatens to go on forever. For MSX, it was the most time-consuming and mentally challenging activity of all.

By early June 1992, the entire structural system, consisting of the instrument section, the electronics section, and a graphite-epoxy truss connecting the two, was fully assembled. Over the next 2 years, all of the other elements were integrated. To identify interface incompatibilities promptly, some elements of all of the instruments were installed at the forward end of the instrument section.

The instrument section provided structural connectivity for the beacon receiver antenna array and the optical bench, to which was mounted the star camera and ring laser gyros for attitude control and detection. The horizon sensors and several DSADs for the attitude control system were also mounted on the instrument section. Reference object ejectors were assembled to a pair of half-panels that were then installed on the forward end of the instrument section. A significant portion of all electrical testing was done with MSX in this configuration.

At the end of April 1994, the SBV sensor, reference object ejectors, optical bench, and beacon receiver antenna array were temporarily removed from the instrument section so that the SPIRIT III sensor could be installed. A major milestone was reached with the installation of the SPIRIT III sensor on 9 May 1994.

During May and June 1994, the integration of UVISI was completed.

At this point, a meaningful, system-wide alignment check of the instruments and attitude sensors could be made. In addition, MSX was now configured for the comprehensive baseline performance test.

## BASELINE PERFORMANCE TEST

The baseline performance test comprised four parts: (1) the spacecraft functional test, (2) the spacecraft performance test, (3) special tests, and (4) mission simulation. One baseline performance test was run at APL before MSX was shipped to GSFC for environmental testing, two were run at GSFC during the thermal-vacuum test, and another was run at VAFB during spacecraft processing.

The spacecraft functional test verified that the system operated properly, i.e., that the subsystems interacted as expected. This was a nominal condition test that did not subject MSX to a wide range of conditions for performance assessment. The spacecraft performance test, on the other hand, was designed to verify performance specifications. Of much longer duration, it tested MSX to extremes under a wide range of scenarios designed to simulate on-orbit conditions. The spacecraft functional test took slightly more than 1 day to complete, whereas the spacecraft performance test took about 4 days.

Certain performance tests had to be conducted individually for reasons of practicality. For MSX, 26 of these special tests were done.

Mission simulation was a ground-based "orbital shakedown" during which MSX was subjected to extremely harsh conditions analogous to the most stressful it would experience in orbit. It consisted of two parked-mode orbits followed by a target track simulation and five additional parked-mode orbits. Included were spacecraft downlink events, such as the 25-Mbps prime science, 1-Mbps wideband, and 16-kbps housekeeping data. Command messages at 2 kbps were generated and uplinked to the spacecraft command receiver. In every instance, command execution was verified.

During testing, the mission operations team, to enhance its proficiency, was given ample opportunity to control the spacecraft. During these periods, the payload test team performed routine tasks and operated in a standby mode, ready to assume control of MSX if a problem occurred.

## ENVIRONMENTAL QUALIFICATION

On 21 June 1994, the Test Interfaces and Requirements Document (TIRDOC)<sup>17</sup> was jointly approved by APL and GSFC and distributed in final form, after 3 years of coordination between engineers of both orga-

nizations. On that same day, MSX and all of its GSE were shipped to GSFC for environmental testing. MSX activities at GSFC began on 22 June 1994, in compliance with the TIRDOC, and continued until 19 September 1994, when MSX and all of its mechanical and cryo-handling GSE were shipped to Andrews AFB for the journey to VAFB.

For environmental qualification, MSX was removed from its shipping container at GSFC, installed on a support structure called the “elephant stand,” and transported on air bearings to the Spacecraft Systems Development and Integration Facility clean room. Operations in the clean room concentrated on preparing MSX for instrument alignment checks, acoustic simulations, pyro-shock tests, and thermal-vacuum tests in the space environment simulator. Figure 2 shows engineers and technicians installing the SPIRIT III sunshade on MSX.

Instrument alignment was checked before and after transit to GSFC and after environmental testing. A good correlation of results provided confidence in the performance of the instruments and attitude detectors.

While accelerometers and thermocouples were being installed on MSX in preparation for the acoustic, pyro-shock, and thermal-vacuum tests, instrument purging with the boil-off from liquid N<sub>2</sub> continued uninterrupted. Likewise, the cooling of SPIRIT III with liquid He and liquid Ar also continued uninterrupted. When the preparations were complete, MSX was disconnected from the SPIRIT III cryogenic GSE, double-bagged, and transferred on air bearings to the acoustic cell for testing.

The object of the acoustic test was to subject MSX to a simulation of the worst launch-vehicle-induced environment. The spacecraft, including all thermal blankets, was in its launch configuration atop the elephant stand and the launch vehicle payload attach fitting. All of the pyrotechnically actuated devices were connected for the pyro-shock testing that was to follow, and the double bagging remained in place to protect the spacecraft from contamination in the acoustic cell, which was not equipped to provide filtered air.

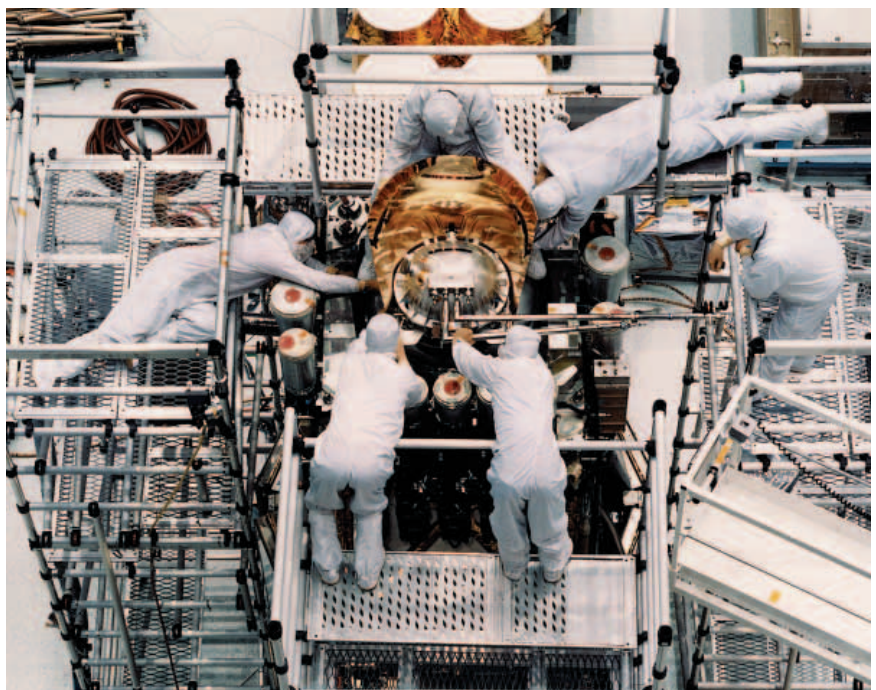
First, MSX was subjected to a functional test, which was repeated after the acoustic test. It was then commanded into its launch mode just moments before the acoustic test began. Although the flight acceptance test lasted 60 s,

total exposure to the acoustic environment lasted about 2 min. The extra time was required for acoustic input calibration and equalization at  $-6$  dB. The post-test indicated that the electrical system survived the acoustic simulation.

The pyro-shock test simulated the actual shock pulses generated by the pyrotechnic uncaging of all of the deployable equipment—antennas and instrument aperture covers—and the release of the clamp band joining MSX via the payload adapter to the payload attach fitting. Consistent with accepted practice, all pyro-initiated events were tested twice.

Not only did these tests provide valuable shock propagation data, they also demonstrated the uncaging and deployment of all of the deployable elements. Another functional post-test indicated that the electrical system survived pyro-shock testing as well. At this point, MSX was ready for the final phase of testing at GSFC in the space environment simulator.

MSX thermal-vacuum testing began on 25 July 1994 and ended on 22 August 1994. The 4-week test program consisted of two hot and two cold thermal balance tests, a hot and cold functional test, and a hot and cold survival test. Test conditions—total testing hours, number of thermal cycles, and temperature levels—were derived from the *Integrated Test Specification for Space Payload Equipment*.<sup>11</sup> The purpose of the thermal-vacuum test was to simulate orbit environments and ensure proper functioning of MSX and its components.



**Figure 2.** Installation of the gold-plated sunshade around the SPIRIT III aperture cover on the forward end of MSX during environmental testing at GSFC.

Specifically, it was designed to evaluate the following:

- Performance of the thermal and power systems in the park mode at both full-Sun and maximum-eclipsed orbits
- Capability of the thermal control system to maintain component temperatures expected during the mission for the eclipsed and full-Sun orbits
- Electrical performance of the subsystems while cycling temperatures to the hot and cold levels specified in the thermal-vacuum test during the baseline performance test
- Capability of the thermal and power systems to support target encounter missions
- Performance of the thermal control system under survival conditions

MSX in its orbital configuration—with thermal blankets in place but minus solar panels—was attached to a mounting fixture in the center of the chamber. Temperature control during the thermal-vacuum test was maintained with a GSFC-developed heater shroud formed into an irregular octagon that completely surrounded the spacecraft. The heater shroud was used to provide equivalent sinks, and the chamber cold wall was set to liquid  $N_2$  temperature ( $-190^\circ\text{C}$ ). Over 400 test thermocouples were installed on MSX to monitor the temperatures of the instruments and support system electronics packages. Thermocouples were placed in strategic locations to evaluate the integrity of the thermal design and operation of the heaters and thermostats, and to establish a correlation between flight telemetry and thermocouple-measured temperatures to verify the performance of the flight temperature sensors.

Aside from the usual startup problems, the thermal-vacuum test ran smoothly, except for one serious problem. Despite all of the planning, a subtlety of the space environment simulator surfaced after the thermal-vacuum test began. If it had not been for several cryo-hose penetrations of the chamber's cryo-liner (shroud), the problem would never have been discovered. The cryo-hoses served as conduits for the liquid He and liquid Ar required to maintain the SPIRIT III telescope at its operational temperature during the test. A little known fact about the shroud was its proclivity to change position whenever liquid  $N_2$  flowed through it. This condition was critical for MSX because no allowance was made for it in the

clearances between the cryo-hoses and the shroud penetrations for them. Tests run years earlier by GSFC indicated that the shroud would “walk” far enough to contact the cryo-hoses and subject them to sizable side-loads. These side-loads could have caused serious damage to the hoses or degradation in the joint seals at the chamber wall feed-through plates, resulting in leakage of liquid He or Ar into the chamber during the thermal-vacuum test. It took 5 days to correct the condition, and the delay in the schedule had to be made up later.

After completion of the thermal-vacuum test, a functional post-test was run. Then, MSX was double-bagged, removed from the space environment simulator, set back down on the elephant stand, and, via air bearings, transported back to the clean room.

### FINAL TESTING, PRE-SHIP PREPARATIONS, AND TRANSPORT TO VAFB

Back in the clean room, MSX was unbagged and reconnected to its cryogenic and electrical GSE. A solar array drive test was conducted, followed by reinstallation of the solar panels (the solar panels were not required for the thermal-vacuum test), alignment re-verification, cleaning, double-bagging, and final cryogenic servicing. After that, MSX was returned to its shipping container and, along with the remaining GSE, transported at 3:00 a.m. on 19 September 1994 to Andrews AFB for the trip to VAFB.

It took about 3 h to load MSX on the C-5 air cargo carrier (Fig. 3) provided by the U.S. Air Force Air



**Figure 3.** MSX in its shipping container is being transferred to the C-5 air cargo carrier at Andrews AFB for the flight to VAFB.

Mobility Command Squadron stationed at Dover, Delaware. For logistical reasons, the Payload Control Center GSE was shipped 1 week ahead of MSX. Preparations at VAFB for the arrival of MSX were explained or illustrated in the *MSX Launch Site VAFB Operations Plan*.<sup>18</sup> The Payload Control Center at VAFB was set up and on-line by the time MSX was cabled and ready for functional verification at the PPF.

## PAYLOAD CONTROL CENTER OPERATIONS

The Payload Control Center was the focal point for all activities related to electrical testing. The baseline performance test, mission simulation test, exclusion zone test, concept of operations test, special functional and subsystem tests, launch readiness tests, and launch dress rehearsals were all orchestrated from the Payload Control Center. With the exception of a couple of RF racks, the AP/TP testbed simulator, battery monitoring/charging equipment, ground power, blockhouse control units, and a variety of monitoring equipment, all of the MSX GSE was located in the Payload Control Center. The exceptions were set up in the PPF control room, 16 km north of the Payload Control Center and adjacent to the PPF clean room where MSX was located.

The spacecraft systems engineer controlled activities at the Payload Control Center, and the program systems engineer coordinated testing. The spacecraft manager controlled activities at the PPF. Spacecraft status, work schedules, test schedules, and current problems were discussed at daily meetings chaired by the APL MSX Program Manager. The daily interchange of technical and administrative information was considered essential to the success of MSX operations.

## PPF OPERATIONS

Most of the activity in the PPF involved mechanical operations, including SPIRIT III cryogenic servicing; package removals and reinstallations; spacecraft handling, cleaning, bagging, and unbagging; instrument alignment verification and purging; reconfiguring for specific tests; localizing air conditioning; thermal blanketing; scaffold assembly and repositioning; and supporting spacecraft electrical testing, as necessary.<sup>19</sup>

PPF activity centered on the SPIRIT III cryogenic servicing. Key to that instrument's success was the constant chilling needed to maintain a high level of internal cleanliness. The goal was to keep SPIRIT III at its operating temperature (about 10 K), which was required for electrical testing. Satisfactory performance at 10 K was a prerequisite to filling the cryostat with liquid H<sub>2</sub> and freezing it for launch by circulating liquid He through cooling coils wrapped around the cryostat's internal reservoir.

Nearly all prelaunch preparations took place in the PPF clean room with MSX clamped to the Delta II payload attach fitting, which was bolted to a floor-anchored spacer provided by McDonnell Douglas. Before testing could start, workers had to position scaffolding around MSX, remove the bagging, connect cryogenic and vacuum hoses to SPIRIT III, connect MSX to its GSE, and uncage the beacon receiver antenna array and rotate it into its flight position.

## MISSION OPERATIONS SIMULATION TEST

The mission operations simulation test (MOST)<sup>20</sup> was one of several tests of the mission integrated readiness test, which was devised to establish the readiness of the MSX postlaunch operations teams and the worldwide network designated to support those operations. The objective of MOST was to demonstrate that the operations teams could carry out daily integrated spacecraft control and assessment operations. MSX served as a testbed. The object was to have the operations teams interface with MSX through the Air Force Space Communications Network on-orbit network configuration and demonstrate daily operations and communications for 12 h of dedicated target event operations and 24 h of early on-orbit operations.

Aside from the usual start-up problems and some minor anomalies that surfaced, MOST was conducted successfully. It gave the operations teams ample opportunity to hone their skills for operating MSX in orbit.

## HYDROGEN TRANSFER AND SOLIDIFICATION

Because excessive handling of liquid H<sub>2</sub> is discouraged for safety reasons, loading SPIRIT III with liquid H<sub>2</sub> was deferred until it demonstrated acceptable electrical performance.<sup>21</sup> The first step was to terminate the flow of liquid He into the cryostat's internal reservoir. (liquid He was used to cool the reservoir for routine performance testing and precooling before introducing liquid H<sub>2</sub>). Then, liquid H<sub>2</sub>, contained in a 1000-L dewar located in an outdoor, limited-access area 7.6 m away from the PPF, was transferred through a large vacuum-jacketed hose connected to a special bulkhead adapter mounted to the wall. A similar hose of the same length was connected to the other side of the same adapter and the cryostat H<sub>2</sub> fill port, giving the liquid H<sub>2</sub> a continuous conduit for steady flow from the 1000-L source to the cryostat.

After about 64 kg of liquid H<sub>2</sub> was transferred, flow of liquid He resumed through the cryostat's cooling coils until all of the liquid H<sub>2</sub> in the reservoir was frozen solid. Keeping the H<sub>2</sub> solid required liquid He circulating through the cooling coils late into the prelaunch

countdown. The intent was to keep the frozen  $H_2$  from reaching the triple point (the temperature and pressure at which all three phases of a substance coexist in equilibrium) too early in orbit to give the contaminated atmosphere surrounding MSX sufficient time to disperse before opening the instrument covers. Delaying the cover openings as long as possible decreases the chance that instrument performance might be degraded due to outgassing residuals from materials on MSX. Ten to fourteen days was considered optimum.

Although liquid  $H_2$  was transferred to SPIRIT III and solidified successfully at the PPF, an anomaly developed inside the cryostat after the transfer, causing a converter to rupture and thereby terminating MSX prelaunch processing on 2 November 1994.

Solidification of the  $H_2$  was considered a major milestone. On the day the failure occurred, MSX was only 16 days away from launch. SPIRIT III was subsequently removed from MSX and shipped to the cryostat developer for disassembly, inspection, and repair. It was returned to VAFB for reintegration with MSX on 5 April 1995.

Several weeks later, with the reintegration process well under way, the pressure in the cryostat's vacuum space could not be reduced to a level low enough to continue with the cooling-down process. This was symptomatic of an internal leak, so the prelaunch processing was suspended again. SPIRIT III was removed from MSX and returned to the cryostat developer a second time for inspection and repair.

## LAUNCH PAD OPERATIONS

Launch pad operations will begin well before the spacecraft arrives from the PPF. It will take several months to get the Delta II launch vehicle integrated in the mobile service tower (Fig. 4) and prepared for installation of MSX. To maintain control over environmental quality in the spacecraft white room of the mobile service tower, the cryogenic GSE and other support hardware required on the pad to service SPIRIT III will be transferred from the PPF to the mobile service tower well ahead of MSX. When MSX arrives at the pad, all of the cryogenic GSE will be in place and seismically restrained, and the white room environment will be fairly well stabilized. The object is to limit the exposure of the white room to the natural environment while

MSX is being transferred into it. Having the cryogenic GSE in place will make rechilling quick and straightforward.

MSX in its shipping container will be hoisted by gantry crane to level 5 of the mobile service tower, stripped of its outer bag, and moved into the white room for the final 14 days of ground operations. Once the container is in the white room and positioned over the Delta II second stage, the gantry doors will be shut. The container will then be lowered until the payload attach fitting contacts the forward end of the Delta II guidance compartment. After the payload attach fitting is bolted to the front end of the launch vehicle, the shipping container will be removed from MSX and stored in the mobile service tower.

After MSX is securely attached to the second stage, the following will occur:

- The hydrogen emergency vent line will be connected to the SPIRIT III emergency vent and the launch pad emergency vent stack.
- The installation of the launch pad hydrogen monitoring system will be completed.
- The MSX instrument purge manifold will be connected to the liquid  $N_2$  boil-off source located at ground level close to the mobile service tower.
- MSX will be connected to the RF and land-line communication links running between the launch pad (umbilical connections) and the Payload Control Center.
- The battery charging and conditioning system and battery air conditioning will be set up.
- The clean room will be stabilized quickly to allow operations to begin on schedule.



Figure 4. The Delta II launch tower overlooking the Pacific Ocean.

- Cryogenic servicing equipment will be connected to the SPIRIT III cryostat to reestablish the frozen H<sub>2</sub> to prevent it from reaching the triple point.
- The Ar servicing equipment will be connected to the SPIRIT III aperture door for cooling necessary to inhibit telescope contamination.
- A spacecraft functional test will be conducted.

For launch to occur by the prescribed date, the flight fairing will be assembled around MSX about 8 days before launch, which is 6 days after the spacecraft arrives at the pad. Access after that will be restricted because most of the areas around MSX will be inaccessible. Large holes provided by McDonnell Douglas in critical areas of the fairing will allow access for certain operations on the pad. Antenna hat coupler installations and removals, safe plug removals, arming plug installations, final ordnance checks, cryogenic hose connections and disconnections, removal of nonflight items, and final thermal blanket closeouts are but some of the operations to be done after the fairing is installed. To minimize contamination, the inner bag will be removed from MSX through the gap between fairing sections late in the fairing integration process.

During the 14 days that MSX will spend on the pad, four functional tests will be run in addition to a launch mode test, a stray voltage test, and a mock launch countdown with the launch vehicle. Two days before launch, a spacecraft readiness review will be held in conjunction with a launch site readiness review.

## CONCLUSION

Much of what falls under the general classification of ground operations takes place in the shadow of ground operations tied directly to spacecraft processing. As a result, much of the planning, coordination, and implementation that occur years before processing go largely unnoticed. Contamination control, security, safety, performance assurance, communications, environmental testing, logistics, instrument purging, cryogenic operations, alignment verification, battery

conditioning, electromagnetic surveys, interface coordination, and documentation all helped MSX to reach the various milestones leading to its ultimate destination. We hope that those unfamiliar with the details of ground operations now have a better understanding of what goes on behind the scenes from the first signs of integration until the words "ignition" and "liftoff" are heard.

## REFERENCES

- <sup>1</sup> *Federal Standard Clean Room and Work Station Requirement, Controlled Environment*, FED-STD-209D (Jun 1988).
- <sup>2</sup> *Product Cleanliness Levels and Contamination Control Program*, MIL-STD-1246B (Sep 1987).
- <sup>3</sup> Baran, S. D., *MSX Logistics and Transportation Plan*, JHU/APL Doc. No. 7334-9195 (11 Feb 1994).
- <sup>4</sup> McDevitt, J., *MSX Emergency Action Plan for APL*, JHU/APL Doc. No. 7334-9188 (Feb 1994).
- <sup>5</sup> McDevitt, J., *MSX Ground Safety Plan for Operations at Goddard Space Flight Center*, JHU/APL Doc. No. 7334-9064 (Jun 1994).
- <sup>6</sup> McDevitt, J., *MSX Ground Safety Plan for Operations at Vandenberg Air Force Base*, JHU/APL Doc. No. 7334-9184 (Sep 1994).
- <sup>7</sup> Schick, S. H., *SPIRIT III Operational Review for Payload Processing Facility and SLC-2W*, USU/SDL Doc. No. 016, Rev. 1 (Jun 1994).
- <sup>8</sup> Johnson, J. L., *MSX Program Protection Plan* (Jul 1993).
- <sup>9</sup> Johnson, J. L., *MSX Program Protection Plan for Vandenberg Air Force Base*, JHU/APL Doc. No. 7334-9235 (Jun 1994).
- <sup>10</sup> Goss, M. E., *MSX Product Assurance Plan*, JHU/APL Doc. No. SOR-1-89036A (Jun 1991).
- <sup>11</sup> Nagrant, J., *Integrated Test Specification for Space Payload Equipment*, JHU/APL SDO 2387-1 (Feb 1982).
- <sup>12</sup> *Technical Services Department Hardware Configuration Management Manual*, JHU/APL Doc. No. TSD-STD-400.1, Rev. 2 (Sep 1993).
- <sup>13</sup> *MSX Program Test Plan*, JHU/APL Doc. No. 7334-9001 (Jun 1994).
- <sup>14</sup> Sadilek, A. C., *MSX Spacecraft Optical Mapping Plan at VAFB*, JHU/APL Doc. No. 7334-9245A (Sep 1994).
- <sup>15</sup> Hartong, G. S., *MSX—Evaluation of the Potential for RF Environmental Exposure of the MSX Spacecraft at VAFB During Launch Preparations and Processing*, JHU/APL Doc. No. S2R-94-273 (Oct 1994).
- <sup>16</sup> Utterback, H. K., *MSX Software Master Test Plan*, JHU/APL Doc. No. S1A-021-90 (26 Feb 1990).
- <sup>17</sup> Fox, H., *Test Interfaces and Requirements Document (TIRDOC)*, JHU/APL Doc. No. 7334-9040 (Jun 1994).
- <sup>18</sup> Baran, S. D., *MSX Launch Site VAFB Operations Plan*, JHU/APL Doc. No. 7334-9009 (12 Aug 1994).
- <sup>19</sup> Kreitz, H. M., *MSX Handling and Prelaunch Operations at the PPF and Launch Pad*, JHU/APL Doc. No. 7334-9046, Tasks 1-4 (Oct 1995), Task 5 (Mar 1995).
- <sup>20</sup> Huebschman, R. K., *MSX Mission Operations Simulation Test at the PPF*, JHU/APL Doc. No. 7334-9304A (Nov 1995).
- <sup>21</sup> Bell, G. A., *Fill and Top-off of SPIRIT III Cryostat in the Astrotech Building*, USU/SDL Doc. No. 014, Rev. 1 (13 Jul 1994).

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