The MSX Flight Operations System

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The Midcourse Space Experiment spacecraft is operated by a multi-organizational Flight Operations System, which is a worldwide ground network of tracking stations and planning, control, performance assessment, and data processing centers. This system prepares and conducts scientific and engineering experiments and recovers the necessary data to satisfy the requirements of the Ballistic Missile Defense Organization. The elements of this operations-based system include teams, facilities, procedures, and their functional relationships, which collectively provide continuous on-orbit support of the spacecraft system.

INTRODUCTION

The Ballistic Missile Defense Organization (BMDO) is conducting the Midcourse Space Experiment (MSX) Program to address critical issues in midcourse target detection, acquisition, and tracking. The objectives of this program include target discrimination and background data collection, functional demonstrations, representative sensor integration demonstrations, and technology integration. This mission consists of an interleaved set of experiments using sensors aboard the MSX spacecraft and other supporting range sensors. The planning and conduct of spacecraft operations necessary to satisfy the requirements of these experiments throughout the on-orbit mission are the responsibility of the Flight Operations Team, supported by the Flight Operations System.

The on-orbit operational lifetime of the MSX spacecraft is 4 to 5 years, and its orbital path is a near-polar, 900-km, nearly-sun-synchronous circular orbit. The spacecraft contains a suite of co-aligned optical instruments designed to collect data on targets or regions of space in the infrared, ultraviolet, and visible wavelength bands, and to measure the local MSX contaminants. Supporting these instruments are spacecraft subsystems that provide power and targeting (attitude) control, and a data handling system stores onboard recorded instrument data and receives command messages from, and transmits data to, ground stations.

Four information channels are used to control the spacecraft configuration and recover scientific and engineering data. A command message uplink channel conveys command messages at 2 kbps (kilobits per second). Downlink channels convey engineering (state-of-health) data, low-rate science data, and prime science data at 16 kbps, 1 Mbps (megabit per second), and 25 Mbps, respectively.

OVERVIEW OF FLIGHT OPERATIONS

Flight operations is that portion of the mission lifetime when the spacecraft is “in flight” or “on orbit.”

It begins with insertion of the spacecraft into the designated orbit and extends to the end of useful mission life. APL has overall responsibility for MSX flight operations.

The mission of the Flight Operations Team is, stated simply, to fly the spacecraft. Specifically, the functions of this team must satisfy the requirements of the BMDO mission as expressed by experiment plans. The plans are scheduled so as to acquire the necessary science data and to assure, through prudent use of resources, operational integrity of the spacecraft. These functions of the Flight Operations Team are accomplished through a ground-based operations network consisting of teams, facilities, and procedures. The primary participants, in addition to APL, are (1) the U.S. Air Force (USAF) Space and Missiles Center Test Support Complex (SMC/TSC), at Onizuka Air Force Base, California, which is connected to a network of Air Force Satellite Control Network (AFSCN) Remote Tracking Stations, and (2) the Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL).

Flight Operations Team Interfaces

Figure 1 depicts the organizational interfaces of the MSX Flight Operations Team. Principal Investigator Teams prepare experiment plans that define spacecraft requirements for the collection of sensor data on specific targets, target sets, or backgrounds. Classes of experiment plans include targets, Earth-limb and celestial backgrounds, shortwave terrestrial backgrounds, surveillance, contamination and data certification, and technology transfer. Principal Investigators work closely with the APL Operations Planning Team to develop experiment plans and supporting spacecraft operations plans that specify timelines, configurations, pointing and tracking strategies, instrument modes, and data storage. Principal Investigators remain closely involved as experiments are scheduled, analyzed, and conducted on the spacecraft.

In addition to Principal Investigator Teams, these teams interface with the Flight Operations Team:

- The Mission Planning Team, led by the BMDO Mission Director, provides a monthly prioritized list of experiment objectives and specifies experiment plans to be scheduled by the Operations Planning Team.
- The U.S. Space Command (USSPACECOM) Space Control Center reviews planned MSX pointing and instrument modes before an experiment is conducted, and postprocessed data afterward, to identify violations of USSPACECOM Regulation 55-12.

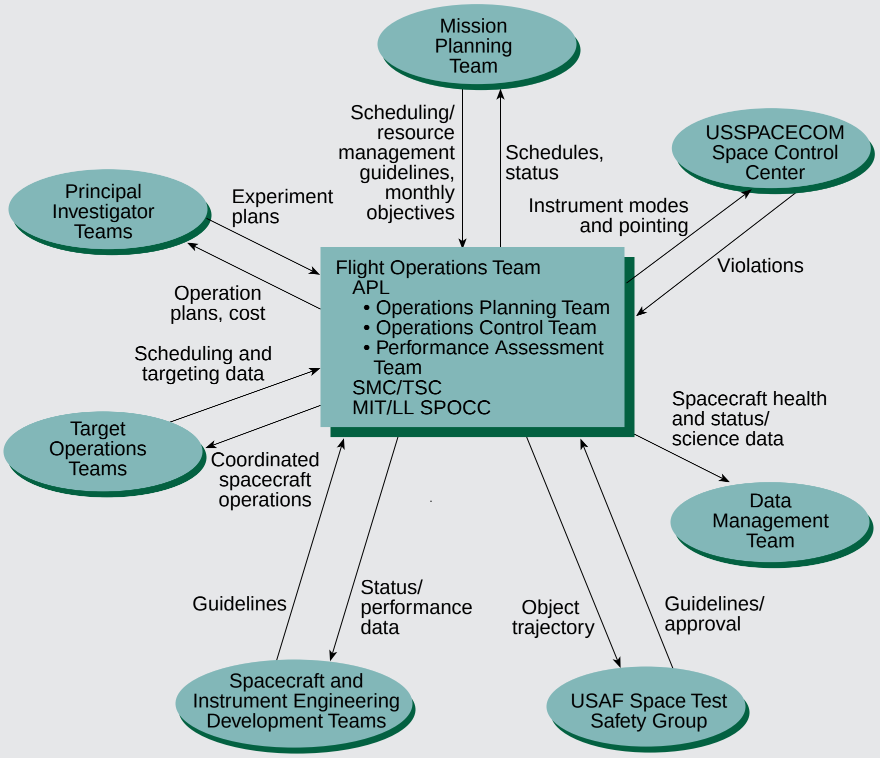

Figure 1. Organizational interfaces of the MSX Flight Operations Team. SMC/TSC, Space and Missile Center Test Support Complex (Onizuka Air Force Base, California); MIT/LL, Massachusetts Institute of Technology/Lincoln Laboratory; SPOCC, Space-Based Visible Processing, Operations, and Control Center; USSPACECOM, U.S. Space Command.

- The Data Management Team manages distribution of mission data, including spacecraft prime science data and related engineering data products, to the data processing and archive centers.
- The USAF Space Test Safety Group is responsible for on-orbit collision avoidance screening of MSX released and deployed objects, including an aperture cover and reference spheres.
- Spacecraft and Instrument Engineering Development Teams assist in performance assessment and support anomaly investigation.
- Target Operations Teams coordinate ground-based launches of targets to be observed by MSX sensors.

The Flight Operations System Ground Network

Figure 2 shows the MSX Flight Operations System ground network. The spacecraft interfaces to this network through ground tracking stations, including the APL MSX Tracking System and a worldwide network of AFSCN Remote Tracking Stations. These stations, which transmit MSX command messages and recover engineering and scientific data, are connected to two control centers: the APL Mission Control Center and the Air Force SMC/TSC.

Scientific data, acquired by the spacecraft's instrument suite and stored on tape, are downlinked to the APL tracking station and preprocessed by the APL Mission Processing Center. Data tapes are distributed by the Mission Processing Center to the following centers:

- Instrument data processing centers located at the Utah State University Space Dynamics Laboratory (Spatial Infrared Imaging Telescope), MIT/LL (Space-Based Visible instrument), Hughes Aircraft Company (On-Board Signal Data Processor), and APL (Ultraviolet and Visible Imagers and Spectrographic Imagers, and the Contamination Experiment)
- The Background Data Center and Missile Defense Data Center, where data are archived.

The APL Performance Assessment Center is primarily responsible for assessing the spacecraft and the Flight Operations System. Primary spacecraft operations planning occurs at the APL Operations Planning Center, an extension of which, located at the SMC/TSC, provides a means of exchanging planning products and information. The MIT/LL Space-Based Visible Processing, Operations, and Control Center (SPOCC) provides a planning center for surveillance experiments as well

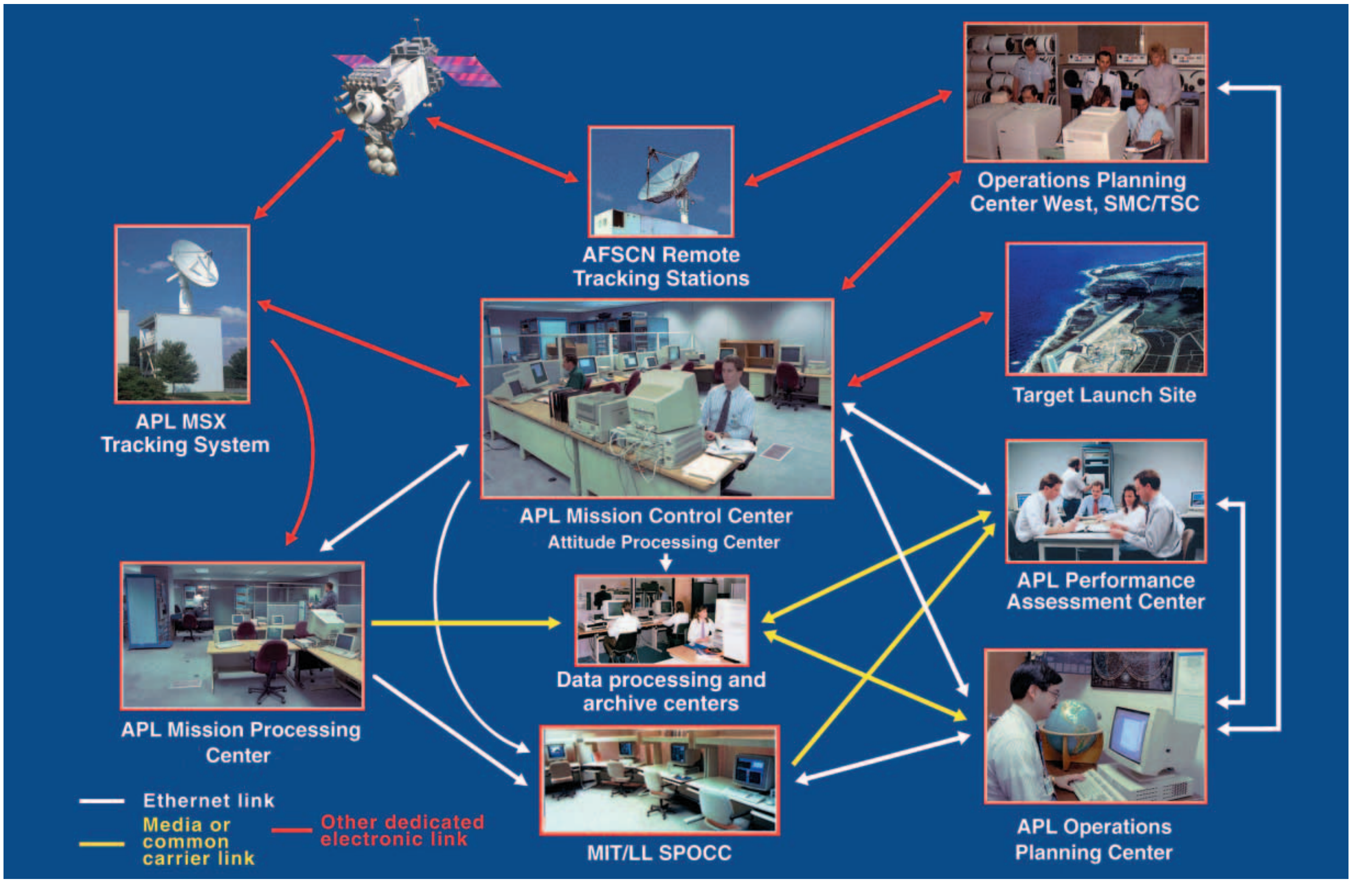

Figure 2. Components of the MSX Flight Operations System ground network. The network consists of facilities at APL, the SMC/TSC, and the MIT/LL SPOCC. The spacecraft interfaces to this network through ground tracking stations, including the APL MSX Tracking System and the AFSCN Remote Tracking Stations.

as an assessment center for the Space-Based Visible instrument. Target tracking experiments are coordinated with the target launch site.

The On-Orbit Flight Operations Team

Figure 3 shows the organization of the MSX Flight Operations Team supporting the on-orbit phase of the mission. The BMDO Mission Director represents the program sponsor, has overall authority, and is supported by Flight Operations Teams representing APL, SMC/TSC, and MIT/LL, which collectively provide complete on-orbit spacecraft operations support.

The APL Flight Operations Manager is responsible for overall coordination of the Flight Operations System and, in particular, for APL personnel and facility activities. He is assisted by a team of five flight controllers who provide the prime interface with the BMDO Mission Director and coordinated direction of the Flight Operations Teams on a round-the-clock basis. The APL Flight Operations Team includes the Operations Planning Team (responsible for long- and short-term spacecraft operations planning and scheduling), the Operations Control Team (spacecraft command uplink, telemetry recovery and monitoring, and processing), and the Operations and Spacecraft Performance Assessment Team (performance trending and anomaly resolution).

The Air Force Space Test Engineer leads the SMC/TSC Flight Operations Team, which includes a Planner/Analyst Team (short-term planning and scheduling), an Orbit Analyst Team (spacecraft tracking and orbit determination), and a Control Point Team (spacecraft command uplink and telemetry recovery).

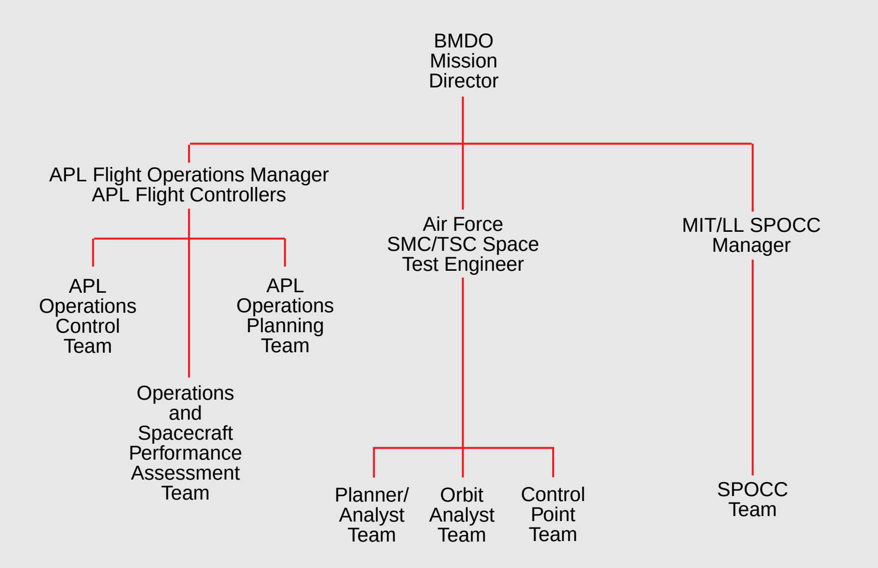

Figure 3. Organization of the on-orbit MSX Flight Operations Team. Three teams, under the authority of the BMDO Mission Director, represent APL, SMC/TSC, and MIT/LL. These teams provide complete support for on-orbit spacecraft operations.

The MIT/LL SPOCC Manager is responsible for all MIT/LL personnel and facility activities supporting operations of the Space-Based Visible instrument and is supported by the SPOCC team, which plans surveillance experiments and evaluates the performance of the instrument.

Experiment Execution

Although the MSX will be tasked with a variety of experiments, the mission was primarily designed to observe, from a space-based platform, target missiles and component reentry vehicles during the midcourse phase of ballistic flight. This concept is depicted in Fig. 4, which shows the MSX, target missile, and ground support network. The figure depicts typical target geometry during the encounter. Before the encounter, MSX command and tracking subsystems are preloaded from the APL Mission Control Center with time-tagged instructions for operating MSX sensors and supporting subsystems.

As with most experiments, MSX, as it approaches the anticipated target trajectory, maneuvers from its thermally and energy efficient parking orientation to the initial targeting point, awaits acquisition, and then tracks the target missile. Sensor data are collected and recorded onboard the spacecraft tape recorders during the observation, which lasts up to 40 min. MSX performance may be observed during the experiment through real-time communication to a local ground station, which relays data to the APL Mission Control Center. When the experiment is complete, the spacecraft returns to its quiescent parked mode to recharge and recool itself.

Later, when the spacecraft again passes over the APL site, the recorded data are downlinked, processed, and distributed to data processing centers.

REQUIREMENTS OF THE FLIGHT OPERATIONS SYSTEM

The design of the MSX Flight Operations System was driven by the proposed experiments and the characteristics of the spacecraft. It was developed in parallel with the spacecraft over a 4-year period to address requirements in three areas: experiment data acquisition, spacecraft command and control, and system reliability and adaptability. These requirements are shown in the boxed insert.

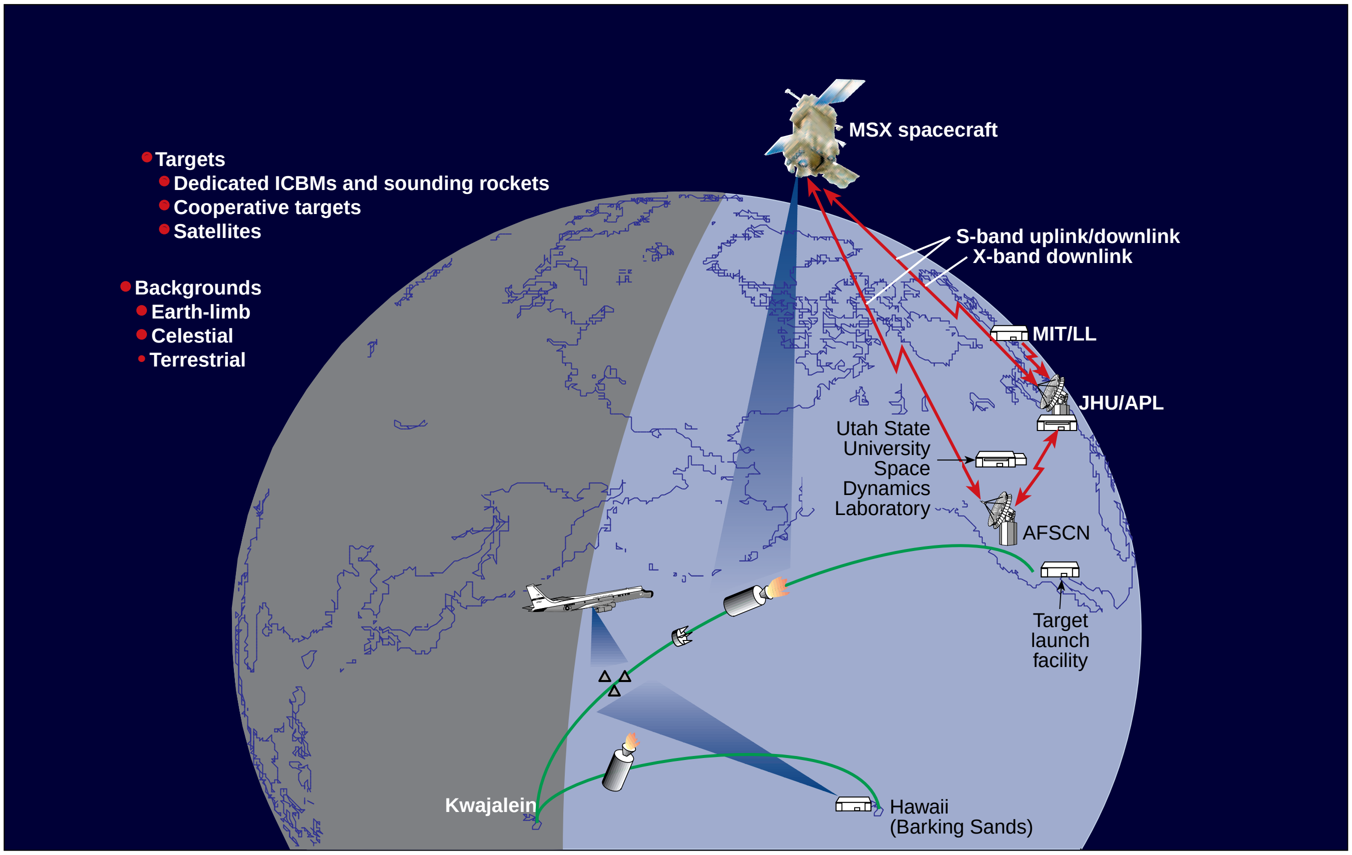

Figure 4. MSX mission concept. The primary goal of the MSX is to observe target missiles and reentry vehicles during the midcourse phase of ballistic flight. ICBMs = intercontinental ballistic missiles.

REQUIREMENTS OF THE MSX FLIGHT OPERATIONS SYSTEM

1. Experiment Data Acquisition Requirements
    - Support the science Principal Investigators by determining the feasibility of experiments.
    - Translate Principal Investigators' experiment plans into spacecraft and instrument configuration sequences for control of attitude, data recording, subsystem configuration, and instrument configuration during data collection events.
    - Schedule data collection events according to the Mission Planning Team's goals for monthly spacecraft use (about four science events per day).
    - Coordinate the use of ground systems that support scientific data collection (uplink of commands, downlink of data, and maintenance of spacecraft health).
    - Downlink and distribute scientific data.
    - Provide reconstructed spacecraft position and attitude data to the MSX scientific community.
2. Spacecraft Command and Control Requirements
    - Maintain ground-based knowledge of the spacecraft ephemeris, and maintain the onboard ephemeris.
    - Direct spacecraft operations via command links on a schedule sufficient to support science data collection and health maintenance.
    - Monitor spacecraft operations via the telemetry downlinks on a schedule sufficient to determine spacecraft health.
    - Manage spacecraft onboard clock correlation to Universal Time.
    - Maintain spacecraft health; detect, identify, and respond to anomalies.
    - Manage onboard power storage and dissipation, thermal loading, cryogen usage, tape recorder usage, spacecraft configuration, autonomy rules, macros, command memory, and attitude in accordance with spacecraft operating constraints; track short- and long-term performance measures.
    - Utilize the AFSCN through the SMC/TSC at Onizuka Air Force Base.
3. System Reliability and Adaptability Requirements
    - Design the Flight Operations System to reduce the probability of human error and to support the accumulation of experience via procedure, documentation, training, etc.
    - Provide flexibility in on-orbit procedures to allow for schedule changes, experiment changes, and single-point failures in the ground system or on the spacecraft.
    - Ensure that the health of the spacecraft will not be compromised by a failure in the Flight Operations System.
    - Ensure that operation of the spacecraft is consistent with required orbital safety procedures.
    - Provide for protection of spacecraft planning and scientific data up to the Secret level; screen data collection events in accordance with USSPACECOM Regulation 55-12.

FLIGHT OPERATIONS SYSTEM ARCHITECTURE

Requirements for the Flight Operations System are allocated into three major functional areas: planning, control, and assessment. Each area includes personnel, equipment and facilities, and processes. Figure 5 depicts the flow of operations, from long-range planning, to monthly planning, weekly planning, daily planning, contact control, data processing, and, finally, assessment.

Operations Planning

This function includes interfacing with the Mission Planning Team and other teams, analyzing the feasibility of proposed experiment plans, translating experiments into configuration sequences, identifying scheduling opportunities for data collection events, and scheduling events. Operations planning also entails generating command sequences for uplink, coordinating the use of ground system assets to support experiment data collection, and generating commands for updating the onboard clock for drift. The functions associated with managing onboard spacecraft resources and operating the spacecraft within its constraints are also allocated to operations planning. To plan future operations, predictions of the spacecraft's state (position, velocity, attitude, and configuration) must be made. Events are prescreened for compliance with USSPACECOM Regulation 55-12.

Planning functions for the MSX are divided among APL, SMC/TSC, and SPOCC. The TSC coordinates the use of AFSCN assets to support the satellite, provides orbital predictions to APL, and maintains the onboard ephemeris to the required accuracy. The SPOCC supports planning functions associated with surveillance experiments. APL performs all other planning functions for the MSX.

Operations Control

Operations control includes configuring the ground system to support MSX operations, command uplinking, and data downlinking. Ground controllers, under the on-shift direction of flight controllers, monitor the health and status of the spacecraft and respond immediately to anomalies that pose a risk to the spacecraft. Operations control clears space safety operations with the cognizant agency and must measure the drift of the onboard timing system relative to precise ground standards. Scientific data collected are evaluated for possible violation of USSPACECOM Regulation 55-12

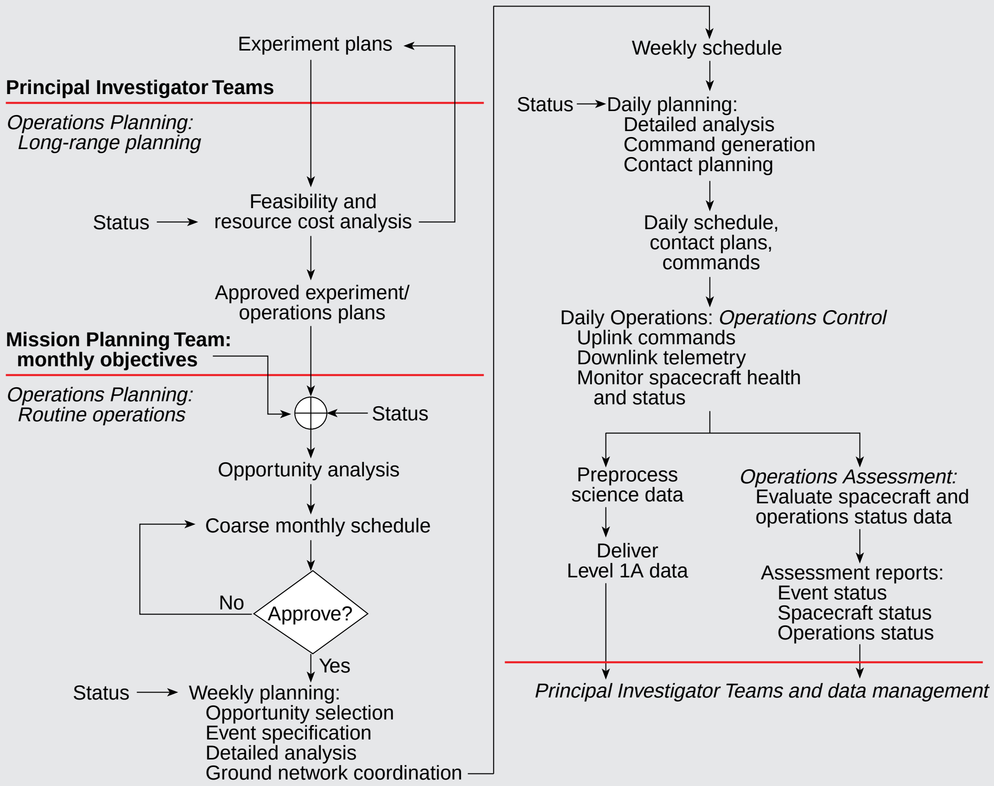

Figure 5. Flow of operations, showing various stages of planning as well as contact control, data processing, and assessment.

and excised if necessary. Telemetry data are divided according to subsystem and instrument and distributed to the data processing and archive centers.

Control functions for MSX are divided between APL and the SMC/TSC. The SMC/TSC configures the AFSCN sites for contacts with MSX and normally controls the spacecraft during those contacts; APL may also control MSX via an Air Force site in "bent-pipe" mode. All scientific data collection commands are uplinked from APL, and all scientific data are downlinked to APL. Data distribution functions are performed by APL.

Operations Assessment

Operations assessment includes evaluating the short- and long-term performance of MSX subsystems against expected performance, and evaluating the effectiveness of the Flight Operations System itself. Operations assessment also includes investigation of anomalies not fully explained during real-time operations.

Assessment functions for MSX are divided among APL and the other organizations that designed instruments for MSX. The APL assessment function provides trending and routine evaluations. When an anomaly occurs, other organizations are called in to assist in the investigation.

DEVELOPMENT AND TESTING OF THE FLIGHT OPERATIONS SYSTEM

The Flight Operations System consists of teams, facilities, and procedures. The system was developed by its users working together with software and hardware engineers, and it is distributed, with elements linked by secure data and voice networks. Many computer architectures and programming languages are employed. Where possible, commercial software is used in lieu of developing special-purpose programs.

Interfaces between the Flight Operations System and the external community are defined in a series of interface control drawings and a data-products document. These documents describe the physical, logical, and timing natures of all interactions. Procedures for the system are documented in (1) the *MSX Operational Constraints and Requirements Handbook*, (2) *Flight Operations Plans, Procedures, and Rules*, (3) the *MSX Operations Center Manual*, and (4) the *MSX Contingency Plan*. These documents, which were prepared by the Flight Operations Team, steer operations teams through daily and sporadic activities.

Testing was performed in three phases: (1) component testing within a facility, (2) system testing of all components within a single facility, and (3) system testing of all facilities, teams, and procedures. Because spacecraft and flight operations development, integration, and test proceeded in parallel, only subsets of the flight operations tests included interaction with the spacecraft.

System-level tests have demonstrated the following:

- Compatibility between the ground system and the spacecraft
- Proper command execution for typical data collection, maintenance, and downlink event sequences prepared by the Flight Operations Team
- The ability of the Flight Operations Team to respond to contingency situations
- Successful interchange of data products with mission planning, data, and scientific organizations
- Successful planning, control, and assessment under both early operations and routine on-orbit concepts of operations.

OPERATIONS PLANNING

Operations planning spans a range of activities, beginning with receipt of experiment plans and ending with delivery of schedules and command files to the control teams. The primary goal of operations planning is to maximize scientific data collection while maintaining the health, safety, and life of the spacecraft and its instruments. Key operations planning elements include MSX orbit propagation, detailed experiment analysis, spacecraft resource analysis and management, command sequence development, and ground network support planning.

The operations planning task is split into long-range planning and routine on-orbit planning, which take place concurrently and continuously throughout the MSX mission.

Long-Range Planning

Long-range planning is an iterative process that takes place between the Principal Investigator Teams and the MSX Operations Planning Team, as shown in Fig. 6. It is typically conducted before launch, but it can also occur throughout the mission as new experiment plans are developed or old ones are revised. Principal Investigator Teams develop written experiment plans that detail the scientific data to be collected using MSX. The plans state the objectives of the experiment and include requirements for spacecraft pointing (e.g., viewing geometry, lighting conditions, and pointing accuracy), instrument configuration, formats and duration of data recording, ground network support, and any scheduling requirements or dependencies.

When an experiment plan is received, the Operations Planning Team conducts a feasibility analysis. First, the plan is examined from the operations perspective, and potential problems are identified to the originating Principal Investigator Team. Next, a

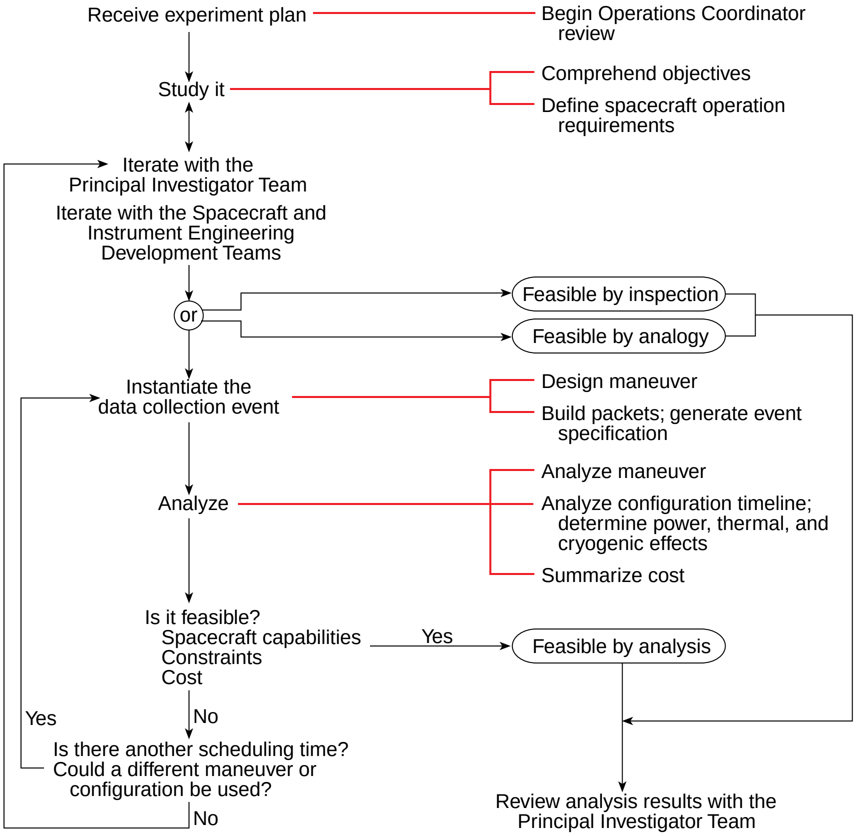

Figure 6. Process used for feasibility and resource cost analysis in long-range MSX operations planning. This type of planning is an iterative process that takes place between the Principal Investigator Teams and the MSX Operations Planning Team. When an experiment is acceptable to both the originating Principal Investigator Team and the Operations Planning Team, it is deemed feasible and placed in the queue for selection by the Mission Planning Team.

representative spacecraft configuration sequence is developed in the form of an event specification that satisfies the requirements of the experiment plan. This command sequence is then used as input to various planning models and analytical tools. The outputs of the planning models and tools, which represent the predicted effects of a given event specification, are analyzed in detail to determine the adequacy of the predicted pointing, the spacecraft power and thermal effects, and the impact of the experiment on the cryogen cooling system of the Spatial Infrared Imaging Telescope III. The event specification and its modeled effects are also examined to ensure that spacecraft operational constraints and rules have not been violated.

The results of this analysis are communicated to the Principal Investigator Team, and the experiment plan is revised as necessary. When an experiment plan is acceptable to both the Principal Investigator Team and the Operations Planning Team, it is deemed feasible and placed in the queue for selection by the Mission Planning Team when establishing monthly objectives.

Routine On-Orbit Planning

This task begins after launch of the MSX and completion of initial, early, on-orbit checkout operations. Routine on-orbit planning has three phases: monthly planning, weekly planning, and daily planning. These phases are conducted continuously and simultaneously in a hierarchial manner. The hierarchy is based on planning concepts developed for the Hubble Space Telescope,[1] which shares many of the challenges associated with a large, multifunctional, multiple-user observatory.

The monthly planning phase results in a "monthly" 28-day schedule of MSX activities. The weekly phase refines the monthly schedule, 7 days at a time, using better orbit predictions, and produces unique event specifications for each experiment to be conducted during the week. Daily planning produces, from the weekly schedule, the next day's final command sequences, schedules, and ground support plans. The hierarchy is shown in Fig. 7.

To some extent, several key functions must be repeatedly conducted to take into account improved knowledge of spacecraft position, target visibility, and ground station availability as the experiment approaches. These functions, which are common to all three phases of planning, include MSX orbit propagation based on the latest measured spacecraft position, detailed experiment analysis (e.g., pointing, power, thermal balance, cryogen usage, constraints/rules adherence) based on the latest orbit predictions and schedule refinements, and analysis and management of expendable resources (i.e., the battery, tape recorder, and cryogen cooling system).

Monthly planning begins 6 weeks before the start of the month being planned. The 4-week monthly planning process begins with the receipt of monthly objectives from the BMDO-led Mission Planning Team. The monthly objectives are effectively a prioritized "shopping list" of experiments to be conducted during the month being planned. Using these objectives and the event specifications of feasible experiments as input, the Operations Planning Team develops a 28-day schedule with an average of four or five experiments per

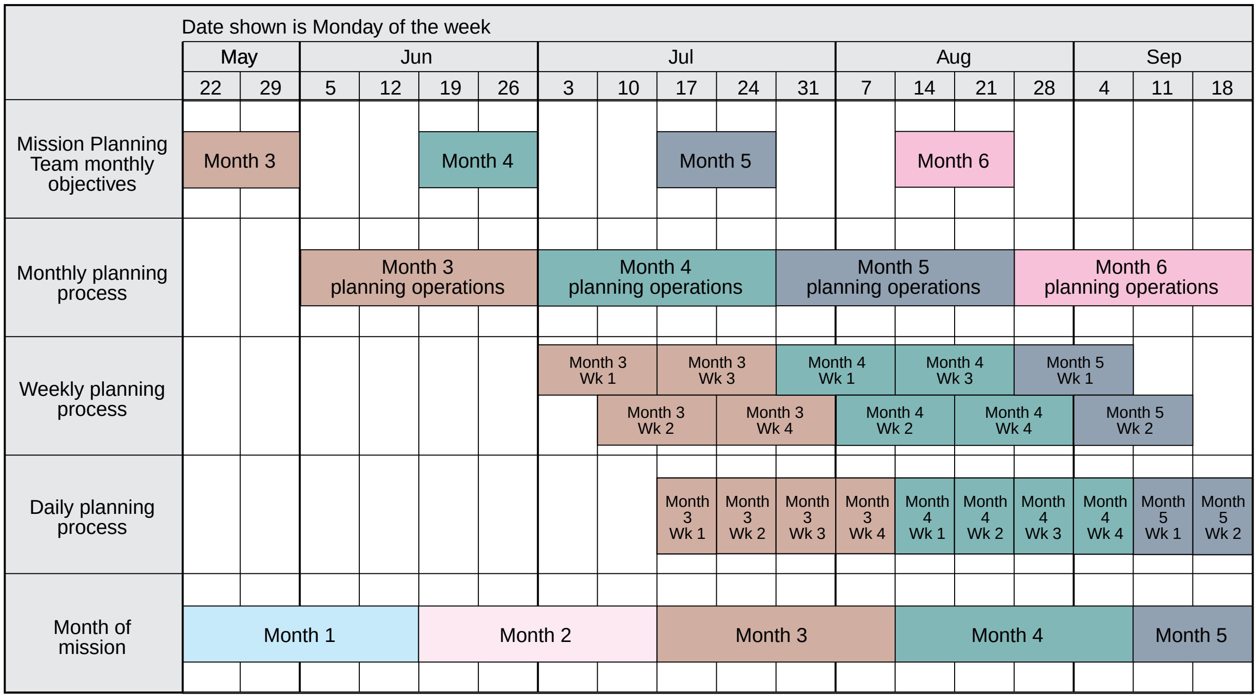

Figure 7. Hierarchy of routine on-orbit operations planning, showing simultaneous monthly, weekly, and daily planning. This type of planning is performed concurrently with long-range planning (Fig. 6) throughout the MSX mission.

day, each scheduled within a several-hour time window. To develop the schedule, the team balances experiment opportunities with spacecraft resources.

Weekly planning for the first week of the month begins at the conclusion of monthly planning, i.e., 2 weeks before the start of the week being planned. The 2-week weekly planning process begins with the development of specific scheduling opportunities for each experiment within the monthly schedule's time windows. A weekly schedule is developed from these opportunities, with each experiment scheduled to the nearest second. The weekly schedule is then checked to ensure that spacecraft resource "costs" are acceptable. For each experiment scheduled, an event specification is produced from the representative sequence developed during long-range planning. Each event specification is then analyzed by one analyst and double-checked by another prior to daily planning.

Daily planning is conducted the day before the experiment. Using spacecraft ranging data and orbit propagators, the SMC/TSC Orbit Analyst Team provides state vectors for use by the SMC/TSC Planner/Analyst Team to upload to the spacecraft. Each experiment is analyzed one last time by the Operations Planning Team. The planned data collection and maneuver sequences are screened for compliance with USSPACECOM Regulation 55-12 and, generally, predicted violations are "blinked," i.e., data collection for offending instruments is temporarily disabled. The SMC/TSC Planner/Analyst Team requests and confirms the use of AFSCN contacts. In addition, routine and special spacecraft health activities, including onboard clock management, are scheduled by both the SMC/TSC Planner/Analyst Team and the Operations Planning Team. Ground activities for command uplink and data downlink are planned by the Operations Planning Team for APL contacts and by the Planner/Analyst Team for SMC/TSC contacts. Finally, command sequence files based on event specifications and ground activities scripts are generated by the Operations Planning Team and provided to the control teams, along with a daily schedule of activities, for execution.

Early Operations Planning

This period of activities begins immediately after launch and lasts for several weeks. It is characterized by initial spacecraft and instrument checkout operations. Unlike the scientific experiments conducted during routine operations, checkout operations are typically conducted when the spacecraft is in contact with the ground so that the operations can be monitored by spacecraft/instrument designers in real time. An 8-week schedule of Early Operations spacecraft activities is developed by the Operations Planning Team before launch. The schedule for the first 7 days on-orbit is generated on a progressive ground contact basis, i.e., spacecraft activities are scheduled for the "next available contact" rather than at an absolute time. This schedule allows the early schedule to remain flexible with respect to launch delays and ground network support schedules. The second 7 days on-orbit are planned on a "day-by-day" basis using the prelaunch 8-week schedule as a template while accounting for any spillover operations from the first 7 days. The prelaunch 8-week schedule is also used as the basis for weekly planning that commences at launch; it allows the transition into routine on-orbit operations planning following the initial 14-day checkout period.

Unique Aspects of Surveillance Experiment Planning

One of the missions of the MSX spacecraft is to demonstrate the feasibility of space-based space surveillance operations. Most MSX experiments are amenable to the hierarchial routine planning process discussed earlier, either because their targets are changing slowly, as with naturally occurring Earth-limb and deep space backgrounds, or because they are under the control of the experimenter, as with dedicated missile launches. Surveillance experiments, however, can require fundamental changes late in the planning process (during daily planning), because space surveillance sensors are typically tasked on a day-at-a-time basis or are required to observe low-altitude satellites, whose ephemeris accuracy is inadequate for long-term planning.

To solve this problem, the MIT/LL SPOCC has been tasked with planning the space surveillance experiments. The SPOCC was selected because it has the expertise and facilities to generate detailed surveillance command sequences at the last minute. As part of routine operations planning, the APL Operations Planning Team allocates scheduling windows and spacecraft resources to the SPOCC. The team then ensures that all surveillance experiments adhere to these scheduling limits as well as to the other spacecraft operational rules and constraints. The details of the process are discussed in Ref. 2.

Operations Planning Staff and Facilities

MSX operations planning is conducted by 15 full-time staff members working in the APL Operations Planning Center. Auxiliary planning equipment is located in the Satellite Control Facility. Remote workstations, designated Operations Planning Center West, are also located at the TSC for use by the TSC Planner/Analyst Team.

Operations Planning Center system hardware consists of a network of 22 DEC workstations and terminals with peripherals to support mass data storage and hard copy output. The OPC system software runs under the Ultrix operating system and includes application software developed primarily in Fortran and C, the Ingres database system, and several commercial packages used to support display generation, data analysis, and word processing. The primary application tools include software to perform orbit propagation, maneuver analysis, power and thermal analysis, scheduling, contact planning, command generation, and spacecraft rule and constraint adherence.

OPERATIONS CONTROL

Overview

Two operations control teams, the Operations Control Team at APL and the SMC/TSC Control Point Team, interface directly with the MSX spacecraft as it passes over ground tracking stations. These teams are responsible for issuing prepared spacecraft command sequences; processing, displaying, and monitoring recovered state-of-health telemetry data; and providing real-time performance assessment of spacecraft subsystems. In addition, downlinked scientific data are preprocessed.

The facilities that support these activities include (1) the APL Operations Control Center, and (2) the Mission Control Center Computer Control System, which is located at the SMC/TSC and interconnected to a worldwide network of AFSCN Remote Tracking Stations. These two centers are linked by high-bandwidth communications circuits that convey spacecraft command messages and telemetry data, planning data files, secure voice, and fax. Signal interfaces to the spacecraft include a 2-kbps command uplink and 16-kbps and 1-Mbps telemetry downlink channels (APL and SMC/TSC), and a 25-Mbps telemetry downlink channel (APL only). All data recovered by the SMC/TSC are forwarded to the APL Operations Control Center. A "bent-pipe" command link may be implemented to provide a means of commanding the spacecraft directly from APL as MSX passes over an AFSCN station.

These control centers operate somewhat independently of each other, and each is allocated specific tasks related to spacecraft operations. The APL Operations Control Center prepares for and manages all APL contacts, uplinks time-tagged experiment data collection and scientific data downlink command sequences for later execution, and recovers scientific data downlinked from the spacecraft at 1 Mbps and 25 Mbps. The SMC/TSC has primary responsibility for planning and supporting AFSCN contacts that are used to schedule and collect ranging data from which to measure the MSX orbit, predict future state vectors, and maintain up-to-date spacecraft onboard ephemeris. Both centers monitor spacecraft state-of-health and provide a real-time assessment function based on the 16-kbps housekeeping telemetry. Both centers respond to anomalous conditions identified by out-of-tolerance telemetry measurements. This separation of operational responsibilities minimizes interfaces between the two centers. Either can maintain a "healthy" spacecraft on its own; however, experiments can be conducted only when both centers are operational.

Contact Operations

A typical contact operation (i.e., an operation that occurs during a pass over a scheduled ground station) begins with a prepass test to assure readiness for the upcoming operation. The spacecraft is programmed by the delayed commands generated by the Operations Planning Team to turn on its telemetry transmitter just before the scheduled ground station contact. When the ground station observes the downlinked telemetry, the MSX state-of-health is quickly assessed, and, if favorable, a predetermined contact plan, defined within a stored ground procedure prepared by the planning teams, is executed. This procedure prompts the operational staff throughout the contact as command messages are uplinked and data are recovered.

Spacecraft performance is continuously monitored, and if an anomaly is detected, a contingency procedure is initiated. Such contingency procedures are predefined spacecraft command sequences. Although only one control center is designated as primary for a particular contact operation, both receive and monitor state-of-health data, communicating status over the dedicated voice network. Once the real-time contact operation is complete, postpass processing occurs to compute the satellite clock offset, forward telemetry data to the Performance Assessment Center, and archive files.

Control Center Configurations

The APL Operations Control Center is configured into functional segments that perform commanding and telemetry acquisition, processing and display of state-of-health, and preprocessing and distribution of scientific data. This center receives, from the Operations Planning Team, daily schedules of planned spacecraft events, contact plans (a stepwise script of ground system activities throughout a planned contact), and files of spacecraft commands to be uplinked.

The MSX Tracking System is the interface between the spacecraft and APL Mission Control Center. The 10-m antenna, together with transmitters, receivers, demodulators, and antenna tracking control subsystems, is capable of commanding the spacecraft and recovering all downlinked spacecraft data, including the 25-Mbps science data. The MSX Tracking System, when furnished with the orbit predictions, automatically schedules and provides the control to acquire and track overhead spacecraft passes. A 5-m backup antenna system with associated telemetry recovery capability is also available. Although a command uplink backup is not available at the APL station, a nearby AFSCN station can be scheduled to provide this function if necessary.

The APL Mission Control Center provides on-line communication to the spacecraft. Spacecraft commanding and the processing and display of 16-kbps state-of-health data occur here. In addition, spacecraft onboard clock accuracy is measured, and offset and drift measurements are forwarded to the Operations Planning Center, where correction commands are produced. The Mission Control Center includes a VAX computer cluster, which consists of dual DEC 3400 servers and a network of 13 DEC 3100 VAXstations, utilizing a Virtual Memory System (VMS) operating with X-Windows. The VAXstation cluster is configured to provide a single uplink command station, and the remaining VAXstations are assigned to function as monitors of on-line state-of-health data by the Operations Control Team and Spacecraft Engineering Teams. Alarm messages are produced when telemetry measurements are determined to violate normal operational values. Also located within the Mission Control Center is the Attitude Processing Center, where MSX attitude subsystem data are processed and analyzed to produce performance status reports, definitive attitude, and sensor alignment files.

The Mission Processing Center receives and preprocesses the 25-Mbps and 1-Mbps scientific data to produce data products for distribution to the data processing and archive community. Data received throughout a day (perhaps 4 to 6 gigabytes altogether) are initially stored on tape, transferred to a computer database, and processed a day later. Processing by this VAX-based, multiple computer system configuration operating under VMS includes storage of raw data on a disk farm network, sorting of data by experiment in time order, and separation by MSX instrument. Before storing the data on 8-mm tape cartridges, designated as L1A tapes, the data are screened for compliance with USSPACECOM Regulation 55-12, and data in violation are excised. Other data stored on L1A tapes include MSX state-of-health, definitive attitude, sensor alignment, and clock correction data. These tapes are distributed to the instrument data processing centers and, accompanied by a composite unsorted L1 data tape, to archive centers. The Mission Processing Center also recovers 1-Mbps engineering data downlinked by the Space-Based Visible instrument and forwards it, in near real-time, to the SPOCC.

The Operations Control Center also includes a secure electronic data network server to manage intercenter Ethernet transfers and to interchange data with other flight operations system components located at the SMC/TSC and SPOCC.

The SMC/TSC control center is composed of a Central Computer System, which hosts the command and telemetry parameter databases, on-line command executive and telemetry processing and display software, and interfaces to the AFSCN Remote Tracking Station network. A local area network, populated by workstations and personal computers, is connected to the Central Computer System. These terminal nodes are used to support off-line command message preparation and spacecraft health and status analysis.

Control Teams

The Operations Control Center is staffed continuously (24 hours/day, 7 days/week) by 15 full-time staff members consisting of ground controllers, Mission Processing Center operators, RF/antenna operators, and maintenance engineers. This team is scheduled to provide a four-staff-member level of support when the MSX passes over the APL station for commanding of the spacecraft. When the MSX passes over the AFSCN stations and SMC/TSC becomes the primary control station, the APL control team monitors only spacecraft health and status, and team size is reduced to three. The team is led by a five-member team of flight controllers, who also provide continuous support.

The flight controller is the central point-of-contact for the entire real-time Flight Operations Team and is primarily responsible for spacecraft real-time performance assessment and the management of contingency operations. Flight controllers obtain clearance for instrument aperture cover release and calibration reference object deployment from the cognizant space safety agency. The ground controller is responsible for the configuration of the ground control system, for spacecraft command uplink, and for state-of-health monitoring. The Mission Processing System operator preprocesses the MSX science data. The MSX Tracking System operator manages antenna tracking and signal processing. The maintenance engineer is responsible for the readiness of the overall control system. This control team maintains voice communications with the Control Point Team located at the SMC/TSC.

Staffing of the SMC/TSC control team includes a real-time analyst to verify general conformance to the contact plan, including command execution verification and spacecraft command memory management, a mission controller to uplink command messages and monitor spacecraft state-of-health telemetry, and a ground controller to specify and manage the configuration of the ground support network.

The goal of the control teams is to maintain an operational spacecraft at all times. When anomalies are detected, real-time assessment is made, and, when possible, contingency command sequences are immediately uploaded to correct the anomaly. If such a simple solution is not practical, the spacecraft is commanded to the benign "safe" mode, and the Operations and Spacecraft Performance Assessment Team conducts further troubleshooting.

PERFORMANCE ASSESSMENT

Overview

The Operations and Spacecraft Performance Assessment Team (OSPAT) is primarily responsible for analyzing and evaluating the performance of the MSX spacecraft and the APL MSX Flight Operations System. The facility used for these functions is the Performance Assessment Center. The core team is staffed by three spacecraft specialists, who provide the spacecraft knowledge-base to the Flight Operations Team. An extension of the team includes control teams at APL and SMC/TSC for real-time assessment, and various members of the spacecraft and instrument engineering design teams with expertise in MSX subsystems and instruments. The engineering teams only participate during periods of anomalous spacecraft behavior, when they provide technical support for problem identification and resolution.

The OSPAT and Performance Assessment Center must interface with many teams and facilities, as shown in Fig. 8. Spacecraft state-of-health data, obtained during real-time station contacts and from playbacks of the spacecraft tape recorder, are forwarded to the Performance Assessment Center. There, the data are used to analyze spacecraft health and status and the status of scientific-data collection experiments. Instrument health and status data, contained in the 25-Mbps prime science data, are processed and analyzed by the instrument data processing centers and performance assessment teams. Status reports are produced and forwarded to the OSPAT, and the information is then incorporated into MSX status reports. When instrument anomalies are uncovered, the OSPAT is advised, and analysis and recovery activities are initiated.

The OSPAT carries out assessments and is responsible for routine analysis and reporting in three areas: events, spacecraft performance, and operations performance.

Event Assessment

The objective of event assessment is to determine whether each spacecraft data collection event executed as planned and to within specifications. An event assessment report is produced for every data collection event.

Event assessment includes the following:

- *Command Verification.* Creation of an "as flown" command sequence for comparison with the planned sequence

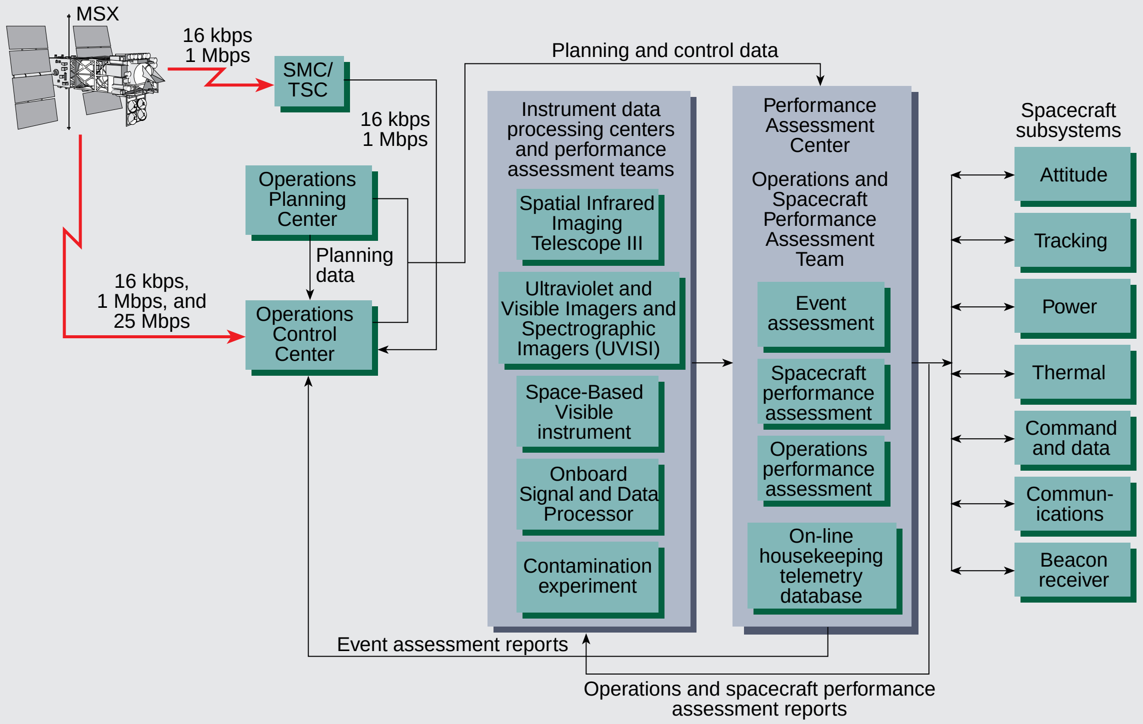

Figure 8. Data flow diagram for the Performance Assessment Center, where performance of the spacecraft and of the APL MSX Flight Operations System is analyzed and evaluated.

- *Pointing Assessment*. Comparison of predicted and actual pointing maneuvers
- *Model Assessment*. Comparison of predicted power minimum, maximum, and average with actual data recorded during the event
- *State-of-Health Evaluation*. Alarm and limit checking of the housekeeping telemetry recorded during the event
- *Anomaly Reporting*. Description of anomalous behavior observed during off-line assessment of the event.

Event assessment begins when the Performance Assessment Center determines that all planning products and housekeeping telemetry data for the data collection event have been received and stored in its database. Actual ("as-run") command execution, onboard MSX, is determined by performing functional verification of time-tagged command execution. Such verification is achieved by monitoring the housekeeping telemetry to verify that the command sequence had the desired effect. When there is no telemetry from the period of command execution, the command history information, as received in housekeeping telemetry, is used to verify that the command was at least properly executed by the command processor. Event assessment also includes evaluation of the MSX's pointing performance as the satellite views designated targets by comparing planned and actual pointing scenarios. All spacecraft telemetry is checked against expected performance criteria.

Event assessment of surveillance experiments is performed by the SPOCC using science data obtained from downlinked 1-Mbps data.

Spacecraft Performance Assessment

The goal of this function is to predict degradation of spacecraft performance and/or failures by performing short- and long-term trending. By repeatedly observing MSX engineering data, trends can be detected and analyzed for performance impact on the spacecraft system. Adjustments can then be implemented to improve operational efficiency and perhaps to extend the life of the spacecraft itself. Often the way in which the spacecraft is operated must be altered. If so, the Opertaions Planning and Control Teams are advised, and experiment and contact plans are adjusted accordingly. The OSPAT is also responsible for the off-line investigation of MSX anomalies and rapid development of corrective measures.

The Performance Assessment Center is designed to automatically generate spacecraft and operations performance assessment reports, including encapsulated PostScript plots of data for recipients with PostScript printers. Reports may include free-form text that describes anomalies, changes in the configuration of the spacecraft or ground system, or operational changes.

The OSPAT is responsible for directing anomaly investigations and implementing recovery procedures.

To assist in these investigations, the team has access to tools developed at the Performance Assessment Center. These tools translate command history, command memory, and autonomy memory while allowing for ad hoc plotting of various telemetry parameters specified in the Performance Assessment Center housekeeping database.

Operations Performance Assessment

This function is an attempt to "close the loop" between the APL Operations Planning, Operations Control, and Performance Assessment Teams in order to increase the efficiency of the Flight Operations System and maximize scientific data output from the spacecraft. The spacecraft has an operational lifetime of 4 to 5 years and was designed for a particular scientific data collection duty cycle. This duty cycle is examined and trended to allow for a high-level assessment of the Flight Operation System's performance. A less than nominal duty cycle implies possible deficiencies in the system and prompts an investigation. Adjustments are then made to restore scientific data collection to optimum levels. Other responsibilities of the team include:

- Definition and generation of MSX onboard autonomy rules and associated actions used in detecting anomalous conditions, preventing potentially perilous situations, and recovery from such conditions
- Development of spacecraft contingency procedures as required for use during real-time contact with MSX
- Support of Operations Planning Center functions, including maintenance of command packets, usage rules, locked (critical) command lists, simulation models, and the spacecraft operational constraints handbook
- Determination of methods of configuring the spacecraft so it will perform in accordance with the requirements defined in the experiment plans.

Performance Assessment Center Capabilities

This facility consists of two open, VMS-based, DEC Alpha workstations, one DEC VAX 3100 workstation, and a network of disks and printers. The Performance Assessment Center is connected to a secure Ethernet network, which provides a gateway to the Operations Control Center, Operations Planning Center, and the secure external network. A connection to the Internet is also available through an off-line, stand-alone workstation, which provides a means of transferring unclassified data to users. A large (18-Gbyte) disk array stores up to two months of on-line spacecraft health and status data and, in addition, a "critical" subset of this data throughout the entire mission. The Center uses an Oracle database and custom-developed and commercial data processing packages. This system can produce a wide assortment of data products in both numeric and graphic form, and it serves as a convenient data analysis tool for spacecraft performance evaluation, especially in resolving anomalies.

The OSPAT is minimally and noncontinuously staffed, so the design of the Performance Assessment Center system emphasizes unattended operation. Data products of other teams and facilities are networked, and portions are extracted and stored in the Performance Assessment Center database for future retrieval. All spacecraft health and status telemetry obtained during real-time station contacts, as well as that recovered from spacecraft tape recorder playbacks, is processed and stored in the database. The data are retrieved, selectively plotted, and distributed. The Performance Assessment Center produces routine plots of predefined telemetry, annotated with alarm limits, weekly and throughout the day. The plots are sent out automatically and analyzed by the OSPAT.

SUMMARY

A Flight Operations System, composed of the newly developed MSX Operations Center at APL and existing Air Force facilities, provides a worldwide ground support network for planning, scheduling, and conducting on-orbit experiments. The system also provides recovery of scientific and engineering data, and monitoring and control of spacecraft health. Experiment plans, developed by Principal Investigators and approved and prioritized for execution by the BMDO-sponsored Mission Planning Team, are analyzed and scheduled by the APL Operations Planning Team. Before experiment execution, time-dependent spacecraft and instrument command sequences are uploaded to the MSX for execution; monitoring and data recovery are performed by the Operations Control Team; and overall MSX health and status are monitored by APL and Air Force control teams. Assessment of the MSX and its ground-based support network is performed by the OSPAT.

These teams, supported by the facilities and procedures of the ground network, provide continuous, round-the-clock operational support to meet the needs of the BMDO and its supporting teams.

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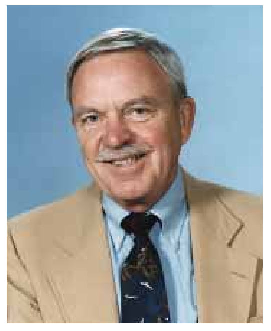

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