MIDCOURSE SPACE EXPERIMENT:
SPACECRAFT OPERATIONS PLANNING AND EXECUTION

A. C. Good, H. W. Kim, J. H. Polaha, and R. D. Reinders

ABSTRACT

The constraints of the Midcourse Space Experiment (MSX) spacecraft which affect thermal and power management, finite onboard recording capabilities, and limited downlink opportunities establish significant bounds under which spacecraft operations and telemetering systems must operate. This paper reviews the MSX mission and data collection planning processes, commanding and execution procedures, data telemetering processes, and the overall impact of spacecraft constraints and downlink nodes to data collection and downlink activities.

INTRODUCTION

The Midcourse Space Experiment (MSX) is a mission sponsored by the Ballistic Missile Defense Organization (BMDO). A primary purpose of the MSX mission is to collect and analyze target and background phenomenology data to address BMDO midcourse sensor requirements. This data will be collected using fully characterized and calibrated onboard sensors which perform optical measurements from the far ultraviolet to the very longwave infrared wavelengths. The MSX mission consists of an interleaved set of experiments using MSX sensors and other supporting sensors. MSX will be launched into a near-polar, 900 km, nearly sun-synchronous orbit from Vandenberg Air Force Base. The overall mission is planned for a four to five year lifetime following launch. The portion of the mission which collects longwave infrared data is expected to consist of the first one to two years since the infrared sensor as a shorter lifetime than the rest of the spacecraft and sensors.

The MSX spacecraft, Figure 1, consists of the spacecraft structure and various support subsystems which provide power, thermal control, command and data handling, RF communication, target tracking, and attitude determination and control. The axes of the optical sensors [space infrared imaging telescope (SPIRIT III), ultraviolet and visible imagers and spectrographic imagers (UVISI), and space-based visible (SBV)] are parallel to one another and point along the spacecraft's +X axis; therefore, pointing any of the optical sensors is accomplished by maneuvering the spacecraft's +X axis. SPIRIT III is a passive mid- to very long-wavelength infrared sensor consisting of a telescope, a six-channel interferometer, a six-band radiometer, and a cryogenic Dewar and heat exchanger. UVISI consists of four imagers and five spectrographic imagers covering a spectral range from the far UV to the near infrared. UVISI also includes an image-processing system for use in tracking targets and aurora. SBV is a visible off-axis, all-reflective reimaging telescope with a thermo-electrically cooled CCD focal-plane array. SBV includes an image-processing system and a temporary data storage buffer for use in surveillance experiments. MSX also contains a suite of sensors for use in measuring the spacecraft's contamination environment, an onboard signal and data processor (OSDP), and a beacon receiver for use in target tracking experiments.

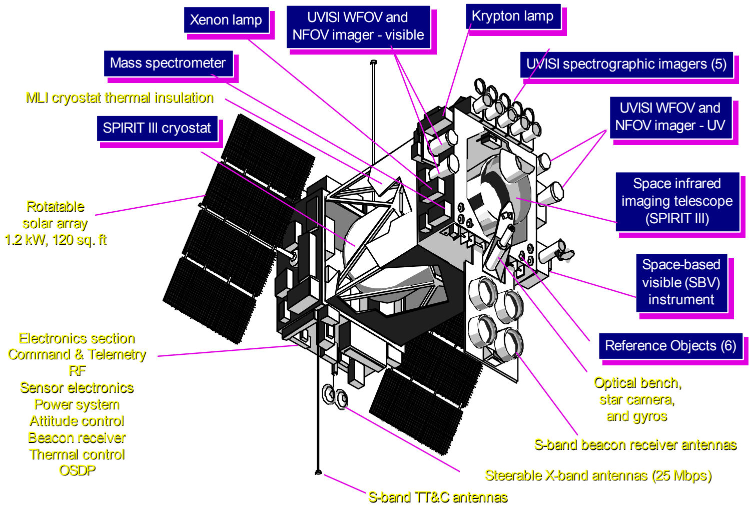

Figure 1. MSX Spacecraft Configuration

Four information channels control spacecraft configuration and recover science data. An uplink channel sends command messages at 2 kbps. Downlink channels return state-of-health data, wideband science data, and prime science data at 16 kbps, 1 Mbps, and 25 Mbps, respectively. Depending upon experiment requirements, the onboard prime science recording rate is selectable at either 5 Mbps or 25 Mbps using a variety of data formats.

The MSX flight operations system has been segmented into three functional areas: planning, control, and assessment. The operations planning system is responsible for orbit analysis, scheduling, resource management, command sequence generation, and interfacing with experiment teams. The operations control system is responsible for uplinking commands, downlinking, processing, and distributing data, monitoring health and status, and responding to contingency situations. The operations and spacecraft performance assessment system is responsible for assessing the performance of both the spacecraft and the ground operations systems. The flight operations network consists of the Mission Operations Center (MOC) at the Johns Hopkins University Applied Physics

Laboratory (APL), the SBV Processing, Operations and Control Center (SPOCC) at the Massachusetts Institute of Technology Lincoln Laboratory (LL), and access to the Air Force Satellite Control Network (AFSCN) via the USAF Space and Missiles Center Test Support Complex (TSC).

MISSION GOALS FOR DATA COLLECTION

Collection of science data to fulfill mission requirements has been segmented into eight separate "phenomenology based" experiment classes which are: earthlimb and aurora backgrounds (EL), celestial backgrounds (CB), shortwave terrestrial backgrounds (ST), contamination (CE), surveillance (SU), data certification and technology transfer (DC), theater midcourse targets (TM), and early midcourse targets (EM). The onboard collection of science data associated with a specific experiment plan is termed a "data collection event" (DCE). Table 1 summarizes the number of experiments and DCEs tentatively planned for conduct on MSX during the first 16 months. On average, four to five DCEs are conducted each day totaling approximately 6-8 gbytes of data per day.

Table 1
Tentative MSX Experiments and Data Collection Events During First 16 Months

	EL	CB	ST	CE	SU	DC	TM	EM	Total
No. of Experiments	17	8	5	13	11	47	4	6	111
No. of DCEs	431	397	27	209	102	861	11	92	2130

CONSTRAINTS AFFECTING EXPERIMENT DATA COLLECTION

Several internal and external constraints affect the collection of science data onboard the MSX spacecraft. The spacecraft, including all subsystems and sensors, must be properly maintained to fulfill its mission life expectancy. Also, the surrounding space environmental conditions, such as the sun, impose constraints on the spacecraft that affect the amount and quality of science data that can be collected. The flight operations team verifies that these constraints are not violated, unless planned.

Two solar cell arrays provide the primary source of electrical power onboard the spacecraft. One 50 A-h rechargeable Nickel Hydrogen battery provides secondary power during eclipses or periods when additional power loads are placed on the spacecraft. Due to the physical characteristics of the battery, the extent of battery depth-of-discharge (DoD) - percentage of power consumed - must be monitored and controlled to maintain optimal performance levels. Large and frequent occurrences of battery DoD will significantly degrade the performance and life of the battery; therefore, battery DoD is limited to 40%. For special target DCEs, DoD is permitted to reach as low as 70%.

The spacecraft utilizes internal (e.g., heaters) and/or external heat sources (e.g., sun, earth, etc.), or lack thereof, to maintain thermal equilibrium. Certain actions can exceed the equilibrium beyond the control of the spacecraft; therefore, care must be taken in the planning of DCEs to avoid temperature extremes. Long recovery times may impact the execution of subsequent DCEs. Several sensors and subsystems have thermal constraints that must be enforced to prevent severe data degradation and/or equipment damage. For example, the SPIRIT III baffle must be maintained below 70 K to properly collect data and below 40 K, on average, to minimize excessive cryogen use. If the baffle temperature exceeds 140 K, permanent degradation of the primary mirror is likely.

There are two redundant tape recorders onboard the spacecraft which serve as the primary devices for recording science data. The data capacity of each tape is 54 Gbits which is equivalent to 180 minutes at 5 Mbps or 36 minutes at 25 Mbps. The data format is Last In First Out (LIFO). The tape recorders are recorded until full and played back until empty to maintain uniform wear on the tape media. The tape recorder is limited to continuous recording of 36 minutes in 25 Mbps mode or 60 minutes in 5 Mbps mode per tape recorder. Continuous playback (25 Mbps) is limited to 13 minutes due to tape head temperature.

The sun is a high intensity light source and can degrade or even damage any of the sensors if they are pointed directly toward it. The moon and earth are moderate light sources and would only degrade or damage the sensors if viewed with improper settings. The onboard Attitude Processor (AP) implements keep-out-zone (KOZ) avoidance logic for the sun and earth to prevent the field-of-view (FOV) of the sensors from slewing in front of the sun and earth unexpectedly during maneuver transitions.

The South Atlantic Anomaly (SAA) is a depression in the magnetic field centered off the coast of Brazil and occupies approximately half of the southern hemisphere. Many DCEs execute outside the SAA to avoid possible interference and damaging effects on the spacecraft and sensors. Spacecraft pointing toward the velocity vector causes space particles and contaminates to impinge on the surface of the sensor apertures and degrade their performance; therefore, pointing is restricted within 25° of the velocity vector for an extended amount of time.

OPERATIONS PLANNING PROCESS

Operations planning is accomplished in four stages: long range planning, monthly planning, weekly planning, and daily planning (Figure 2). Each of these phases occurs simultaneously and continuously. DCE analysis functions are fundamentally the same during each planning phase; however, the timelines and emphasis vary as event execution approaches.

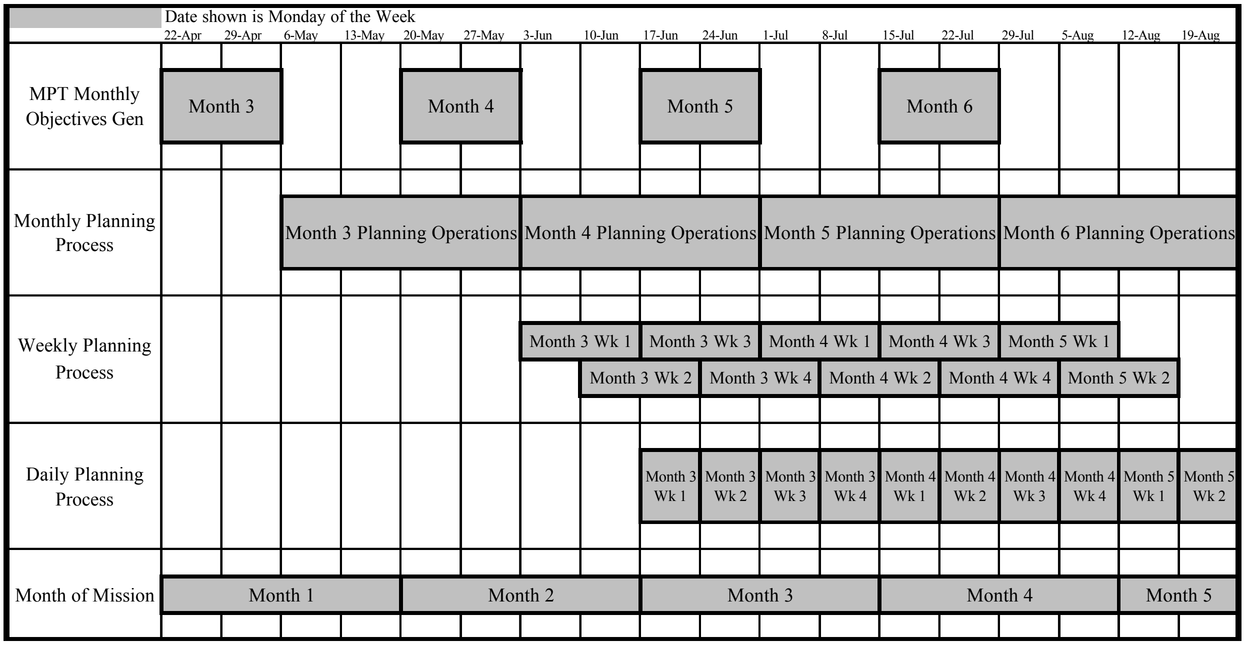

Figure 2. MSX Monthly, Weekly and Daily Planning Timelines

Long-range planning is the phase where the feasibility of each experiment is determined. Feasibility analysis is the evaluation of a proposed experiment using a representative set of spacecraft commands to determine whether or not the experiment can be supported by the MSX system, taking into account the spacecraft and ground support network capabilities and constraints. Monthly planning commences every four weeks when a BMDO-led Mission Planning Team (MPT) evaluates experiments that have been declared feasible and generates a set of monthly objectives, which are transmitted to the APL Operations Planning Center (OPC). Four weeks of planning are required to plan a month (28 days) of spacecraft activity. The monthly planning process ends with the distribution of a monthly schedule which is delivered two weeks prior to the start of the month being planned.

Weekly planning begins two weeks before the start of the week being planned. Orbit propagation and analysis are performed, and the orbit analysis files are used to support analysis of all scheduled DCEs. The OPC performs this event analysis to ensure that all DCEs remain within their allocated resource "cost budget" (e.g., battery DoD, SPIRIT III baffle temperature), and to ensure that changes in the DCE execution time (T-zero), since monthly planning, are within acceptable limits. The weekly planning process ends with the distribution of a weekly schedule.

Orbit propagation and analysis are performed again at the start of each daily planning day to provide the latest orbit geometry data available in support of final DCE analysis and for planning of the day's ground station contacts and science data downlink events. The OPC also plans, schedules and analyzes all spacecraft maintenance, ground contact, and science data downlink events for the day being planned. At the conclusion of this daily planning activity, the OPC generates, verifies, and distributes event command sequences, daily schedules, ground contact plans, and daily plans for onboard tape recorder usage.

SCHEDULING: BALANCING EXPERIMENT OPPORTUNITIES VS. RESOURCE USAGE

An “event opportunity” is a potential time window in which a DCE could be scheduled (i.e., satisfies the desired viewing conditions while not violating constraints). Once scheduling opportunities have been defined, the Scheduler (a member of the APL OPC team) begins to place DCEs on the monthly schedule. Event opportunities are divided into six-hour blocks of time (i.e., only one DCE is scheduled within each six-hour block). While placing DCEs on the schedule, the Scheduler continuously monitors five key “cost” parameters: (1) tape recorder usage, (2) tape recorder head temperature, (3) battery DoD, (4) battery temperature, and (5) SPIRIT III baffle temperature. These cost parameters must be maintained within predetermined tolerance levels, and if any one of the five parameters stray outside the limits, a DCE(s) must be deleted, modified or rescheduled.

Several types of analysis, grouped into three general areas, are performed in the OPC to support planning and scheduling: orbit analysis, opportunity analysis, and event analysis. Orbit analysis predicts the spacecraft's position, velocity, and attitude as well as orbit milestones and the visibility of the spacecraft from specified ground stations using a spacecraft state vector received from the TSC. The state vector is validated and then propagated for the month/week/day being planned, and the results are stored in files which are used to support subsequent event analysis. Opportunity analysis is the identification of opportunities to execute a DCE associated with a feasible experiment in the time frame currently being scheduled. Event analysis includes the functions of kinematic and engagement analysis, power/thermal analysis, and cost analysis. Event analysis also includes an automated verification of proper spacecraft command usage based on a set of rules, and a summary of spacecraft operational constraint violations. The OPC's Constraint Checker software ensures that no constraints will be violated that affect the success of the event, degrade data quality, and/or damage spacecraft equipment. Constraints are separated into "hard" and "soft" categories. Hard constraints are those which are damage related or involve physical design limitations. Soft constraints are those considered costly in terms of spacecraft resources. After a DCE is created, the user must run its command sequence through the OPC's Rule Checker software which uses a set of usage or logic rules that verify that a user has assembled the commands together into an event that will execute safely. OPC software also produces "Spacecraft Cost Reports" which include an overview of the predicted "costs" of the DCE. These costs include: tape recorder storage, command memory storage, cryogen depletion, and power usage.

CONTROL OPERATIONS

Daily planning products are distributed to the APL Mission Control Center (MCC) from the OPC in two groups. Both groups of products contain contact plans (detailed instructions for the execution of APL contacts), command sequence files and reports for DCEs, and the schedule of operations for the upcoming 12-hour and following 24-hour periods. The command sequence files for each event are processed in the MCC and uplinked to the spacecraft in the 24-hour period from 0400 GMT on Day D (product group 1) to 0400 GMT on Day D+1 (group 2). Once loaded into the spacecraft command processor memory, the DCEs will typically execute within the following 12 to 18 hours. Recorded data from those events will typically be downlinked 12 to 24 hours after execution. Total data collection turnaround time [from sending of the file to MCC to receipt of prime science data in the APL Mission Processing Center (MPC)] is estimated to be between 48 and 60 hours. MCC software takes the contact plans, assembles the maintenance events called out from files already resident in the MCC, and processes the command sequence files for each DCE and each APL downlink event (i.e., a set of spacecraft X-band/S-band/tape recorder on/off control commands) sent with the contact plans. This processing takes the form of merging the discrete event files, by time of planned execution, into one file, referred to as a "runstate," for each contact. It is then the runstate that is executed on the spacecraft by MCC personnel during the planned contact.

Every contact is planned to have certain operations conducted. There are routine, every contact, maintenance events which are required for the determination of spacecraft health and status. Additional maintenance events will be scheduled for conduct on a less frequent basis. Typically, every APL contact will have prime science X-band telemetry downlinked from the spacecraft tape recorders. In addition, two APL contacts every day will also be devoted to uplinking a block of “delayed commands” to be executed at a later time out of UT memory. Each contact plan contains instructions for the execution of that specific contact in terms of what maintenance events are scheduled, whether there is to be prime science (25 Mbps) or wideband (1 Mbps) data downlinking, or both, and what, if any, delayed execution commands are to be uplinked. Figure 3 illustrates the flow of operations during APL contacts.

Science data consists of prime science, that data recorded by the spacecraft tape recorders during DCEs, and wideband science which is data collected and stored by the SBV sensor during space surveillance DCEs. As shown in Figure 3, the average contact duration usable for prime science data downlinking (i.e., tape recorder playback) is approximately 12 minutes. (The downlinking of prime science data is constrained to occur at elevations greater than 5° to avoid multipath effects which would otherwise be present in the X-band link.) Due to the properties of the MSX orbit, ground station contact over the APL site is limited to five to six contacts per day, which occur in two contact clusters. To provide for a margin of safety for surrounding properties, ground antennas are limited to travel no lower than 2° above the horizon. MSX flight operations has also instituted a procedural constraint to not plan any contacts with unimpeded durations of less than six minutes. These constraints reduce the useable contact frequency for the APL ground site to four to five contacts per day. Since the APL MOC is also the only site which can receive X-band, approximately 40-60 minutes of prime science data can be downlinked per day. This affects the duration and number of DCEs that can be performed each day; a few DCEs recording at 25 Mbps can easily fill up both tapes. All uplink of commands and downlink of wideband science data are also performed at the APL MOC site. The uplink data channel is serial so that real-time commanding and loading of delayed commands must be performed separately. Because of the quantity of data involved, available contact time is maximized by having the commands that perform downlinking (KG encryptor settings, X-band transmitter and gimbal commands, and tape recorder playback commands) execute out of onboard command memory. Wideband science data is downlinked via real-time commands issued from the ground.

The determination of how many delayed execution commands can be uplinked is a function of two factors: transmission rate and length of time available for UT uplinking in the particular contact. The length of time available for uplinking delayed execution commands itself is a function of a number of factors. As shown in Figure 3, prior to

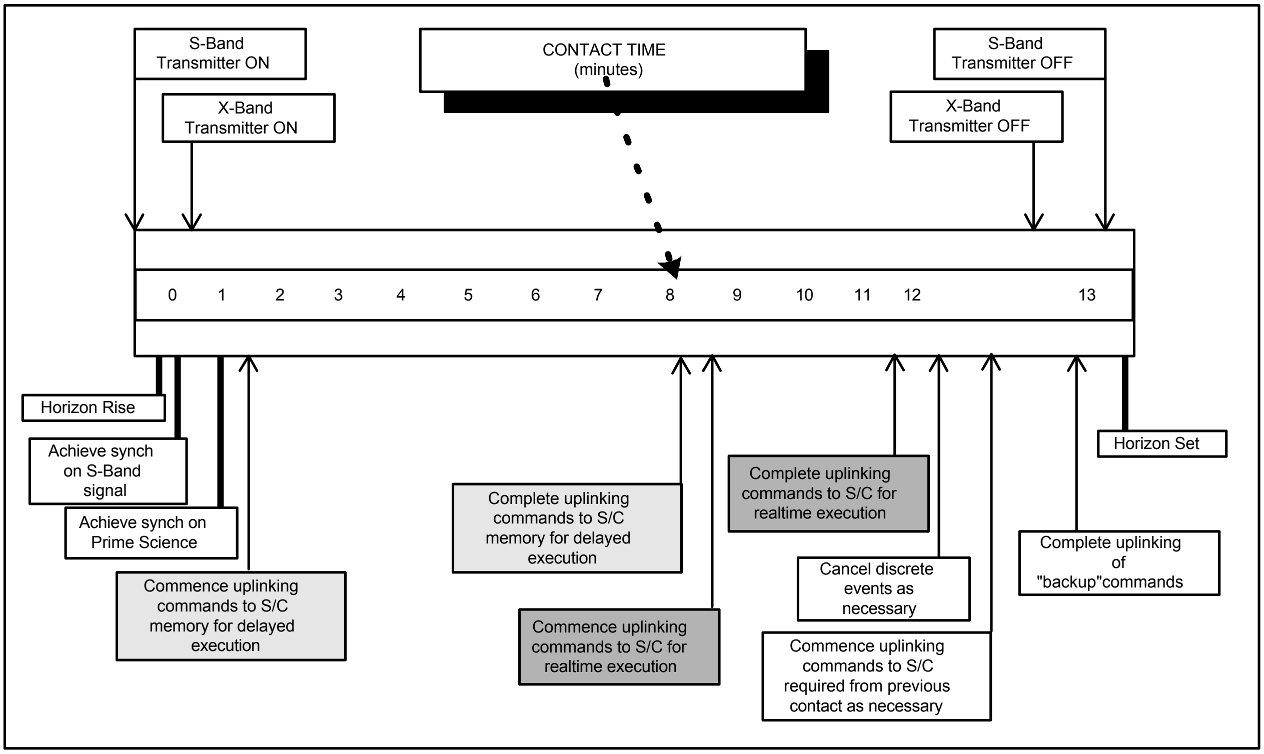

Figure 3. Flow of Operations During APL Contacts

commencing the uplink, synchronization on the X-band data received from the spacecraft is required to ensure that there are no timing conflicts occurring within the C&DH subsystem which might adversely affect the downlink. Time during the contact must also be allocated to allow for the uplinking of commands for real-time execution by the spacecraft, such as the commands to downlink wideband science, perform any maintenance activity, and, if necessary, cancel delayed commands previously uplinked. In addition, time must be available for uplinking commands for any events that were to have been uplinked previously but were not.

In the actual uplinking process, time ordered delayed execution commands for both DCEs and APL downlink events are grouped into 100 command message blocks. This blocking allows a transmission rate of 200 commands per minute to be realized. Once all the message blocks are uplinked, the spacecraft is commanded to transmit back to the ground site, the contents of the memory locations just loaded. These retransmitted contents are compared and verified in MCC to an expected image of the memory locations. This dump/compare/verify process must be taken into account in the overall timeline; experience indicates that this process requires approximately 90 seconds. Miscomparisons, typically caused by data dropouts due to signal fluctuations in either the initial or return transmission, if they occur, require retransmission of unmatching memory locations during the remaining time available during the contact (or if necessary, during the follow-on "backup" contact). Based on previously discussed constraints, the amount of time available for uplinking of delayed execution commands is reduced to be on the order of six to eight minutes. The number of delayed execution commands (DCEs plus APL downlink events) that would be planned for uplinking in one contact, at this time, is conservatively limited to 1200. With five APL contacts per day and eight minutes of uplink time per contact, a total of 40 minutes is available for uplinking commands in a day; however, a programmatic requirement to provide backup contact time in the event of contingencies reduces the amount of planned uplink time by a factor of two. Thus over the period of one day, only approximately 20 minutes of contact time can be used for uplinking. This results in 4000 commands per day that can be planned for uplinking; subtracting out the downlink events (approximately 100 commands per planned contact) leaves about 3500-3600 commands per day for DCEs.

While all DCE command uplinking and prime science data downlinking are performed only at APL, spacecraft contact with other ground sites is required to support ephemeris accuracy requirements. Without spacecraft ranging capability at APL, ephemeris determination using ranging data from AFSCN sites is done by the TSC. In order to meet accuracy requirements, the TSC will schedule and plan for six to eight AFSCN sites per day for operation with the spacecraft. While no delayed command uplinking of DCEs will be performed by TSC, in the event of an emergency, the capability exists to send commands to the spacecraft from the MCC at APL through TSC. TSC's planning of AFSCN contacts consists of the transmission of commands to set up the spacecraft's S-band transmitters for turn-on at later times (over the planned AFSCN sites). In addition to performing ranging duties, the TSC will transmit commands for real-time execution of maintenance events that allow for the monitoring of spacecraft health and status.

SUMMARY

The collective suite of MSX sensors and supporting subsystems provide a broad range of data collection potential; however, operational constraints represent a significant challenge to fulfilling this potential. The flight operations system has been designed to meet this challenge while minimizing operational costs. This has been accomplished by balancing mission goals with operational constraints via a hierarchical planning process for spacecraft scheduling, resource management, and constraint adherence coupled with robust operations control timelines and techniques which account for backups, contingencies, and ground station obscura. The resultant flight operations system should be able to achieve the ambitious mission goals while still ensuring that the spacecraft is operated in a safe manner and will meet its design lifetime.