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Joint Operations Planning for the Midcourse Space Experiment Satellite

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The Midcourse Space Experiment (MSX) satellite is intended to gather broadband phenomenology data on missiles, plumes, naturally occurring Earth-limb backgrounds, and deep-space backgrounds. In addition the MSX will be used to conduct functional demonstrations of space-based space surveillance. The Applied Physics Laboratory is charged with the detailed operations planning required to implement all of the experiments run on the MSX satellite, except the space surveillance experiments. The nonsurveillance operations are generally amenable to being defined months ahead of time and being scheduled on a monthly basis. Lincoln Laboratory is charged with implementing the space surveillance demonstrations on the satellite. The planning timelines for these demonstrations are fundamentally different from those for the other experiments in that the specific experiment sequence and pointing must be refined shortly before execution. This allocation of responsibilities to different organizations implies the need for a joint mission planning system for conducting space surveillance demonstrations. This paper details the iterative, joint planning system, based on passing responsibility for generating commands for surveillance operations from the Applied Physics Laboratory to Lincoln Laboratory for specific scheduled operations. The joint planning system, including the generation of a budget for spacecraft resources to be used for surveillance events, has been successfully demonstrated during ground testing and is being validated to support launch within the year. The planning system developed for the MSX satellite forms a model possibly applicable to developing distributed mission planning systems for other multiuse satellites.

Introduction

THE Midcourse Space Experiment (MSX) is a satellite-based experiment sponsored by the Ballistic Missile Defense Organization (BMDO) to be flown in a low Earth orbit. MSX was initially conceived as the first extended-duration, long-wave infrared (LWIR) phenomenology measurement program sponsored by BMDO; however, these early objectives have evolved into a more comprehensive experiment. MSX is now a multiyear experiment designed to collect broadband phenomenology data on missiles, plumes, naturally occurring Earth-limb backgrounds, and deep-space backgrounds. In addition, MSX will be used to collect spacecraft contamination data, to integrate, validate, and transfer advanced technologies to current and future BMDO systems, and to conduct functional demonstrations of space-based space surveillance.

MSX will be launched from Vandenberg Air Force Base into a near-polar, low Earth, near-sun-synchronous orbit. Shown in Fig. 1 and discussed further in Ref. 1, MSX consists of the satellite superstructure, three primary optical sensors, contamination instrumentation, and the spacecraft support subsystems. The optical axes of the three primary sensors [space infrared imaging telescope (SPIRIT III), space-based visible (SBV) sensor, and ultraviolet–visible imagers and spectrographic imagers (UVISI)] are parallel to one another and point in the $+X$ direction. The support subsystems consist of the power subsystem, the thermal control subsystem, the command and data-handling subsystem, and the attitude determination and control subsystem. In addition, MSX houses a beacon receiver and onboard signal and data processor.

The SPIRIT III sensor is a passive mid- to very long-wavelength infrared sensor and is the primary instrument aboard MSX for collecting target and background phenomenological data. SPIRIT III consists of a telescope with a 35.5-cm-diam aperture, a six-channel interferometer, a six-band radiometer, and a cryogenic Dewar and heat exchanger. The lifetime for SPIRIT III operations, which will be limited by the cryogen supply, is currently projected to be 18–24 months.

The UVISI sensor has been developed with a primary mission to collect data on celestial and atmospheric backgrounds. Other UVISI missions include target characterization in the UV regime and observation of contamination particulates in conjunction with the contamination instruments. The UVISI sensor consists of four imagers and five spectrographic imagers covering a spectral range from far UV to near infrared. The imagers include wide- and narrow-field-of-view sensors in both the visible and UV ranges and also include filter wheels to select various passbands. UVISI also includes an image-processing system, which will be used for closed-loop tracking of targets and aurora.

The SBV sensor, discussed in Refs. 2 and 3, is the primary visible-wavelength sensor aboard MSX. It will be used to collect

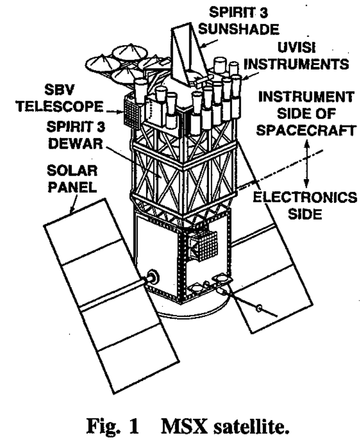

Fig. 1 MSX satellite.

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data on target signatures and background phenomenologies, but the primary mission of SBV will be to conduct functional demonstrations of space-based space surveillance. SBV incorporates a 15-cm, off-axis, all-reflective reimaging telescope with a thermoelectrically cooled charge-coupled device (CCD) focal-plane array. SBV also includes an image-processing system, an experiment control system, a telemetry formatter, and a data buffer for temporary data storage.

The collective suite of MSX instruments and supporting subsystems provide a broad range of data-collection potential; however, a significant number of operational constraints have been imposed by spacecraft and instrument designers in order to achieve safe operation and to maintain the desired mission life (five years overall, including two years for SPIRIT III). These constraints include limitations on boresight pointing relative to the sun, moon, and Earth, restrictions on warming of the SPIRIT III Dewar and baffle, bounds on battery depth of discharge and temperature, and thermal and duty-cycle limits for the onboard tape recorders. The combination of these operational constraints with the BMDO goal of 14 data-collection events per day represents a significant challenge to the MSX flight operations system, comparable to that encountered by the Hubble Space Telescope as discussed in Ref. 4.

The MSX flight operations system consists of facilities at Applied Physics Laboratory (Operations Planning Center, Mission Control Center, Mission Processing Center, Performance Assessment Center, and Attitude Processing Center), at Lincoln Laboratory (SBV Processing, Operations and Control Center), and at the USAF Test Support Complex at Onizuka Air Force Base, which interfaces with the SGLS ground station network. This collection of facilities is referred to as the "extended" MSX Mission Operations Center. A BMDO-led Mission Planning Team instructs the Mission Operations Center on a monthly basis on the type, number, and priority of experiments to be conducted. The planning centers at Applied Physics Laboratory and Lincoln Laboratory then develop operations planning products (e.g., schedules, contact support plans, command loads), which are provided to the Mission Control Center and the USAF Test Support Complex for execution. Spacecraft science and housekeeping data are collected by the Mission Control Center and the USAF Test Support Complex and then processed by the Mission Processing, Performance Assessment, and Attitude Processing Centers as well as disseminated to the MSX data community.

Space Surveillance

Currently the United States maintains a worldwide network of ground-based sensors tasked with the acquisition of tracking data on all man-made objects in orbit around the earth. These sensors include a network of passive optical systems, which are limited to a short duty cycle by poor weather and by daylight. Since foreign-based sites are progressively more expensive and inconvenient to support, it is natural to ask whether ground-based sensors could be supplemented or replaced by satellite-based sensing systems. Satellite-based sensors are not limited by daylight operation or poor weather, and a single satellite-borne sensor can sample the entire geosynchronous-belt satellite population several times per day.

One of the missions of the MSX satellite is to demonstrate the feasibility of space-based space surveillance operations. One of the three principal MSX sensors, the SBV sensor, has been specifically designed to provide visible-band satellite tracking data. The SBV consists of a 15-cm optical telescope with high off-axis rejection optics designed to acquire good satellite track data close to the bright Earth limb. In addition to the visible data from the SBV, track and optical signature data from the other MSX sensors are of interest to the space surveillance community. There is particular interest in the data from the SPIRIT III long-wave infrared sensor, which promises the ability to detect satellites in the shadow of the earth.

The mission planning required to execute space surveillance activities is fundamentally different from that required to execute the other MSX missions. Normally space surveillance sensors are tasked on a day-at-a-time basis by Space Command. In addition, Space Command provides special updates to the sensor tasking for special events, such as new launches, which require reactions on short timelines (minutes to hours). This operational tempo is significantly shorter than the normal MSX mission planning process, which requires the operation to be well defined at the monthly planning level, which occurs as much as 10 weeks before the execution of the event on the spacecraft. If the routine MSX planning timeline were followed and space surveillance experiments were preplanned, the ephemeris of many low-altitude satellites targeted for observation would have changed enough to put them out of the sensor field of view by the experiment execution time. In addition, the normal MSX planning procedure contains no provision for generating observations in response to quick-reaction experiments such as the launch of a new satellite.

The mission planning for the Space Surveillance experiments on the MSX satellite requires the ability to leave considerable flexibility in the experiment timing and attitude profile to be followed by the MSX in the experiment execution until late in the experiment planning process. Under "normal" circumstances the details of the operation, consisting of the list of satellites to be observed, the attitude profile for the MSX and the data acquisition times can be defined one to two days before the execution on the MSX. Special quick-reaction events, such as acquiring track data on a newly launched satellite in its transfer orbit to the geosynchronous belt, require reaction times on the order of hours.

Joint Planning Process

The mission planning required to operate a satellite as complex as the MSX is a large task under any conditions: however, it is complicated further by the breadth of the experimental missions to be conducted by the satellite. References 5 and 6 provide background on the issues related to planning such missions. Most of the MSX experiments are amenable to long-term planning either because their targets are slowly changing (e.g., naturally occurring Earth-limb and deep-space backgrounds) or because they are under the control of the experimenter (e.g., dedicated missile shots). This long-term planning process allows time for the mission planners to communicate with the principal investigators to clarify the details of a specific experiment in the planning process. The long-term planning requirements and process discussed here are not by any means unique to the MSX. For example, Ref. 7 discusses the approach taken for the Hubble Space Telescope, which shares many of the planning complexities of the MSX. On the other hand, the space surveillance experiments designed at Lincoln Laboratory require fundamental modifications late in the planning process on timelines that admit little manual intervention. Thus, the MSX program was faced with a fundamental decision to either implement a single, automated, general-purpose planning system that would accommodate the complete set of diverse MSX experiments on a timeline driven by the most stressing experiment, or to build a long-term planning system for the majority of the experiments and allow a link into the planning process from a more automated system dedicated to planning the space surveillance experiments. For reasons of economy and to minimize the complexity of the entire implementation, the second option was chosen. Since the expertise needed to fulfill the space surveillance mission planning function resides at Lincoln Laboratory, the center for surveillance experiment planning was located there in the SBV Processing, Operations and Control Center (SPOCC).

To simplify the planning procedures and to allow the parallel planning of experiments, the following three principles were adopted by the organizations involved:

1) The planning team at Lincoln Laboratory is responsible for complete operation of the MSX spacecraft and all its sensors during the time period scheduled for a surveillance experiment. Thus, the Lincoln Laboratory team will receive the MSX in a given standard configuration, known as parked mode, will generate all the command information for both the satellite and sensor subsystems required to implement the data collection, and will return the spacecraft to the standard parked mode upon completion of the event. The Lincoln Laboratory planning team is responsible for abiding by all spacecraft constraints and operating rules during the conduct of surveillance events.

2) The long-term planning for space surveillance events will consist of allocating time intervals and resource budgets to the events.

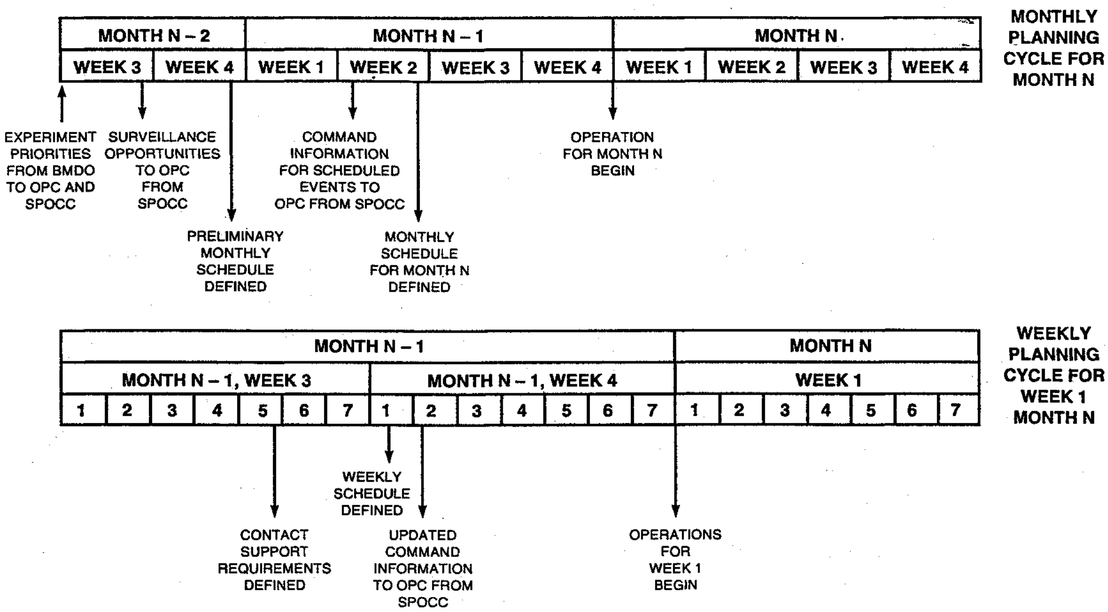

Fig. 2 Monthly and weekly planning cycles for MSX experiment.

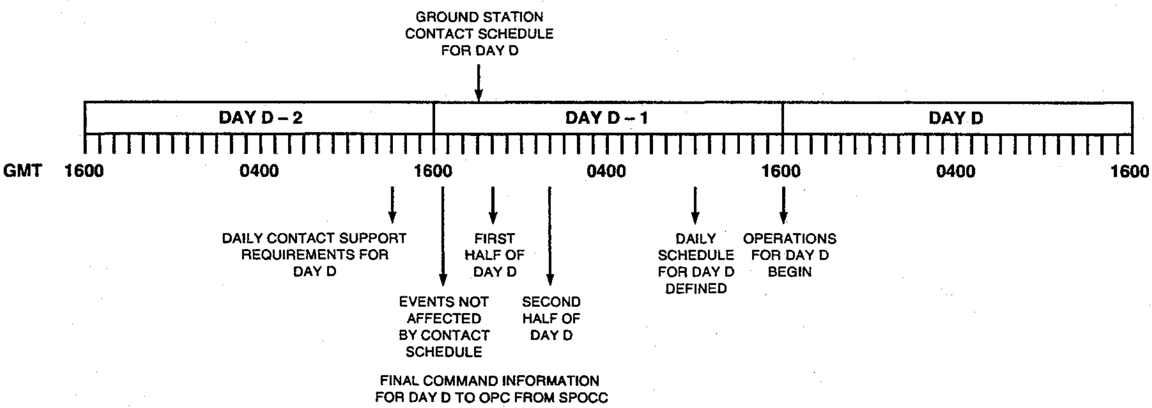

Fig. 3 Daily planning cycle for MSX experiments.

Thus, it has been agreed that the specific modes of satellite operation for surveillance experiments will be left to be filled in the day prior to conduct of the event. However, during the long-term planning process, the experiment will be scheduled during a specified time interval, and the integrated effect on the MSX resources, such as battery depth of discharge and changes to the spacecraft thermal state, will be agreed upon on a "not to exceed" basis.

3) The final responsibility for safe spacecraft operations will belong to Applied Physics Laboratory, which will check all command information generated by Lincoln Laboratory. The check will be automated and will be conducted shortly before upload of the commands to the MSX.

These three principles enable the parallel planning of operations at the two centers by clearly separating the responsibilities of each planning center during each of the planning intervals necessary to operate the MSX. However, they also require an overlap of capability between the two planning sites, because both must be able to generate command information for the entire satellite. This duplication was accepted as a cost of having a distributed planning system.

The planning system for the MSX goes through four phases of activity, as shown in Figs. 2 and 3, to generate a data collection event for the satellite. The phases and the interaction between the planning centers for surveillance events are described below.

Opportunity Analysis

The planning centers are given experiment priorities on a monthly basis by the BMDO-run Mission Planning Team. The priorities are provided six weeks before the start of the month being planned. Once the priorities are received, each planning center—the Operations Planning Center (OPC) and SPOCC—analyzes the experiments for which it is responsible to determine feasible times for which data may be collected. For surveillance experiments, items such as target visibility, sun angle, and proximity to the Earth limb or Earth shadow are considered, and a list of feasible times is compiled. The opportunity list includes the start and duration of each feasible event start time, the event duration, the desirability of that particular feasible time compared with others on the list, an indication of the accuracy of the estimated event start time (e.g., if the satellite to be observed has a low altitude, the time it becomes visible will not be precisely known 10 weeks in advance), and a pointer to an example set of command information for that type of event. The space surveillance opportunity list and the example command information sets are provided to the Operations Planning Center for integration with the other experiments in the monthly planning process.

Monthly Planning

The OPC combines the opportunity lists for each of the different types of experiments and constructs a schedule of data collection events to be conducted during the month. Since the MSX spacecraft is not designed for 100% duty cycle, the scheduling process must pay close attention to the use of spacecraft resources. In addition, the cryogenic SPIRIT III sensor is very sensitive to the thermal state and history of the MSX. To estimate the resources that will be used by the space surveillance events, the OPC analyzes the sample command information provided by SPOCC for each event type and estimates the change in battery depth of discharge and the thermal deltas for critical elements. These estimated resource expenditures now become a "not to exceed" budget for the conduct of the surveillance data collection event. The actual pointing and targets may be considerably different, but the integrated effect on the spacecraft resources may not be any larger than that defined during the monthly scheduling process. The OPC generates a monthly schedule for the MSX operations during the month, and—after suitable iteration with BMDO and SPOCC—the schedule is published. SPOCC then provides the OPC with preliminary command information for all of the space surveillance events as scheduled. The weekly planning process is then started for the first week of the planning month as shown in Fig. 2.

Weekly Planning

Weekly planning is largely used by the OPC to update non-space-surveillance experiments to reduce the amount of work needed at the daily planning level. In addition, the uplink and downlink requirements for the earth stations in the SGLS network are compiled and input into the scheduling process at the Test Support Complex. Reference 8 discusses the functions of the SGLS network and the Test Support Complex. For surveillance experiments, the automated SPOCC planning system is rerun taking into account the updated ephemerides for the intended targets (if known at the time) and the MSX, and an update of the event start times is provided to the OPC along with revised command information for each event to be executed during the planning week.

Daily Planning

The final mission planning occurs at the daily planning level, which occurs the day before the events are to be executed on the MSX, as shown in Fig. 3. At that time the final uplink and downlink schedules are known, the orbital geometry of the MSX and the targets is available with sufficient accuracy, and tasking lists are available from Space Command for tasked experiments. At that time SPOCC generates final sets of command information for each event during the day and provides them to the OPC for analysis and inclusion in one of the three command upload creation cycles run during each day for the MSX. SPOCC is responsible for generating command information that is compliant with all MSX constraints, operation rules, and resource budgets determined during the scheduling process. The OPC conducts a final, automated analysis of the events as provided by SPOCC and, if they are compliant with the agreed rules, incorporates them into the command load.

Quick-Reaction Events

A number of space surveillance events require shorter timelines than provided by the daily planning process described above. These include events such as the launch of a new satellite, which is scheduled well in advance, but is such that the actual launch time is not known with sufficient accuracy until after the launch. A series of special procedures have been developed to plan events requiring a very quick response from the planning system. The procedures require that an interrupt window be defined at the monthly planning level. The window defines a range of times during which normal MSX operations can be disrupted in order to collect data on a specific event if it happens. The ability to capture the event depends on the availability of suitable prescheduled ground-station uplinks that may be used to uplink new commands to the MSX. This is a major constraint on the operation of this model, which is necessitated by the inflexibility of the SGLS ground-station scheduling process. Once a quick-reaction event has been declared, SPOCC will generate commands to observe the satellite, based on tipoff information from Space Command (such as the time of launch in the case of a new launch), and will forward the new commands to Applied Physics Laboratory for inclusion in an uplink, which will cancel the existing commands and replace them with those required to execute the quick-reaction event observations. Preliminary timing tests run on the planning process indicate that SPOCC can have the required command information ready for transmission to Applied Physics Laboratory within 30 min of the launch and that Applied Physics Laboratory can process the results in time to track a satellite in a transfer orbit to geosynchronous altitude. Final timing tests and procedure verification will take place after a period of operational experience with the MSX under the normal planning process.

Conclusions

In order to accommodate the mission planning for a broad range of diverse experiments to be run on the MSX satellite, a distributed mission planning system has been defined and implemented. Under this model, the MSX mission planning is accomplished for all nonsurveillance experiments using a long-term planning process at the Applied Physics Laboratory OPC. Space surveillance experiments are planned by Lincoln Laboratory and carried in the Applied Physics Laboratory planning schedule as event durations and resource utilization budgets without the details of the operation, which are provided to the OPC during the final daily planning process in command-ready form.

This system of distributed mission planning has been developed for a complex multifunction, multimission spacecraft where the expertise needed to conduct mission planning for various mission types is distributed between two locations. The advantage of the process as defined is that the two planning centers can conduct the mission planning functions in parallel, each adding the details of the operation as they are available or according to its capabilities. The event is held in the master schedule by budget allocations and schedule placeholders until the final details are available. Having each planning center responsible for generating command information for the entire spacecraft for the events for which it is responsible simplifies the interaction between planning centers considerably, since each can consider the other's events as "black boxes" until the final details are provided in a complete package. The disadvantage of this approach is that each planning center needs to understand and be capable of commanding every satellite function that will be needed to satisfy its events.

Given that many of the satellites launched currently are large multifunction payloads containing a broad range of instruments, collecting data for a diverse user set, the MSX planning system experience may yield broadly applicable lessons. For example, Ref. 9 discusses the planning requirements related to the proposed Space Station, which shares many of the challenges discussed in this paper. The main requirement to implementing such a cooperative planning system has been a mutual understanding of each participant's mission requirements and a willingness on the part of all parties to consider all the alternatives and to negotiate a sensible approach to solving the mission planning puzzle.

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