The MSX Mission Objectives

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A suite of state-of-the-art sensors, including a cryogenic infrared scanning radiometer and Fourier transform spectrometer, several visible and ultraviolet imagers and spectrographic imagers, and a set of contamination monitoring instruments, has been integrated with a highly capable spacecraft for a planned launch into a polar orbit. The optical sensors cover the spectrum from the far ultraviolet (110 nm) through the very-long-wave infrared (28 μm). The Midcourse Space Experiment (MSX) satellite, funded and managed by the Ballistic Missile Defense Organization, is a long-duration, "observatory"-style measurement platform that will collect several terabytes of high-quality data on terrestrial, Earth-limb, and celestial backgrounds; Intercontinental Ballistic Missile–style targets; and resident space objects. Whereas the principal focus of MSX is to collect phenomenology data in support of ballistic missile defense objectives, it will also gather carefully calibrated data in support of civilian efforts in terrestrial and atmospheric remote sensing and astronomy. This article focuses on the DoD mission objectives of the MSX program.

INTRODUCTION

The functions of Ballistic Missile Defense Organization (BMDO) midcourse sensor systems are to detect, acquire, and track targets and to discriminate lethal from nonlethal objects. (Midcourse refers to the phase of missile flight between boost and reentry.) To perform these functions, the systems must be designed to interpret the behavior and resulting signatures of the expected targets and the effects of the backgrounds against which these targets will be viewed. A successful design, therefore, requires detailed characterization and careful modeling of potential targets and their associated phenomenology, and high-fidelity models of the terrestrial, Earth-limb, and celestial backgrounds. These data and models are required across the optical spectrum, over the entire globe, and for an extended period to account for seasonal and geographic variations.

The BMDO and its predecessor, the Strategic Defense Initiative Organization (SDIO), developed a suite of phenomenology models to meet these requirements, such as the Optical Signature Code and the Strategic High-Altitude Radiance Code.[1] These models were incorporated into a framework code called the Strategic Scene Generator Model,[2] which provides validated scenes at the resolution, wavelength, frame rate, and field of view of a candidate sensor under development or test. The BMDO and SDIO also sponsored a number of experiments to provide data to validate the codes. Past space experiments included the so-called Delta series and two shuttle payloads on STS-39, the Infrared Background Signature Survey, and the Cryogenic Infrared Radiance Instrumentation for Shuttle.[3] Although these experiments returned valuable data, they were of short duration or limited resolution or sensitivity. The MSX is designed to overcome these limitations and provide the necessary data sets over the globe, during all seasons, and at the required resolution and sensitivity.

The primary purpose of the MSX is, therefore, to collect and analyze target and background phenomenology data to address BMDO midcourse sensor requirements. The MSX will demonstrate midcourse sensor functions from space, collect midcourse target and background data, and demonstrate critical sensor technologies (Fig. 1). It will gather optical data from the far ultraviolet (110 nm) to the very-long-wave infrared (out to 28 μm) with fully characterized, carefully calibrated sensors. It will also amass imagery at high sensitivity and high spatial resolution, and compile spectra at moderate to high resolution and very high sensitivity.

The MSX satellite, having an expected 5-year lifetime, is scheduled to be launched on a Delta II booster from Vandenberg Air Force Base, California, into a Sun-synchronous orbit at an altitude of 898 km and an inclination of 99.16°. The MSX instruments are the Spatial Infrared Imaging Telescope III (SPIRIT III)—a cryogenic radiometer and spectrometer with an estimated 18-month cryogen lifetime—the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) sensor system, the Space-Based Visible (SBV) surveillance camera, the On-Board Signal and Data Processor (OSDP), and a suite of instruments to monitor contamination on and around the spacecraft. To augment the MSX sensor data and facilitate analysis, other spaceborne and ground-, aircraft-, and sea-based sensors will be used throughout the mission. To conserve cryogen, activities during the cryogen lifetime will be concentrated on above-the-horizon data collection and target missions; only 50 to 100 h of below-the-horizon measurements will be made.

Figure 1. This artist's concept of the MSX spacecraft in orbit includes representations of the principal MSX missions of demonstrating ballistic missile tracking (lower left), cataloging resident space objects (lower right), and collecting phenomenology data on terrestrial, celestial, and Earth-limb backgrounds. The central importance of complete, careful, instrument calibration is represented by the NIST-calibrated reference sphere (left center)—one of six that will be released from the spacecraft.

TARGET FUNCTIONAL DEMONSTRATIONS AND PHENOMENOLOGY

The MSX Early Midcourse and Theater Midcourse Principal Investigator teams will carry out functional demonstrations and collect phenomenology data on well-characterized midcourse targets. Functional demonstrations will establish the ability of a space-based sensor to acquire and track threat objects in the presence of real backgrounds using current optical sensor technology. Target phenomenology data will be used to validate target signature models such as the Optical Signature Code.

Functional Demonstrations of Acquisition and Tracking

The early midcourse phase of a ballistic missile engagement begins with the release of the postboost vehicle. Subsequent activities include maneuvers to position the reentry vehicles for proper targeting and any activities associated with target deployment, such as spin-up and release. The late midcourse phase begins when the target complex is still seen as a cluster of closely spaced objects but is beginning to evolve into individually resolved objects. In either phase, the postboost vehicle and reentry vehicles may use techniques to confuse the surveillance sensors, including, for example, the deployment of decoys that mimic warheads, traffic balloons to confuse tracking and discrimination sensors, and chaff. In addition, various design elements of the postboost vehicle or reentry vehicles may be intended to alter or eliminate signature features that could aid in discrimination.

The primary focus of the Early Midcourse target experiments team is the resolution of issues in the tracking and evolution of closely spaced objects, metric and radiometric discrimination, deployment phenomenology, and postboost vehicle tracking. These experiments will lead to the development of the first extensive database of early midcourse target signature phenomenology observed from a space-based sensor.

The Theater Midcourse team is concerned primarily with late midcourse flight. It will address issues of acquisition, tracking, data fusion, and discrimination for the midcourse phase of both strategic and theater ballistic missile defense engagements. In addition, unique data will be obtained on the behavior of long-wave infrared (LWIR) and visible target signatures, which will permit the detailed correlation of infrared signatures and their phenomenology with both body rotational dynamics and dynamics evolution.

Target Signature Data Collection

The MSX target signature measurement requirements will be addressed in a dedicated MSX strategic missile flight, two cooperative theater missile defense flights, and probably other cooperative target launches or targets of opportunity. The MSX early midcourse dedicated flight will use the Operational Deployment Experiment Simulator (ODES) postboost vehicle to deploy 26 midcourse objects of various types under differing deployment conditions. The Theater Midcourse team cooperative missions include two launches of Talos/Sergeant/Aries boosters from Wallops Island, Virginia, to test the ability of a space-based sensor to track theater missiles against terrestrial backgrounds. They will deploy surrogate tactical reentry vehicles as well as some strategic reentry vehicles and penetration aids (decoys or signature-masking material). In addition, the two Aries upper stages will be intentionally fragmented to form debris that will permit testing of bulk filtering techniques.

During all dedicated and cooperative target flights, the objects will be viewed simultaneously by the MSX satellite and a number of aircraft-, ship-, and ground-based sensors to establish ground truth and to provide data for sensor-to-sensor correlation studies. Other experiments will acquire background data in target track mode with realistic engagements to investigate acquisition and tracking functions under various stressing (spatially complex or cluttered) backgrounds.

The key targets on all flights are of near-term strategic and theater interest, and include reentry vehicle surrogates, lightweight replicas, traffic balloons, and a solid aluminum 18-cm sphere with an emissive coating that functions as an in-flight calibration aid. At least one object in each class will carry lightweight dynamics and temperature instrumentation to collect in-flight truth data. In addition, one object in each target complex will carry a Global Positioning System transponder for metric truth.

SPACE SURVEILLANCE DEMONSTRATIONS

The MSX satellite will also be used to demonstrate space object surveillance from a space platform and develop a database (catalog) of resident space object observations. The goal of space surveillance is to create and maintain current goniometric (angle measurement) and radiometric information on all man-made objects in Earth orbit. Resident space objects include active payloads, rocket bodies, upper stages, and space debris. The present ground-based space surveillance network has limitations in coverage, capacity, sensitivity, available optical wavelengths, and accuracy. The MSX will be the first space-based platform to investigate wide-area space surveillance with sensors covering optical wavelengths from the ultraviolet to the LWIR.

These catalog maintenance experiments are designed to exploit the greater observing opportunities afforded by a space-based platform to address the issues of coverage (area of the sky) and capacity (number of objects tracked at one time). These experiments must account for spacecraft constraints, communication limitations, and data accuracy, as well as uncertainties in the existing catalog. Objects to be brought into the catalog come from new launches, lost objects, or breakups. New launches are the most stressing to the space surveillance network because of the requirement to catalog these objects during their first revolution.

Photometric and radiometric data can also be used in conjunction with high-fidelity satellite models to identify a particular satellite design (e.g., spin-stabilized cylinders) and operational status, a process called space object identification. There are also three experiments concerning space debris. One will use all MSX sensors to develop a multispectral model of space debris. A survey experiment will compile a database of existing debris. The third experiment will capture a satellite breakup, should one occur, and provide detailed data on the resulting debris and its relation to the existing debris.

BACKGROUND PHENOMENOLOGY

A major objective of the MSX mission is to obtain definitive data sets of celestial, Earth-limb, and terrestrial backgrounds that could be encountered by operational surveillance sensors. The background measurements will be used to obtain precise radiometric values in specific optical bandwidths at high spatial resolution in order to assess the operational limitations that infrared and ultraviolet background clutter impose on surveillance systems. These spatial clutter data will be supplemented by the spectral sensors, which will provide critical diagnostic information to understand the spectral content within the broad radiometer bands. The spectral sensors will also provide additional data to validate the background models such as the Strategic High-Altitude Radiance Code.

Celestial Backgrounds

The MSX mission will provide unique capabilities to extend the observational database for celestial backgrounds. In the LWIR, the SPIRIT III sensor has about the same sensitivity as the Infrared Astronomy Satellite (IRAS), but about 30 times better spatial resolution. (IRAS was a NASA/United Kingdom/Netherlands satellite that mapped 96% of the sky in four spectral bands from 8 to 120 μm during a 10-month mission in 1983.) The SPIRIT III interferometer spectral resolution ranges from comparable to 10 times better than IRAS. In the ultraviolet, the imagers and spectral imagers will be the most sensitive ever flown for astronomical measurements (Fig. 2).

Three celestial background experiments are designed to complete the LWIR database. They will map the areas of the sky missed by IRAS; high-source-density regions, primarily along the galactic plane, where the IRAS survey was confused by multiple sources on a detector; and the sector less than 60° from the Sun. Source lists from these experiments will be combined with the IRAS point source catalog, and knowledge of source positions will be improved by identifying the LWIR sources with stars in astrometric catalogs to create an all-sky infrared astrometric catalog. LWIR photometry will be performed on a number of stars for scaling spectral composites or templates that will then be compiled into a stellar atlas to be used for *in situ* calibration of space-based systems. Asteroids will be observed to ascertain their suitability as calibration sources.

Other experiments to characterize background clutter include observations in the galactic plane to probe galactic structure; to map extended sources such as HII (doubly-ionized hydrogen) regions, large galaxies, and areas of bright infrared structure due to interstellar dust; and to characterize fine-scale features in the solar system such as cometary dust trails and the zodiacal dust bands. Interferometry will be performed on sources with infrared spectral features (e.g., AGB stars and other evolved objects, HII regions, planetary and reflection nebulae) as well as spectral mapping of large bright regions such as the galactic center and the Orion Nebula.

Atmospheric Backgrounds

Atmospheric background measurements will be collected as functions of tangent altitude, latitude, season, and atmospheric conditions, including quiescent, geomagnetically disturbed, and auroral. The amount and intensity of the structure in a background scene are two of the fundamental limits to the performance of an optical sensor; these two factors produce

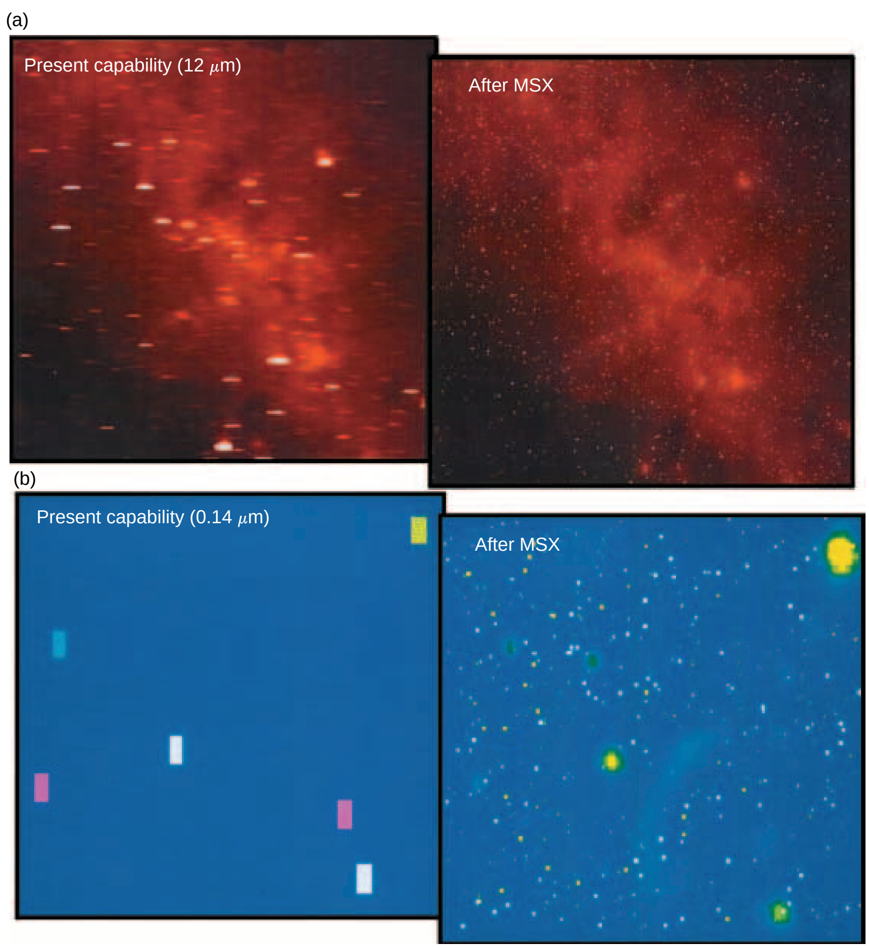

Figure 2. The MSX will significantly improve the existing infrared and ultraviolet celestial database resolution. (a) The infrared picture at about 12 μm with the best current data (left) and a simulation of what MSX will produce (right); (b) The ultraviolet picture at about 0.14 μm with the best current data (left) and a simulation of what MSX will produce (right). (Photographs courtesy of the U.S. Air Force Phillips Laboratory.)

false targets in the image processor, forcing the tracking processor to deal with many more potential target trajectories than otherwise would be required. The goal is to define the intensity and spectral content of small-scale spatial irregularities of Earth-limb ultraviolet, visible, and infrared backgrounds and to determine their global distributions, associations with specific phenomena, and frequencies of occurrence. Earth-limb background experiments will measure the radiance and structure from nadir to limb, viewing geometries at tangent heights up to 300 km. The atmospheric phenomena to be measured include aurora, airglow, mesospheric clouds, noctilucent clouds, joule-heated atmospheres, and stratospheric warmings. Several experiments will be coordinated with ground-based facilities (principally sites for airglow and auroral observations) and space-based assets such as the Defense Meteorological Satellite Program and the National Oceanographic and Atmospheric Administration (NOAA) 11 and 12 satellites.

Terrestrial Backgrounds

Terrestrial backgrounds will be observed episodically by the MSX sensors with particular interest in two wavelength regions where the mean radiance and the spatial structure are reduced due to atmospheric absorption. In the 0.2- to 0.3-μm wavelength region, the middle ultraviolet (MUV), the solar albedo is approximately 4 orders of magnitude less than in the visible region due to absorption by ozone. An objective of the MSX program is to characterize small-scale MUV spatial structure in the nadir views of sunlit atmospheres. Similarly, middle wavelength infrared terrestrial backgrounds will be observed in two selected bandwidths in the region of strong carbon dioxide absorption at 4.3 μm. Experiments are planned to probe the atmosphere for small-scale structure as a function of altitude. Observations coordinated with corollary assets will provide diagnostics of atmospheric conditions, cloud types, water vapor profiles, aerosol content, and temperature profiles. Corollary sensors include the Department of Energy Atmospheric Radiation Measurement sites;[4] NOAA 11 and 12 satellites; and sites in the National Science Foundation Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) network.[5]

SENSOR CHARACTERIZATION AND CALIBRATION

The careful calibration of the instruments aboard the MSX spacecraft is a critical component in the chain of events from the collection of data to the correct scientific interpretation of those data. The MSX program has recognized this fact by insisting that the data from this experiment meet stringent quality requirements for accuracy and precision. Because of the amount and diversity of the data that will be collected during the mission, the MSX program cannot operate as similar programs have in the past.

A New Approach to Data Processing

Past practice has been to produce and archive a Level 2 database (i.e., calibrated data, in engineering units) as the standard product provided to investigators. However, many space programs in the past have produced Level 2 data products only to find that the calibration that was used was not correct, or that the sensor had not been fully understood and the calibration was therefore inappropriate. The result was that the entire Level 2 database had to be produced again. For the MSX program, where the volume of Level 1 (i.e., raw, unprocessed) data will be several terabytes, a reprocessing task of this magnitude would have enormous resource allocation implications. Therefore, the MSX program has taken a different approach—that of producing the Level 2 data sets as they are required. Thus, the scientific analysis begins with the best calibration and instrument performance certification available at the time, and analysis that begins late in the program will have the benefit of the accumulated instrument and calibration experience up to that point.

The MSX flight data will be delivered to the scientific investigators along with the procedures and calibration routines required to convert the Level 1A data (i.e., digitized, decommutated, time-ordered) to Level 2 data. This conversion will be performed at the investigator's home institution. The software package that will convert the data from Level 1A to Level 2 is called CONVERT. The CONVERT process is certified by the Data Certification and Technology Transfer principal investigator team and will be recertified each time the calibration of the instrument is adjusted during the mission. The certification process will begin with the oversight of the instrument calibration and the design of the CONVERT algorithms and software. It will be completed with the demonstration of successful conversion of standard test data, provided initially by the ground calibration and later by flight data.

Sensor Calibrations Using Multiple Approaches

The calibration of the optical instruments aboard MSX includes both ground testing and on-orbit measurements. The error budget for the calibration is based on the final specification for the radiometry of the data produced by the MSX sensor suite. The ground chamber testing will probe all of the sensors' radiometric and goniometric performance specifications and will provide data that directly demonstrate that the instruments meet all of their performance specifications prior to flight. The ground calibration data will also be compared with the response of the SPIRIT III sensor to very stable internal sources that will provide a link to the on-orbit calibration data and establish the long-term drift in the response as the result of aging of the various optical components. All of the ground test chamber data are traceable to National Institute of Standards and Technology (NIST) standards.

The on-orbit calibrations will use standard reference objects. Stars and other celestial objects will be used to verify the ground radiometric and goniometric calibrations. The MSX program has supported a ground-based, NIST-traceable measurement program that was designed to measure about 30 reference stars over 5 years, beginning 2 years before flight. These stars are the basis for the external calibration of the long- and short-term repeatability of the sensor on orbit. Because the ground-based observations cannot cover the entire spectrum due to atmospheric absorption, the relative spectral response calibration will be based on not only the reference star photospheric emission models, but also on the measurement of six NIST-calibrated reference spheres that will be periodically released from the spacecraft. Five black emissive objects will provide secondary infrared calibration sources. One reflective object will validate models of the upwelling earthshine, which is one of the larger uncertainties in the radiometric error budget for the emissive spheres. The spheres have a diameter of 2 cm and are spring-deployed at about 13 m/s. Figure 3 summarizes this multifaceted approach to calibration.

Characterization of Contamination Effects

The optical sensors on MSX are designed to strongly reject off-axis radiation, since they will be viewing dim targets in the presence of bright sources such as the Earth. Careful baffling and superpolished mirrors can provide excellent performance, but any contamination quickly degrades that performance by an order of magnitude or more. To completely understand the collected data, it is important to know how this performance varies with time on orbit. The suite of contamination sensors on MSX is designed to provide these data; it includes a pressure gauge, neutral and ion mass spectrometers, quartz-crystal microbalances (with one adjacent to the SPIRIT III main mirror), and flash lamps that work in conjunction with the UVISI instruments to monitor particulates and water vapor in the fields of view of the optical sensors. The response of the sensors to internal stimulators and standard stars, as well as their off-axis performance, will be monitored over their lifetimes and compared with the contamination data to assess the impact of contamination on the design of operational sensors. These contamination data will also be used to validate the spacecraft contamination control plan and a contamination model that can be used by future spacecraft designers.

CONCLUSION

The MSX satellite has a suite of state-of-the-art radiometers, imagers, and spectrometers covering the spectrum from the far ultraviolet to the very-long-wave infrared. It will not only provide data to answer fundamental questions about the performance of BMDO surveillance systems, but it can serve as a highly capable observatory to collect data of broad scientific interest and of potentially high value to the nation. The infrastructure for experiment planning, operations, and data reduction and analysis is in place. It is expected that there will also be many lessons learned about the operation of a tasked spacecraft, distributed data processing, and the efficient archiving of very large data sets that will be of interest to the civilian space community.

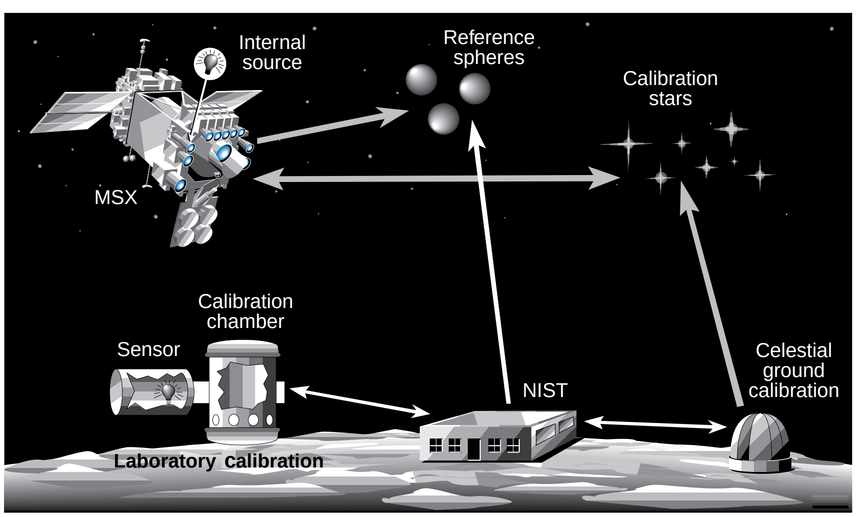

Figure 3. The calibration of the MSX optical sensors incorporates multiple sources both on the ground and in orbit, all traceable to the NIST.

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