# OBSERVATIONS OF THE ORBITAL DEBRIS COMPLEX BY THE MIDCOURSE SPACE EXPERIMENT (MSX) SATELLITE

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## ABSTRACT

The Midcourse Space Experiment (MSX) spacecraft offers a unique opportunity to observe debris at multiple, simultaneous wavelengths, or in conjunction with other sensors or prior data sets. Launched from California into a near sun-synchronous orbit (99° inclination, 888 km circular orbit) on April 24, 1996, the MSX hosts a suite of sophisticated sensors. These include an infrared telescope and interferometer, a visible light telescope, and an ultraviolet telescope and spectroscopic imager. In addition, flash lamps, quartz crystal microbalances, and other systems allow the satellite to measure the contamination environment. The spacecraft carries calibration spheres for instrument calibration and atmospheric drag studies. This paper reviews the experiment plans, their implementation for debris targets/volumes of interest, data reduction techniques, and preliminary results.

## 1. INTRODUCTION

The MSX (Fig. 1) offers an unprecedented capability to assess the particulate environment, from microns to large spacecraft. The vehicle's primary instrument is the 35 cm aperture SPIRIT III infrared radiometer (5 bands between 6 and 28 μm) and interferometer (4-5 μm). Our primary instrument, however, is the 15.2 cm aperture Space Based Visible (SBV) telescope; this instrument is sensitive to 300-900 nm wavelengths. Finally, Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instruments, sensitive to 110-900 nm, round out the optical sensor suite. Other sensors include quartz crystal microbalances (to measure particulate contamination), a mass spectrometer, a BRDF monitor (to monitor the degradation of the optics), and flash lamps. In particular, a Xenon flash lamp has been used in concert with the UVISI wide field of view imager to observe the micron-sized contamination environment. The expected lifetimes of all instruments are 5 years, with the exception of the SPIRIT III. This instrument, limited by the cryostat's hydrogen load, was expected to be functional for 12 to 18 months. Unfortunately, cryogens were exhausted in February 1997, thus ending the cryogen phase of operations.

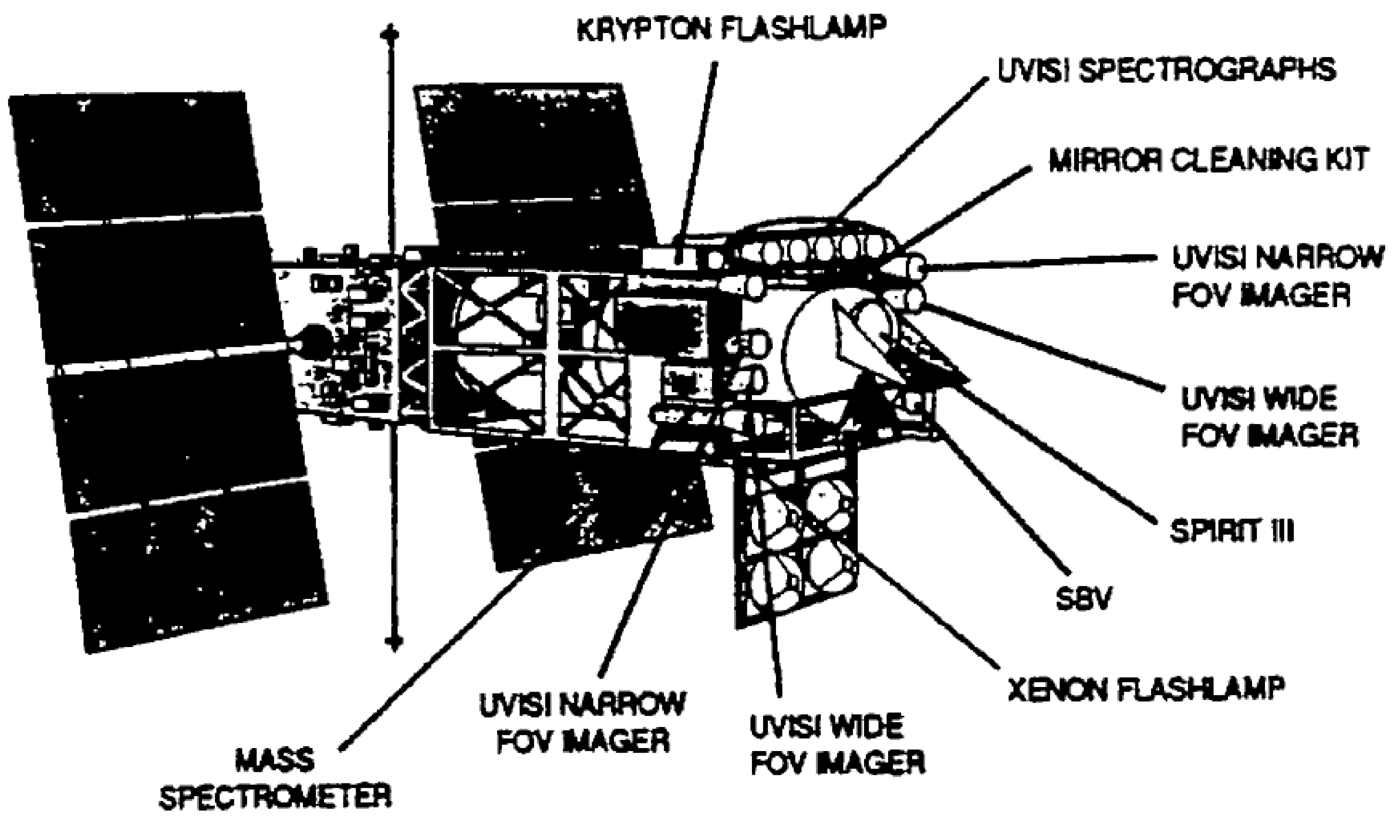


Figure 1. The MSX in operational configuration; principal instruments are identified.

## 2. EXPERIMENT PLANS

The MSX Space Surveillance Principal Investigator (PI) team (Dr. Mike Gaposchkin, MIT/Lincoln Laboratory team leader) has sponsored and implemented two dedicated debris observation experiments. These concern multicolor observations of cataloged objects and statistical volume searches of MSX-local space.

### 2.1 Detection and Characterization (SU11)

The primary goal of this experiment plan is to observe cataloged debris concurrently in the visible and infrared (IR) wavelengths (cryogen phase) or in the visible (post-cryogen phase). The former category yields information about the phase function, albedo and diameter of the debris. Visible light-only observations can expand the database of available observations gathered from ground-based observations and the concurrent cryogen phase observations and to better the current interpretation of albedos and phase functions. A secondary goal is the comparison of debris clouds for systematic differences.

Target lists were generated for several debris clouds of interest. Table 1 details these target clouds; note that they span the range of fragmentation types from a hypothesized collision (*Cosmos 1275*) to low intensity and high intensity explosions. Anomalous (*Cosmos 1484*) and deep space (*Telecom/INMARSAT rocket booster*) clouds are also included. MSX has observed other resident space objects (RSOs), in addition to the cloud members, under the auspices of this experiment.

| Cloud Name | COSPAR designator | Source/Number of cataloged objects |
|---|---|---|
| NOAA 3 | 1973-086 | Delta/197 |
| Nimbus 6 | 1975-052 | Delta/235 |
| Cosmos 1275 | 1981-053 | Payload/305 |
| Cosmos 1484 | 1983-075 | Payload/35 |
| SPOT-1 | 1986-019 | Ariane 1/489 |
| Telecom 2B-INMARSAT 2-F4 | 1992-021 | Ariane 4/13 |
| Cosmos 2227 | 1992-093 | SL-16 *Zenit*/216 |
| STEP 2 R/B | 1994-029 | Pegasus-HAPS/613 |

Table 1. SU11 Observation Targets.

2.2 Ram/Wake Observations (SU12)

The goal of this experiment is to search MSX-local space for close approaches by particles 1 cm and greater in diameter and thereby statistically characterize the environment. Observations are conducted by the SBV only. The frequency of observation is governed by the local debris spatial density and relative velocities and MSX optical, focal plane, and onboard signal processor programming. Figure 2 depicts the approximate azimuth distribution in the local horizontal plane of

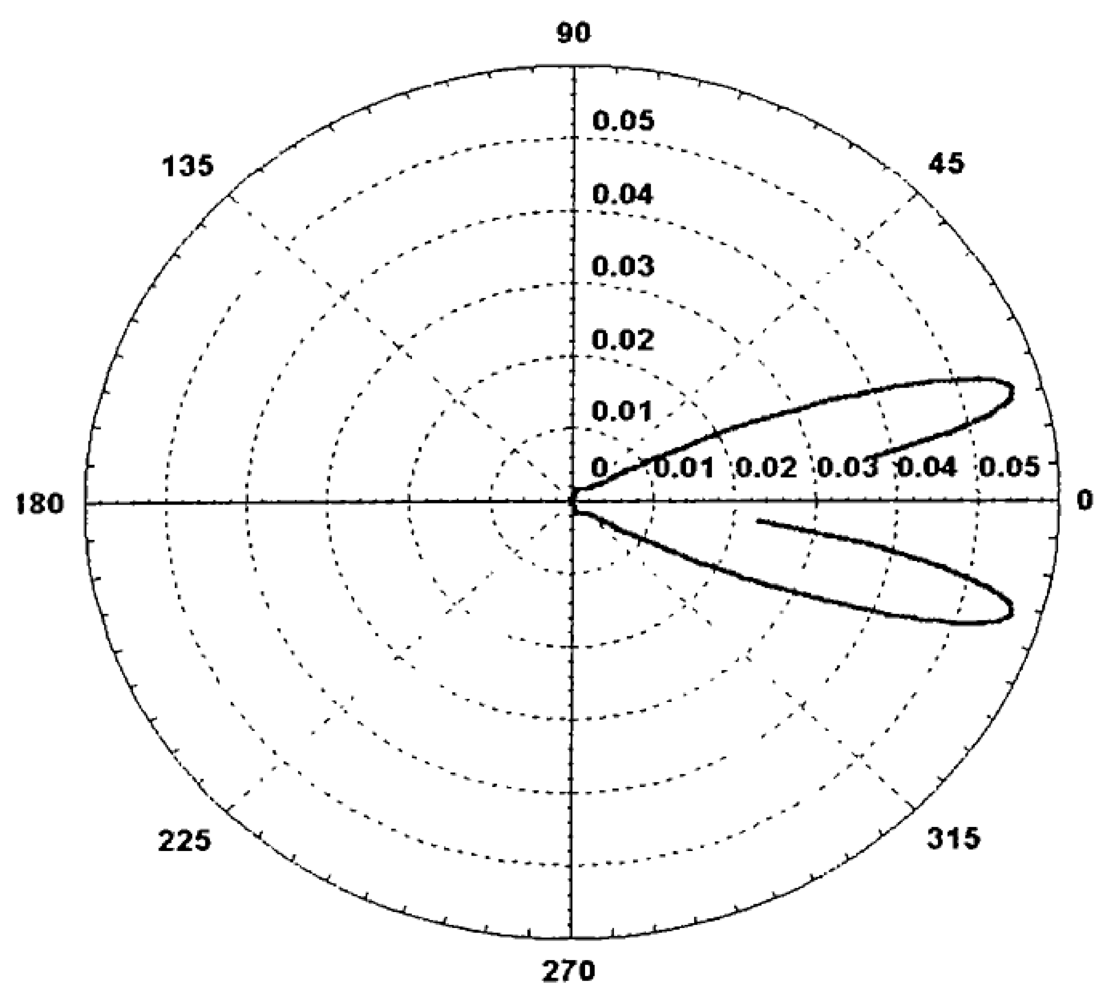


Figure 2. Azimuth distribution of close approaches.

objects impacting or approaching the MSX, in which case the bilobed distribution of Figure 2 is symmetric about the vertical axis. Azimuth is measured with respect to the MSX velocity vector, and radial units are relative; the MSX operational orbit is fairly insensitive to the latest revision of the NASA engineering model (Ref. 1). MSX beam pointing is optimized to maximize the product of debris flux and detection fan surface area so as to maximize the dwell time of objects within the detector fan.

2.3 RSO Fragmentation (SU13)

This Quick Reaction Event (QRE) experiment plan was originally scheduled to observe satellite fragmentations within days of the event. Observations would be queued by the passage of a new debris cloud through the US Space Surveillance Network (SSN) AN/FPS-85 (Eglin) or Naval Space Surveillance radar fences. However, current funding and staffing limitations have eliminated this, and all other QREs, from implementation.

## 3. DATA REDUCTION AND ANALYSIS

The visible (or ultraviolet) light flux observed by the SBV may be described by the equation:

$$F = k \cdot \Omega \cdot A \cdot \int S(\lambda) \cdot Q(\lambda) \cdot d\lambda, \qquad (1)$$

over the bandpass $(\lambda_1, \lambda_2)$ [nm]. This bandpass is determined by the target spectral response function Q and as such incorporates losses at the surface of the satellite. $S(\lambda)$ is the spectral solar irradiance [PAMREF0] at one astronomical unit (AU) [$W/m^2/nm$]; The factor k represents the spectral response of the focal plane charge coupled device (CCD), losses in the reflecting surfaces, *etc*. Taken together, the integral and k may be replaced in Eq. 1 by:

$$F = \Omega \cdot A \cdot F_O. \qquad (2)$$

Here, $F_O$ is the flux [$W/m^2$] incident at the target; the quantity $\Omega$ represents the solid angle [sr] subtended by the target, and is defined by:

$$\Omega = \pi \cdot (r/R)^2 \qquad (3)$$

where r is the radius of the target [m] and R is the range of the target from the MSX [m]. A is the Bond albedo, or the wavelength-averaged albedo of the target. In general, the albedo of a target is the ratio of the reflected light to the total incident light. The Bond albedo is defined by:

$$A = A_g \cdot \Phi(\theta). \qquad (4)$$

$A_g$ is the geometric albedo presented to the observer or observing station and $\Phi$ is the photometric function or, more commonly, the phase function. The phase function depends upon the phase angle $\theta$. The phase angle is defined as the angle between a target-MSX vector and a target-sun vector.

The visible light flux incident at the target, $F_O$, is not an obviously measurable quantity; however, the calibrated magnitude of the object is readily measured by the SBV. The apparent magnitude, $m_i$, of two objects (Ref. 2) is given by:

$$m_1 - m_2 = -2.5 \cdot \log_{10}(f_1/f_2), \quad (5)$$

where the $f_i$ represent observed energy fluence. Since $F_O$ is the visible light incident at the target object, this quantity may be replaced by the solar apparent visual magnitude, -26.78. Solving for the ratio of visible light flux at the object to that measured at the MSX and rearranging Eq. 2 and inserting Eq. 5, we obtain:

$$A \cdot \Phi(\theta) \cdot r^2 = (R^2/\pi) \cdot 10^{-0.4 \cdot m - 10.712}. \quad (6)$$

Magnitudes have been calibrated using Landolt star fields and the SBV has a limiting visual magnitude of approximately 14.

IR-wavelength SPIRIT III observations are generally similar, except that the IR flux is defined by:

$$F_{IR} = \Omega \cdot \int \varepsilon(\lambda) \cdot g(\lambda) \cdot B(\lambda,T) \cdot d\lambda, \quad (7)$$

where $F_{IR}$ is the calibrated IR flux [$W/m^2$], $g(\lambda)$ is the SPIRIT III response function, $\varepsilon(\lambda)$ is the emissivity, $B(\lambda,T)$ is the Planck function [$W/m^2/\mu m$], and T is the target's temperature [K]. Eq. 7 may be used in conjunction with the visible light relations to estimate physical properties of the debris (*e.g.* target radius), or may be used independently to derive the temperature of the target by ratioing band-to-band IR flux. Both band-to-band and absolute radiometric calibrations demonstrate a high degree of repeatability and accuracy.

### 3.1 Concurrent Visible/Infrared Observations

A computer-based analysis system has been assembled which will allow an analyst to estimate the albedo and radius of an RSO by matching these characteristics with the observed visual magnitude and thermal emission (Ref. 3). Thermophysical models (Ref. 4) for flat plates and spherical targets, as utilized by previous attempts to collect multicolor debris data, are required by this iterative technique.

Given the known positions of the MSX, the RSO, and the sun, the solar phase angle is easily determined. Assumptions regarding the phase function and the thermophysical target model (including the target's emissivity and non-uniform IR "beaming" parameters) are present. However, ancillary data sets (*e.g.* the NASA radar cross section-size catalog (Ref. 5) or known RSO construction details) may be applied to the results of the iterative solver to refine the assumptions and therefore the results.

### 3.2 Visible-Only Observations

These operations are conducted during SU11's post-cryogen phase and SU12 data collection events. Statistical estimates of the albedo and phase function may be used by the analyst to solve for the target diameter *via* Eq. 6. These estimates may be derived either from the results of § 3.1 or by the use of ancillary data sets. Distributions of albedos and phase functions collected by Henize and coworkers using the NASA CCD Debris Telescope and its predecessors (Ref. 6) or laboratory measurements (Ref. 7) of hypervelocity impact debris provide such a means of reducing SBV-only observations.

### 3.3 Related Experiments

The MSX Contamination PI team (Dr. O. Manual Uy, Johns Hopkins University/Applied Physics Laboratory team leader) sponsors several experiments of interest. These include measurement of small particles (1 μm diameter or larger at cross-field relative velocities of between 1 mm/s and 50 m/s) released by the spacecraft as a function of orbital position (dawn/dusk); local geophysical environment; and spacecraft attitude and slew rate (Ref. 8). In addition, this PI team hosts the experiment to measure the orbital decay of the onboard 2 cm diameter calibration spheres. Five emissive black spheres, all solid, were deployed successfully during the cryogen phase. The hollow gold sphere was not deployed.

## 4. EARLY RESULTS

### 4.1 Detection and Characterization (SU11)

All observations to date have consisted of concurrent SBV and SPIRIT III operations. Observations of members of the *Cosmos 1275* and the *Cosmos 2227*, *Nimbus 6* R/B, and *Telecom/INMARSAT* rocket body debris clouds have been collected. In addition, non-fragmentation debris RSOs have been observed during this experiment.

As of this writing, the concurrent visible and IR data have not been released for analysis at NASA Johnson Space Center. *Convert*, the computer program which converts raw SPIRIT III data to calibrated and registered data sets, is undergoing continued development. Delivery, and analysis, of these data therefore awaits the completion of this effort.

4.2 Ram/Wake Observations (SU12)

This experiment has been run, in SBV-only mode, a total of seven times. During these opportunities, a total of approximately 200 minutes of data have been collected. These data include two categories of observations: targets correlated with the SSN catalog, and uncorrelated targets (UCTs).

Correlated targets (including intact and debris RSOs) were observed in low Earth orbit, deep-space transfer or operational orbits, and middle Earth orbit. All were in the far field, and as such will be analyzed in a manner similar to SU11 targets.

A total of 120 uncorrelated events were observed using exposure times of 0.4 and 1.6 seconds per frame; these possess a length of 6 or more pixels across the SBV's focal plane. Shorter streaks were excluded from further consideration by the SBV on-board signal processor. However, reasonable assumptions as to phase angle, albedo, and target relative velocity across the line of site indicate that a frequency of 120 per 200 minutes significantly exceeds the expected count rate.

In order to characterize the response of the SBV to cosmic ray events and other transient phenomena, closed door (dark) frame sets were collected by MIT/Lincoln Laboratory personnel (Ref. 9). A significant number of the UCTs observed thus far may be similar in nature to these dark frame events. However, a dependence upon latitude, such as one might expect during South Atlantic Anomaly or magnetosphere passage at the poles, is not readily apparent in an initial analysis of these data.

## 5. STATUS AND CONCLUSIONS

At this time, a data reduction pipeline has been established at NASA Johnson Space Center. When concurrent visible and IR SU11 data are received, the data will be processed to estimate the albedo, phase function type, the temperature, and the diameter of RSOs. Debris clouds shall also be examined to determine whether they display statistically significant differences in these characteristics.

MIT/Lincoln Laboratory has been requested to collect full frame data sets so that investigators may examine the frequency of streaks of various lengths across the focal plane as well as possible dependencies upon geophysical location, local environment, solar weather, etc. The results of this analysis shall be applied to the SBV-processed data to eliminate anomalous events and false UCTs. After anomalous events have been eliminated, the remaining data may be compared against current environmental models.

As the MSX enters its post-cryogen phase of operations, a significant opportunity exists for SBV observations. Utilization on the order of 8 hours per day is possible. Therefore, SU11 and SU12 data collection events will be continued in order to increase the sample size of RSO and UCTs and therefore better the statistics of these measurements. The authors look forward to publishing quantitative findings as early as possible.

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