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AIR FORCE MAUI OPTICAL STATION (AMOS) ORBITAL DEBRIS DETECTION PROGRAM

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ABSTRACT

The United States Air Force Phillips Laboratory has been conducting nightly observations of the debris environment using the Air Force Maui Optical Station (AMOS) and the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) facilities, both of which are located at the Maui Space Surveillance Site, collecting approximately fifty to sixty hours of observation per month during twilight periods. The goals of this program will be discussed, with emphasis on the detection program. This includes discussion of telescopes and sensors available, how they are used, choice of telescope, and mode of operation. Also discussed will be the data collected, and the correlation of our detections with the our local catalog of space objects. Analysis is presented for observations taken during the last two years, both at the Maui site as well as the Diego Garcia GEODSS site.

1. INTRODUCTION

The Air Force Maui Optical Station (AMOS) is conducting searches, measurements, and analyses of orbital debris for Air Force Space Command and the Phillips Laboratory (PL) in support of the Air Force Orbital Debris Measurements Program. The objective of this program is to detect orbiting objects not currently in the United States Space Command Space Surveillance Center (SSC) catalog. Once detected, further objectives are to track, catalog, and maintain those objects locally, to determine statistics on detected objects, and perform relevant analyses. In addition to this surveillance activity, AMOS is also automating the detection and analysis process, and developing a prototype surveillance system for detection of orbital debris. The AMOS program is a joint effort between various government and contractor agencies to employ the wide field of view optical sensors at the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) site at the Maui Space Surveillance Site (MSSS) and narrow field of view tracking sensors at AMOS (also located at the MSSS). There are several partners in this program. Air Force Space Command provides the funding and the direction for the program. Phillips Laboratory provides the program management, as well as simulation and analysis. Phillips Laboratory also provides the search, measurement, and analysis capabilities using its AMOS facility in Hawai'i. Rockwell Power Systems (RPS) is the prime contractor for the AMOS facility, with additional support from Rockwell International. The prime contractor for the GEODSS facility is Planning Research Corporation (PRC). Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) provides PL with capabilities similar to that of AMOS, at the Experimental Test System (ETS) in New Mexico. The success of this program depends quite heavily on the support and cooperation of all of these organizations.

2. BACKGROUND

The United States Space Command is responsible for the SSC satellite catalog. The sensors available for this task are primarily radar sensors and optical sensors. These categories are further broken down into dedicated sensors, which are controlled directly by Air Force Space Command, and contributing sensors, which may have other tasks. The GEODSS facilities and the Maui Optical Tracking and Identification Facility (MOTIF) are dedicated sensors, while the AMOS sensors are contributing sensors. For an object to appear in the SSC catalog, it must be observed at multiple sites and by multiple observations. This is not generally a problem when the objects are routinely detected by radar sites. However, if an object is first detected by an optical site, it may be that the radar cross section (RCS) is very small, and the object may not be seen by radars. In addition, since optical sites observe passively, a given object may be visible only at discrete locations in its orbit. Therefore, it may be more difficult to catalog and maintain these objects. There are numerous sources of orbital debris (95% of the trackable satellites in the SSC catalog are debris objects), but they can generally be considered in three categories. They can be the result of normal space operations (rocket bodies, staging events, abandoned spacecraft) , the result of satellite aging (thermal stress, atomic oxygen reactions), or they can arise from satellite fragmentation (deliberate destruction, propulsion related, collision) (Ref. 1) The size of these objects ranges from rocket bodies and non-functional satellites meters across, to microscopic particles not visible to either radar or optical sensors. It is generally postulated that the number of orbital debris objects increases rapidly as the size decreases.

Orbital debris is a problem which has potential to threaten the safety of existing and future space programs. As the number of debris objects increases, so does the chance of collision. Many of the studies on the effect of space debris concentrates on the probability of losing a satellite. A problem just as significant is the loss or degradation of satellite subsystems due to collision. An SDIO official recently attributed leaks in the thruster subsystem and subsequent loss of thruster capability on the PL Miniature Seeker Technology Integration (MSTI) satellite to orbital debris (Ref. 2)

One of the findings of the Office of Technology Assessment of the United States Congress in 1990 was that "lack of adequate data on the orbital distribution and size of debris will continue to hamper efforts to reduce the threat that debris poses to spacecraft." (Ref 3) The Air Force Orbital Debris Measurements Program is an effort to generate data to increase the information available to the community on distribution and size of existing orbital debris.

3. OPERATIONS

The operational goals of this program are to detect, track, catalog, and maintain new objects. During real time operations, only the detect and track goals are achieved. During post-processing, all goals are either achieved or supported.

A wide variety of equipment and resources are available to the Orbital Debris Measurements Program. The optical assets include a multitude of sensors and mounts at both the MSSS as well as Diego Garcia. The optical assets at the MSSS include a total of eight telescopes on seven mounts, with a wide range of associated sensors. A brief description of the MSSS assets is shown in Table 1. Note the availability of visible and infrared photometric sensors, imaging sensors, and video capability. Video equipment is available both at the MSSS, located at the 3,000 meter summit of Mt Haleakala, as well as the support facility located at sea level in the town of Kihei. A broad range of computer equipment is also available. The platforms most commonly used in support of the program include products from Silicon Graphics, Sun, Datacube, and Macintosh.

TELESCOPE	APERTURE (m)	SENSOR	RESPONSE (μm)
1.6	1.596	AATS	.4-.8
		CIS	.4-.8
		PHIAT	.35-1.0
		PIS Array	1.2-5.9
		ASR	1-30
		Boresight TV	.4-.8
		ELSI	2.2-5.5 8-13.5
1.2 (B29)	1.219	MATS	.4-.8
		AMTA	3-23
		CMP	3-.92
		Boresight TV	.4-.8
1.2 (B37)	1.219	MAIS	.4-.8
		LLLTV	.4-.8
LBD	0.635	Boresight TV	.4-.8
BD/T	0.815	BATS	.4-.8
		Boresight TV	.4-.8
GEODSS Main	1.01	Video	.4-.8
GEODSS Aux	0.38	Video	.4-.8

Table 1. MSSS Optical Assets

3.1 Real time operations

3.1.1 Detection

The most appropriate sensor at the MSSS for the detection process is the sensor with the widest field of view. The sensors which vie for sensor-of-choice are the two GEODSS main telescopes, with a nominal field of view of 2 degrees and sensitivity of 16th magnitude, and the GEODSS auxiliary telescope, with a nominal field of view of 6 degrees and sensitivity of 13th magnitude. Which of these telescopes to use is the first decision which must be addressed. The greater field of view of the auxiliary allows search of a greater volume of space, scaling by the linear increase rather than the area increase, since the objects pass across the field of view. The greater sensitivity of the main allows detection of fainter (smaller) objects, which should scale as the number of objects greater than the minimum size detectable. Preliminary analysis indicates that, if detection rate is the most important factor, the choice should be the GEODSS auxiliary telescope. (Ref. 4) The best way to test this hypothesis is to observe in the same direction with both telescopes, simultaneously. However, since the GEODSS sites are required by contract with AF Space Command to always have two sensors on-line supporting their primary mission, AMOS has access to only one GEODSS sensor at the MSSS at any given time.

The second decision which must be addressed is the search mode to use. There are several types of searches which are used at the AMOS site. If the objects of the search are the resultant particles from a recent breakup, the search technique will be different than if the object of the search is the handoff of a recently discovered object from the ETS in New Mexico. Other object-oriented searches include follow-up searches for objects in the AMOS Analyst catalog (those objects which have been observed at the MSSS or ETS, but are not yet in the SSC catalog), or looking at objects which are expected to break up soon, based on historical data (e.g., SL-12 Proton fourth stages or Delta second stages). In addition, AMOS also performs zenith stares, where the search objective is not to detect any specific object.

The modes chosen for these searches fall into two broad categories: staring and scanning searches. The staring search is simply pointing at a fixed position and waiting for an object to pass through the field of view. The scanning search is where the telescope mount follows a hypothesized debris orbit, and is primarily used to detect objects in the debris cloud resulting from a recent breakup. Although the staring search mode provides the best volume coverage for debris detection, the effective sensor sensitivity is reduced by the trailing of the image due to its relative motion across the field-of-view during an exposure. For the GEODSS auxiliary telescope, this motion results in a loss of detection sensitivity of 1.5 to 0.2 stellar magnitudes for objects in 300 to 1000 km orbits, respectively. (Ref. 5)

The most common search mode is to use the auxiliary telescope in a staring search. GEODSS is tasked by AMOS for approximately 60 hours of observation per month, primarily during morning and evening twilight: terminator passes, at which time the objects are solar-illuminated but the sky background is dark. The video data from the ISIT camera is recorded on 3/4 inch tape for additional processing and analysis.

Correlation of objects with the SSC catalog is performed in real time using the RPS code WorldView. The Prototype AMOS Computer Control System (PACCS) is a system developed jointly by the Phillips Laboratory and RPS which can control all of the AMOS and MOTIF mounts simultaneously. For the Orbital Debris Measurements Program, the PACCS operator views two screens: the video output of the GEODSS ISIT camera, and the output of the WorldView program. The WorldView program has access to a star catalog, as well as the entire SSC catalog. It projects on its screen the star field at which the GEODSS telescope is pointing, as well as those satellites expected to cross the GEODSS field of view. Since the SSC element set may be old, and the predicted appearance of the satellite may be off by several degrees and/or several seconds, the satellite appears on the WorldView screen as a "bead on a wire", with the "wire" appearing on screen for some time before and after the expected appearance of the satellite. The flow of events is shown in Figure 1. If the same object appears on both screens, the object being observed by GEODSS is already in the catalog, and is of no further interest. If an object appears on the WorldView screen, but is not seen by GEODSS, that object is flagged for further study (comparison of objects seen by radar or optical sensors, but not both, discussed later in this paper). If an object appears on the GEODSS screen but not WorldView, it is likely

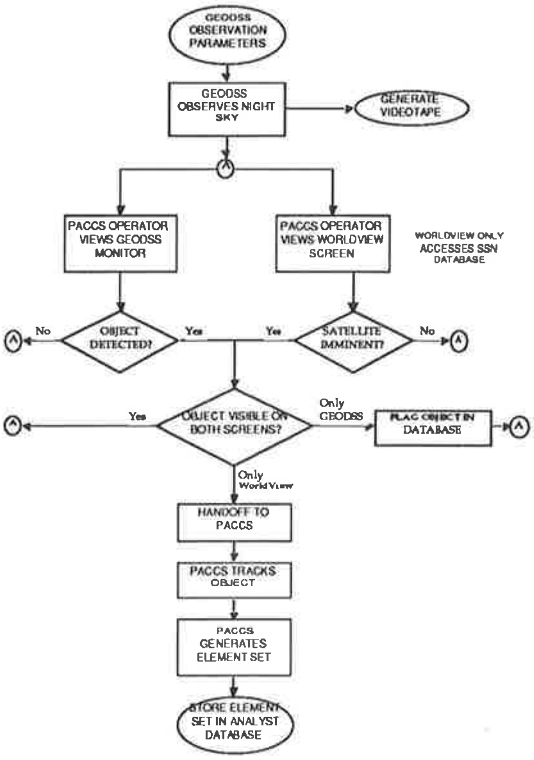

Figure 1. Real time flow chart

a new object, and is therefore handed off to a tracking sensor.

3.1.2 Tracking

There are several sensors at the MSSS which are appropriate for tracking objects. The only sensor eliminated from consideration is the GEODSS sensor being used for detection. If this sensor were to be used, the detection of other objects would be precluded during the track of the first object. This is not desirable, so the operational mode is that GEODSS continues its detection mission while the tracking sensor takes on the tracking mission. Any of the sensors at MOTIF or AMOS would be acceptable. The sensor usually chosen is the one which is not being used by other missions at the time. Currently, it is the Beam Director/Tracker (BD/T). Under some circumstances, however, it may be appropriate to use a sensor with greater sensitivity, with different instrumentation, or larger acquisition field of view. In any case, the system which controls these sensors is always PACCS, since this system has the greatest flexibility. In principle, multiple mounts can be simultaneously dedicated to tracking debris objects.

The operator uses a mouse-driven cursor to take observation positions from the GEODSS screen. The azimuth and elevation of each point is determined by the offset of the cursor from the center of the screen and the mount position of the GEODSS telescope. Using the positions and the derived velocity, an Earth-Centered Inertial (ECI) state vector is estimated and a track file generated using a third order Runge-Kutta two body orbit propagator. The PACCS operator then takes control of the tracking telescope and attempts acquisition on the wide field of view camera, based on the track file. By putting offsets into the mount position after acquisition has been accomplished, the object is centered on the boresight of the camera, and marks are taken on the object. Marks are taken as long as the debris is visible in the boresight camera, and fed into the Kalman filter to determine a final ECI vector. If the debris object is bright enough, a video tracker is used to keep the object centered on the boresight automatically. The ECI state vector is then converted into an element set which is suitable for detecting the object on the next orbit, or perhaps several orbits later. It is important to detect the object again as soon as possible to refine the element set.

Once the track of the object deteriorates, due to slant range, illumination, cloud cover, etc., the PACCS operator returns his attention to the GEODSS screen, and the detection process begins again, searching for the next uncorrelated object which passes through the GEODSS field of view. During this entire time, GEODSS has been maintaining its search profile, with its output video signal being recorded for post-processing.

3.1.3 Additional Data

It is often of interest to determine albedos of objects, and eventually sizes of objects, independent of radar measurements. This is accomplished using a radiometric analysis of simultaneous visible and longwave infrared measurements with MSSS instrumentation. The technique used is similar to that used by astronomers to determine the albedos and sizes of asteroids. The basic theory is that while a large, dark object may be visually as bright as a small, highly-reflective object, it will be hotter, hence brighter, in the thermal infrared. For this reason, AMOS periodically looks at debris objects in both the visible and the infrared.

3.2 Post-processing operations

3.2.1 Detection

The primary data used in the post-processing phase of operations is GEODSS video data which has been previously recorded on 3/4 inch tape. These tapes are transferred daily from the observatory on Mt. Haleakala to the Kihei facility, and processed under more benign conditions.

Processing consists of detection of targets moving against the background star field, recording the object entry and exit times and positions, and determining brightnesses based on comparison with calibrated stars. The positions are converted to apparent right ascension and declination and reported to Air Force Space Command for correlation with the catalog of known satellites for that date. The observations are also processed to obtain initial estimates of object orbital height and inclination using a circular-orbit approximation.

Detection originally was accomplished using human operators (Air Force or Rockwell personnel) to view the videotapes, and log all events for later processing. Much of this time-consuming process is being automated, and the human operator will play a much smaller role. Because of the large amounts of data which must be processed, it is desirable to process the data at video frame rates. Otherwise, the overall process would take much longer than the time available, and the data would begin to backlog. AMOS has chosen to use the Datacube MaxTower system to perform the analysis. (Coincidentally, this is the same platform which MIT/LL has chosen, which allows unexpected synergism.) Although AMOS is continuing to examine alternative algorithms, the current technique uses the equivalent of background subtraction and creation of "super frames." A fuzzy mask of the background star field is generated, and then successive frames are added together, using this fuzzy mask. "Super frames" comprised of several seconds worth of data are then generated, and the human operator is able to view a processed "tape" which is approximately four minutes long, compared to the original tape which is approximately one hour long. This pass comprises the detection phase.

In addition to the correlation which takes place in real time, correlation also takes place in the video processing phase. Every object detected during processing of the videotape is correlated with the SSC catalog, as well as the local AMOS Analyst catalog. Because of the very short time for which an object is visible as it crosses the GEODSS field of view, it is not possible to obtain a very good element set for the object. Nevertheless, it is possible to screen the objects in the SSC catalog to determine possible correlations, based on time of observation, inclination, and altitude. This correlation process uses a series of filters, ranging from coarse to fine, until final correlation is achieved. If the object is not correlated, it is assigned a new AMOS identification number and inserted into the AMOS Analyst catalog. If the object is correlated with an object in the SSC catalog, it is ignored and the next object is analyzed. If the object is correlated with an object in the AMOS Analyst catalog, this observation is used in conjunction with previous observations to generate a better element set, which may be used to either detect the object on its next pass, or to hand it off to another site, such as the ETS.

4. RESULTS

The most intensively processed data to date resulted from a multi-site debris observing campaign organized by Air Force Space Command in August 1992. The Air Force PARCS Radar in South Dakota operated at increased sensitivity for a seventy-two hour period, with three optical sites (the Maui and Diego Garcia GEODSS facilities and the MIT/LL facility near Socorro NM) observing at every available twilight surrounding this period. Fourteen hours of Maui GEODSS auxiliary telescope observations, and four hours of Diego Garcia main telescope observations, were obtained for eight twilight periods over a six-day interval. Eighty-five objects were detected with observed brightnesses ranging from 0 to llth stellar magnitudes. Of these detections, fifty-four objects (sixty-three percent) correlated very closely with cataloged satellites. Approximately thirty-seven percent of the detections did not correlate. The brightest of these uncorrelated targets has an optical cross-section of 10 square meters (assuming a specular sphere) or an effective diameter of 3.5-meters. Space Command is continuing to analyze the results of the observing campaign and will be attempting to correlate detections between sites as well as with the catalog.

In Figure 2 , radar cross section (RCS) is plotted against normalized visual magnitude (NVM) for those objects observed during the coordinated debris campaign which were also in the catalog. NVM is the magnitude of the object if it were at a slant range of 1000 km. Superimposed on this figure is a plot of RCS versus NVM for specular spheres of albedo 0.08 and 1.0. Within the constraints of this model, the line representing 1.0 albedo is a relatively conservative estimate of minimum object size. Using this line as a basis for size estimation of the uncorrelated objects from that same campaign, Figure 3 shows their apparent size as a function of altitude. Note that some of these objects, which do not correlate with anything in the SSC catalog, are quite large. It is apparent from this data that radar sites and optical sites are sensitive to different subsets of the entire orbiting population. There are some objects which are very bright visually, but which apparently have very small radar cross section. This is a subject of active interest, and is a high priority within the Air Force Debris Measurement Program. AMOS is in the process of establishing a database within the AMOS Analyst catalog that monitors those objects which are not seen by radar, but consistently seen by optical sites, as well as those objects which are routinely seen by radar, but rarely seen by optical sites.

5. CONCLUSIONS

It appears that the optical sensors may be sampling a different debris environment than the radar sensors used to maintain the catalog. Some objects which have a large RCS have a low optical brightness, while some objects with small RCS have

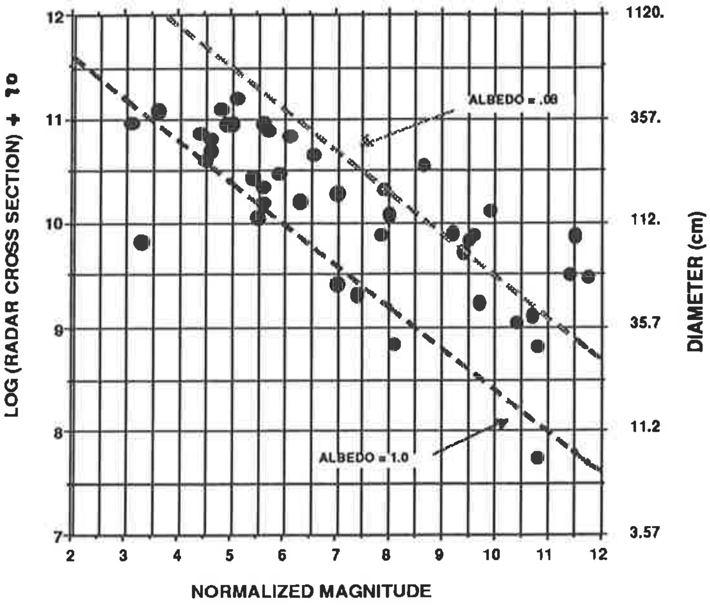

Figure 2. Maui/PARCS Results

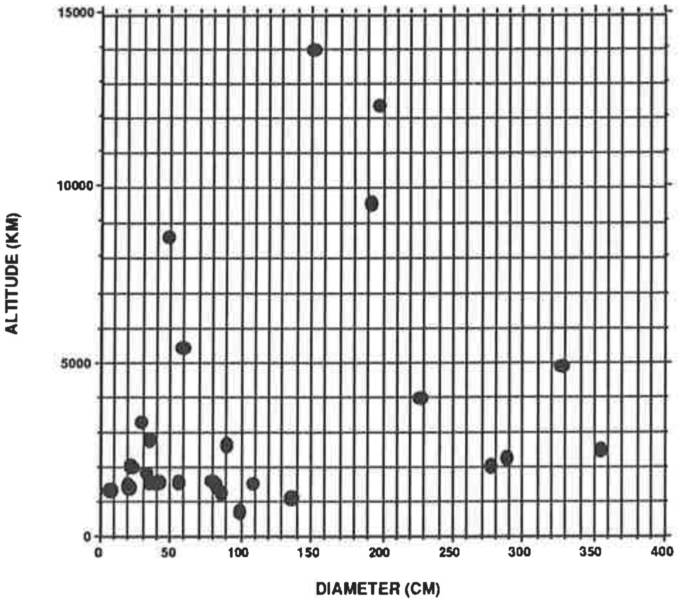

Figure 3. Altitude/Size Distribution

quite large brightness. Some of the debris objects we have seen that are not in the SSC catalog are quite large, possible meters in size. A database is being constructed of objects which radar sites see but optical sites do not, and vice versa. It is expected that as this database grows, our understanding of the properties of these objects will grow as well. Several hypotheses involving debris material and orbital properties are being investigated, including the possible materials and structures which would lead to these apparent disparities, and the orbits which are more often represented in each catalog.

6. REFERENCES

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