

IAC-10.A6.1.5

ORBITAL DEBRIS DETECTION AND TRACKING STRATEGIES FOR THE NASA/AFRL METER CLASS AUTONOMOUS TELESCOPE (MCAT)

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The Meter-Class Autonomous Telescope (MCAT) is a 1.3m f/4 Ritchey-Chrétien on a double horseshoe equatorial mount that will be deployed in early 2011 to the western pacific island of Legan in the Kwajalein Atoll to perform orbital debris observations for the National Aeronautics and Space Administration (NASA) and the Air Force Research Lab (AFRL). MCAT will be capable of tracking earth orbital objects at all inclinations and at altitudes from 200 km to geosynchronous. MCAT's primary objective is the detection of new orbital debris in both low-inclination low-earth orbits (LEO) and at geosynchronous earth orbit (GEO) down to 2 and 10 cm diameters respectively. MCAT was designed with a fast focal ratio and a large field of view (FOV). The primary detector is a closed-cycle-cooled 4Kx4K 15 μ m pixel CCD camera that yields a 0.96° diagonal field. For orbital debris detection in widely spaced angular rate regimes, the camera offers low read-noise performance over a wide range of framing rates. MCAT's 4-port camera operates from 100 kHz to 1.5 MHz per port at 2 and 10 electron (e⁻) read noise respectively. This enables low-noise multi-second exposures for GEO observations as well as moderate (one frame per second) exposures for LEO. GEO observations will be performed initially using a counter-sidereal time delay integration (CSTDI) technique which NASA has used successfully in the past. For LEO observations two methods will be employed. The first, Stare and Chase Mode (SCM), will perform a static or sidereal stare, then detect, discriminate, acquire, and track objects that enter the MCAT (or its auxiliary telescope) field of view and which satisfy specific rate and brightness criteria. The second, Orbit Survey Mode (OSM), will scan specific orbital inclination and altitude regimes, detect new orbital debris objects against trailed background stars, and adjust the telescope track to follow the detected object. Orbits generated by SCM and OSM will be used for reacquisition by MCAT (and other assets) and as inputs to the orbital object environment definition. All three operational modes, as well as photometric and astrometric reduction will be fully automated. MCAT, its objectives, and its methods, are described herein.

I. INTRODUCTION

The earth orbital environment is populated with both functional spacecraft and the remnants of prior launches. The remnants, consisting of inactive payloads, spent rocket bodies, operational debris, and explosion or collision byproducts, (collectively *space debris*), pose a significant and increasing risk to current and future space activities via the possibility of on-orbit collision. Monitoring the earth orbital environment is a primary responsibility of US Air Force Space Command (AFSPC), a service component of US Strategic Command (USSTRATCOM). The Joint Space Operations Center (JSpOC) manages maintains and operates the Space Surveillance Network (SSN) which continuously observes the orbital object environment via a global

array of ground-based optical and radar sensors. SSN sensors enable JSpOC to actively maintain a comprehensive catalog (containing 21,000 tracked objects, of which 16,000 are cataloged as of June 2010) of the LEO (Low Earth Orbit), MEO (Middle Earth Orbit), and GEO (Geosynchronous Earth Orbit) orbital populations extending down to sizes of approximately 10, 50, and 100 cm diameter respectively [1].

The Orbital Debris Program Office (ODPO) at NASA's Johnson Space Center (NASA-JSC) has primary responsibility for defining the debris population for objects below the SSN detection limit. To this end, ODPO provides observational capability and conducts extensive data reduction, modeling, and collision risk analysis as part of its role in supporting civilian space activities. ODPO's current contributing sensors include NASA's Goldstone (X-Band) radar, the Haystack (X-Band) and Haystack Auxiliary (Ku-Band) radars operated by MIT Lincoln Labs [2], the Michigan Orbital Debris Survey Telescope (MODEST) – a 0.6 m Schmidt operated by the University of Michigan at Cerro Tololo Inter-American Observatory (CTIO) [3], the 0.9m CTIO Cassegrain operated by the Small and Moderate Aperture Research Telescope System

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(SMARTS) Consortium, and the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, HI [4]. Retired sensors include primarily the CCD Debris Telescope (CDT) – a semi-portable 0.32 m Schmidt constructed and operated by ODPO at multiple sites [5], and the 3.0 m Liquid Mirror Telescope (LMT) – an f/1.5 prime focus Newtonian operated at the NASA Orbital Debris Observatory in Cloudcroft, NM [6].

NASA's suite of both radar and optical sensors has been selected to address deficiencies in understanding the orbital object population. Gathering population statistics in the mm and cm size regime, well below the SSN detection limit, is performed by the radars. Unlike most SSN radars operating at lower frequency/longer wavelength (and thus larger size detection limit), those operating in X and Ku bands enable them to effectively probe the millimeter sized component of the debris environment. Demonstrating the importance of their contribution, NASA's analysis of its radar data indicates there are currently greater than 500,000 cm or larger sized targets in LEO – far in excess of the SSN tracked cataloged and tracked population [7]. As active sensors the radars operate independently of lighting conditions and can ostensibly observe continuously, but they are also effectively range restricted to LEO due to outbound/return power-law losses. Beyond LEO, optical sensors, viewing solar illuminated targets, are less range restricted than radars, however their observations are weather and illumination dependent. Optical sensors gather photometric information (brightness, time dependence, phase function, low-resolution spectroscopy) to ascertain sizes via application of albedo values. The albedos themselves are normally derived from cross-correlated radar size estimates and optical observations, coupled with extensive mathematical modeling to remove selection effects [8]. An optical population has been derived for LEO, MEO, and GEO orbital regimes – the later being an active area of interest. Ultimately, because of the significant variation in the radar and optical response of orbital debris targets (due to their material construction, topology, and time dependent orientation), combining radar and optical derived populations yields a more comprehensive view of the orbital object population and thus more accurate collision risk assessments and improved mitigation efforts.

The experience gained utilizing each of these instruments for orbital debris studies, from observational techniques to optical design to detector selection, is being incorporated into MCAT. Even site selection was driven in large part by the desire for co-location with radars so that simultaneous optical and radar properties could be observed for debris objects.

II. MCAT DESCRIPTION

The MCAT project was conceived jointly by NASA-JSC's ODPO and the US Air Force Research Laboratories (AFRL) Detachment 15 as a tool to detect, track, and study space debris. From the outset, MCAT was designed with manifold capabilities in terms of target detection, discrimination, acquisition, tracking, astrometric and photometric characterization, and accessibility to orbital regimes. MCAT will sample the earth orbital object population from 200 km through GEO altitudes, down to 2 and 10 cm diameter sizes respectively, and at all orbital inclinations. It will operate initially at optical wavelengths but the design accommodates an IR sensor for future work. Importantly MCAT will autonomously execute any one of a suite of observational modes tailored to specific targets of interest.

Even with the geographic diversity and coverage of the SSN, low-inclination and near-geostationary orbits have been historically under-sampled. Due to its low-latitude, site availability, and existing infrastructure, the United States Army Base at Kwajalein Atoll, Republic of the Marshall Islands, was chosen by NASA and AFRL as a suitable location for MCAT. At 8.98° North latitude, and 167.6° West Longitude, Legan Island, within the atoll, provides a dark site (20.7 mag/square arcsecond R-Band; 21.5 in V), enabling access to both low-inclination LEO orbits (200 km altitude at 0° inclination) and GEO longitudes that are not accessible to other sensors. Although a sea level site is not ideal from a benign environmental or atmospheric extinction perspective, Legan is well suited in terms of orbit accessibility. The nearby radar complex on Roi-Namur Island, 40 km NNE of Legan, and the potential for simultaneous radar and



Fig. 1: Close-up of Legan Island (8.98° N, 167.6° W) in the Kwajalein Atoll, Republic of the Marshall Islands. As part of the Reagan Test Site (RTS), extensive infrastructure and technical support is available due the US Army presence on the atoll. A conception of the MCAT facility is indicated via numeral one (I). Facility construction will begin first quarter of fiscal year 2011.

optical observations of orbital debris targets, significantly expands MCAT's utility at the chosen site (Fig. 1).

Several unique elements have been incorporated in the MCAT design so that it can achieve its mission objectives. Achieving the faintest orbital object detection limits with maximized field size dictated the optical design. A large (> 1 meter diameter) aperture was desired but at a focal length which still provided an adequate field of view (survey fence). Cost, detector accessibility/interchangeability, and field aberrations eliminated Newtonian, Schmidt, and Cassegrain configurations and their variants. A modified Richey Chretien (RC) design employing primary and secondary mirrors of equal and opposite curvature, and a sub-aperture aspheric corrector plate, was chosen. This gives a flat field, free of coma and astigmatism. The relatively fast $f/4$ focal ratio is an ideal solution that allows a large aperture while still realizing a near one degree FOV with a conventional large-format detector. DFM Engineering Incorporated (DFM) had several 1.3 m $f/4$ RC telescopes already in production and was selected to construct MCAT. The optical prescription has an 87 mm (0.96°) image circle, 15 micron (μm) 80% energy spots at field edges (30 μm at corners), and well controlled lateral chromatic aberration. Throughput is 68% despite the over-sized secondary (48% aperture diameter) necessary to provide the unvignetted image circle. Secondary collimation is achieved via 5-axis support and the secondary heading is Invar metered with respect to the primary. Focal and collimation stability is expected to be a few microns in the thermally stable Legan environment. Figure 2 shows a DFM 1.3m $f/4$ RC under construction for another customer. It is very similar to MCAT.

While initially operating solely in the optical regime, MCAT is near infrared (NIR) capable with bandwidth extending to 4.0 μm and enough back focal distance (20 cm) to accommodate a dichroic mirror allowing simultaneous multi-spectral (optical/IR) observations. The MCAT optical detector, manufactured by Spectral Instruments Inc., utilizes a 4Kx4K Charge Coupled Device (CCD) from e2v Technologies (Fig. 3). With 15 μm pixels, the plate scale is 0.75 arcsecond/pixel, thus Nyquist sampling the expected 1.5 arcsecond nominal seeing on Legan. At 1.9-2.0 electron (e^-) read noise and negligible dark current (at -100°C), the CCD is well suited for multi-second GEO exposures. Possessing four read ports and peak 1.5 MHz read rate, the CCD is also suitable for moderate frame rate, short exposure MEO and LEO observations, albeit at higher read noise (10 e^-). While SSN tracking by MCAT, where orbital elements are known a priori, or Orbit Survey Mode (OSM), where specific orbit tracks are scanned, is possible at all altitudes, the



Fig. 2: A 1.3 m $f/4$ Ritchey Chretien telescope under construction at the DFM Engineering Incorporated facility in Longmont, CO. The OTA incorporates a 5-axis stage for secondary collimation, Invar metered truss, and a primary mirror cover. The double horseshoe mount provides a stable equatorial mount for a low latitude site with the added benefit of unobstructed north polar and south horizon access. The MCAT design is very similar to this unit.

maximum frame rate (about one frame per second (fps)), limits MCAT's real time target detection, discrimination, and tracking via Stare and Chase Mode (SCM) to approximately 2000 km orbital altitude and higher. This is due to the requirement that two or more sequential detections are required to generate an initial trajectory. The MCAT CCD cannot frame fast enough to produce two frames within the field crossing time (FCT) of a target below 2000 km (e.g. FCT \sim 0.4 seconds at 200 km). Addressing this limitation, MCAT will use two approaches to extend its SCM capabilities to 200 km altitude. Primarily, a high-transmittance Liquid Crystal (LC) shutter will be used in front of the MCAT CCD as a solid state chopper to generate an asymmetrical notched streak – thus yielding rate and direction as a target transits a single frame. This method maximizes sensitivity by using the full detection capability of MCAT reduced only by the LC shutter's 20% residual opacity. Secondly, a wide field, high sensitivity auxiliary telescope (\sim 0.4 m diameter), equipped with a high frame rate Scientific Complementary Metal Oxide Semiconductor (sCMOS) detector will be used (albeit at reduced sensitivity). The 1.3 m RC design employs a large optical tube assembly (OTA) and thus requires a stable mount. This requirement is compounded by the need for \pm 3 arcsecond (arcsec) pointing repeatability plus tracking ability ranging from sidereal (with less than 0.04 arcsec RMS jitter) to 2.2 $^\circ$ /second (the angular rate of a 200 km



Fig. 3: MCAT’s primary detector manufactured by Spectral Instruments Inc. utilizes a 4-port 4Kx4K CCD from e2v Technologies. With 15 μ m pixels, the focal plane plate scale is 0.75 arcsecond/pixel and the diagonal FOV is 0.96°. With 1.9-2.0 e⁻ read noise, the detector is particularly well suited to longer exposure GEO and MEO survey work. At higher frame rates LEO altitudes to 200 km are accessible in OSM or in SCM with a high-speed shutter.

LEOs in circular orbit). The inherent stability of horseshoe mount, with its large footprint and balanced load eliminating significant counter-weighting, satisfies these MCAT requirements. Since a primary MCAT objective is GEO observations, an equatorial mount was deemed essential to simplify sidereal tracking and eliminate field rotation. A double ended horseshoe with large north and south polar bearings and only modest inclination from horizontal satisfied this constraint. The equatorial design offered the added benefit of unimpeded LEO tracking without the singularity inherent in an alt-azimuth configuration. Since access to low inclination, low altitude targets is essential, the cutaway horseshoe south bearing enables southern access to 12° elevation (corresponding to 0° inclination targets at 142 km altitude). With 8000 kg of moving mass, the MCAT horseshoe bearings are hydrostatic – eliminating common wear and [some] periodic error issues. Precision encoders and a stable bore site allow absolute encoded field position to be read directly to ± 3 arcseconds anywhere on the sky – simplifying in-frame astrometric reduction, or replacing it entirely when frame rate limitations or crowded background fields preclude an in-frame astrometric solution.

MCAT’s optical and mechanical attributes were carefully conceived to create a solid platform for complex orbital object detection, discrimination, acquisition, tracking and photometric operations and provided a firm basis for development and operation of its software suite.

III. MCAT MISSION

Understanding the Earth orbital environment and thereby accurately evaluating the effects on human spaceflight activities, requires estimation of the number distribution function (NDF) that describes the orbital population. An exact description of the number of objects of a given size, orbit, material, topology, etc is not feasible, so an NDF is derived from remote sensing telescopes and radars that represents an approximation to reality. The accuracy of the approximation relies in large part on a subset of inputs derived from empirical and theoretical models and intelligent assumptions. Returned radar signals, when processed through a frequency dependent size estimation model (SEM), yield an object radar size (radar cross section) [9]. Optical brightness, coupled with both a transformational albedo (derived via a sophisticated bias-reduction methodology) [10] and a simplistic phase function assumption, yields an optical size. Neither the radar nor optical size of a single target is, except by chance, the actual physical size. But the ensemble of measurements does approximate reality and yield a working NDF that produces, among other things, reliable collisional risk assessments. It is in the context of improving the NDF by expanded sampling of all orbital regimes, and improving the inputs and assumptions used for signal processing, that MCAT and its objectives were conceived.

MCAT must fulfill multiple missions. Primarily, it must detect new debris at GEO and LEO. Secondly, it must provide detailed characterization of SSN targets and new debris. The characterization includes time dependent photometry and spectrophotometry for both single and multiple orbital passes, giving insight into short and long term variations which include, target rotation/orientation and space weathering effects. At the tertiary level, MCAT must observe targets of opportunity simultaneously with Kwajalein range radars. This will provide data crucial to refining and improving signal processing methods – ultimately leading to higher fidelity sizes and NDFs.

From its conception, MCAT was designed to execute its missions autonomously. Tasking, data acquisition, data reduction, and even some analysis aspects, will be ultimately automated to the extent that user intervention will be minimal or optional. As such, MCAT will provide a tangible demonstration of the philosophy that many observing and processing capabilities can be engineered into a remote sensing system, thus minimizing the time from observation to analysis and relieving staff to perform crucial and intellectually challenging interpretation tasks. The placement of MCAT in a remote locale is in large part facilitated by its eventual autonomous status.

IV. MCAT TECHNIQUES

Telescopically remote sensing the orbital object environment can be sub-divided into five distinct phases: detection, discrimination, acquisition, tracking, and target observation. The first, detection, is governed by telescope and detector attributes and the mode of operation – whether a staring or scanning survey to find new orbital debris, or studying a specific target. Detection capability is determined by the minimum signal measureable against the shot and detector noise characterizing the target “image” (point-like or streak), the target background field, and the instrument. If simple detection were sufficient, exposures would always be selected to maximize the target signal to noise ratio (SNR) in every image. The need to discriminate the target against a sometimes complex background and to assess its motion for acquisition and tracking means that exposures are sometimes below optimal. To enable in-frame astrometry for example, star streak length should be less than half the field width. Similarly, to determine object motion, two detections are often required in a single field crossing. Thus frame rate may dictate shorter exposures, greater on-chip pixel binning, and thus reduced sensitivity. Collectively, these requirements, given the canonical set of albedo and phase function assumptions, translate to a limiting target diameter for each orbital altitude and each observing mode.

The second phase, discrimination, is, as the name implies, the process whereby those objects that are detectable, are actually distinguished from the background, their motion characterized, and their SSN catalog status assessed (correlated target – CT, or uncorrelated - UCT). This step is intensive and pivotal. The fact that an object can be theoretically detected does not necessarily imply that it can be discriminated for purposes of acquisition, tracking, or measurement. Culling faint moving targets from often cluttered or streaked background star fields is non-trivial. Without the benefit of image processing software (SW), the effort has required the skill of trained observers to manually review thousands of hours of collected data to identify targets. Even with SW assistance, secondary review has often been required due to SW inadequacies and processing errors, thus creating a significant labor and time intensive bottleneck in the sequence from observation to data extraction. For MCAT to function properly, target discrimination must be performed automatically, accurately and in near real time. In Stare and Chase Mode for example, a moving (or occasionally static) target must be discriminated against a slowly drifting star field (or a static field if the stare is a sidereal track). Object angular rate and position angle of motion are then determined from the image’s appearance (length and orientation of the streak or the survey motion if a point). Two images are required to determine direction of motion (unless an asymmetrical beam

chopper is used). In Orbit Survey Mode (OSM), wherein specific orbital inclinations and altitudes are surveyed, the situation is compounded by field crowding from passing background stars as the telescope slews at rates up to 2.2 deg/sec. This background clutter results in some loss of detection sensitivity. In SCM or OSM, target appearance can range from point-like (rare) to a streak (typical) and must be differentiated against a stellar background of streaks (or point if sidereal) whose length depends on the survey rate and exposure time. Once discrimination is achieved, a decision is made whether to acquire and track the target and whether correlation with the SSN is to be performed. Since accurate target discrimination is a cornerstone of MCAT’s autonomous operations, sophisticated and highly-optimized astronomical image processing algorithms employing current astronomical techniques are in development. The target metrics and identification must be obtained quickly (of order the FCT) to enable phase three - acquisition - to occur at a latter point downstream during the illuminated portion of the orbital pass.

Acquisition occurs by calculating the proper look ahead distance along the orbit track, then accelerating/decelerating the telescope to this location with it tracking at the proper rate/direction to initially maintain the target within the telescope FOV. MCAT is designed with sufficient acceleration and deceleration capability to acquire any LEO target after the initial, near real time, discrimination phase.

Phase four, tracking, involves continuously monitoring the target position and drift and then updating the rate and direction as required to maintain the target near field center. At the end of a track, a preliminary orbit can be calculated and reacquisition during a subsequent pass can be attempted if desired. The orbit will be derived astrometrically in-frame (with multi-order image scale transformations) whenever possible and via encoded pointing position otherwise (modeled and corrected over the accessible hemisphere). Although it is not NASA’s responsibility nor desire to maintain an orbital debris catalog, MCAT’s ability to generate preliminary and refined orbit solutions expands its utility as a contributing sensor to the SSN network. Orbit generation will also assist with definition of the orbital object environment especially as it pertains to GEO high area to mass objects with time dependent, eccentric orbits that are the subject of intense scrutiny.

The first four phases culminate in the phase five close photometric observation and characterization of the target. Gathering time dependent spectrophotometry, and phase and orientation dependent brightness, along single and multiple orbit tracks enables a more comprehensive investigation of object geometry, material construction, and topology. Coupled with simultaneous radar observations, a real time comparison can be made between optical cross

section using canonical metrics, and radar cross section, to divine how these quantities vary and correlate (if at all) with observable optical behavior. Part of the genesis of MCAT and its planned autonomy is that data reduction will be performed in-situ and in real time wherever possible. Key observables will be extracted and returned daily to NASA-JSC for prompt analysis and incorporation into ODPO's environment models. It is expected that MCAT's ability to provide comprehensive and timely data will improve collisional risk assessments. Over time MCAT's ability to amass complete metric descriptions of a statistically significant subset of the orbital object population may lead to the categorization of multiple subsets with similar properties. This may in turn lead to a preliminary optical size estimation model (OSEM) that allows more flexible descriptors than a single phase function or transformational albedo and consequently provides higher fidelity sizes that may apply to different object classes [11].

V. MCAT MODES

CTM: Catalogue Tracking Mode

Acquiring and tracking previously SSN catalogued objects, or any object with a known two-line element set (TLE), serves several potential purposes. Because CTM exercises many of the mount, optical, and detector functions, ranging from timing to coordinate transformation to image and data handling, it is the first operational mode that will be used for MCAT in the initial post-deployment acceptance and testing phase. The TLE is converted to a 7-element vector defined by two angular coordinates, two angular velocities, two angular accelerations, and time and then input to the MCAT telescope control system (TCS) for tracking. Operating simultaneously along the track, the SI CCD camera is commanded to acquire image frames with an exposure, binning level, and read rate dictated via a pre-calculated look-up table (Fig. 4) customized for each orbital tracking rate and mode. This accommodates angular variations due to perspective and elliptical orbits. Orbital objects at all inclinations from 200 km LEO to beyond GEO altitudes, including near-earth objects (NEOs), are accessible to MCAT.

Trials will include treating CTs as UCTs to test the functionality of the MCAT SW target discrimination algorithm and adjust if needed. Similarly an orbit will be derived using in-frame astrometry and mount encoded positions to independently check each method and verify that MCAT will generate a useable TLE for new (UCT) detections. Against un-crowded background fields, CTM could use exposures equivalent to several FCTs

Height (km)	Rate (deg/s)	Exp (s)	Bin Factor	Plate Scale (")	Readout Time (s) (Rate Mhz)	Total Time per Frame (s)	Track Cover (%)	Data (MB) 90°Arc
200-500	2.23-0.87	0.15-0.39	8	4.76	0.228 (1.5)	0.378-0.62	40-63	56-34
500-1000	0.87-0.42	0.39-0.81	4	2.38	0.359 (1.5)	0.75-1.17	52-69	113-73
1000-2000	0.42-0.2	0.81-1.72	2	1.19	0.883 (1.5)	1.7-2.6	48-66	200-130
			8	4.76	0.84 (0.1)	1.6-2.6	49-67	13-8
2000-5000	0.2-0.07	1.72-5.0	2	1.19	0.883 (1.5)	2.6-5.9	66-85	130-57
			8	4.76	0.84 (0.1)	2.6-5.9	67-86	8.3-3.6
5000-GEO	0.068-0	5+	1	0.68	3.0 (1.5)	8.0	63+	170+
GEO (nom)	0	5	2	1.19	10.67 (0.1)	15.68+	100	~40

Fig. 4: MCAT CCD detector lookup table specifying various exposure, binning, and frame rate parameters for different orbital regimes. This specific table was calculated for use with CTM.

to maximize the extreme detection capability available in this mode, but in-frame metrics are generally only possible if the exposure is limited to contain star trails within the FOV. Thus exposures are generally limited to about half the FCT, yielding an approximately 20th magnitude detection limit (10 cm diameter) at GEO (19th magnitude at LEO). This limit also reduces background shot smearing and crowding. All-sky-mapping and high speed retrieval and drift simulating algorithms currently under development may eventually give MCAT the ability to correlate even crowded multiple FCT exposed fields by comparing actual drift images with those generated from star catalogues.

Once proven, MCAT will track known targets to facilitate in-depth analysis of time dependent optical properties for an ensemble of objects and compare these with past and simultaneous radar observations in an effort to develop the OSEM. When operating autonomously, MCAT can self-schedule CT observations at will with no human intervention. MCAT's derived TLEs may actually be used to improve the SSN itself – making MCAT a contributing sensor. When accessing Kwajalein range data, MCAT can also acquire any object being monitored and tracked by range radars.

CSTDI: Counter-Sidereal TDI at GEO

MODEST successfully implemented a specialized GEO survey technique that has detected approximately one hundred GEO UCTs. To minimize solar phase angle (and thereby maximize reflected return), the method involves tracking MODEST at the sidereal rate, near the earth's anti-solar point – at various positions near the edge of the earth's penumbral shadow. This survey pattern has been used by previous researchers [12] to survey various regions of the GEO belt as well as the stable orbital plane created by solar-lunar perturbations on uncontrolled GEO objects (Fig. 5).

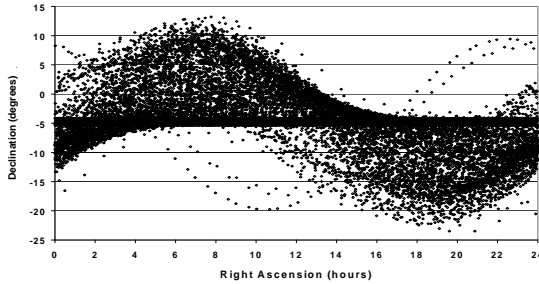


Fig. 5: The earth orbital environment at GEO as viewed from Cloudcroft, NM. The GEO controlled objects occupy the horizontal band at -5° Declination. Solar-Lunar perturbations distribute uncontrolled objects towards the ecliptic plane.

The MODEST imaging methodology is unique because rather than acquiring still frame exposures, it couples simultaneous sidereal mount tracking with electro-optical tracking to effectively freeze each GEO longitude as the survey proceeds across the sky. This is performed by aligning the CCD read direction East-West and then performing Time Delay Integration (TDI) at a rate that counters the telescope sidereal track. Stars become streaks and GEO objects at fixed longitude are recorded as point-like images. Uncontrolled GEO objects (not station-kept) appear as short streaks with generally random orientations (elongations). If their motion can be discerned, follow-up observations are possible using the CTIO 0.9 m SMARTS telescope. In the MODEST application, typically 6-8, five second TDI exposures are acquired for each GEO longitude and multiple occurrences are required for classification as a detection and to quantify object motion for follow-up (Fig. 6). Much faster readout capability with a new MODEST CCD camera (nearly identical to the MCAT camera), will enable longer TDI exposures and thus greater detection sensitivity. The counter-sidereal TDI (CSTDI) approach is ostensibly equivalent to the still framing method wherein the anti-solar point is followed but in a stepwise framing fashion involving stopping the sidereal track during multiple time exposures and then slewing back to center the same star field. Counter-sidereal TDI however is more efficient as it avoids lost time to slew and settling, and, importantly, the background star field never changes – making target discrimination much easier. The method's

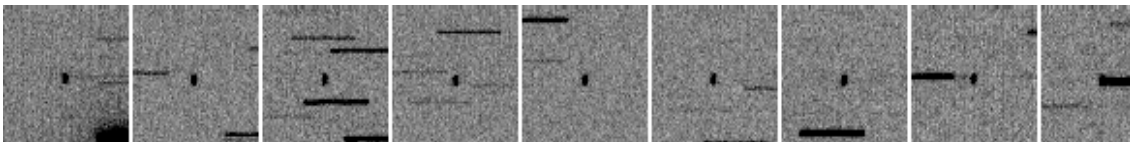


Fig. 6: MODEST detection of a GEO orbital debris using the CSTDI technique. The horizontal streaks are background stars. Image extracted from the full frame.

disadvantage is slight loss of field exposure for the field strips adjacent to and furthest from the CCD serial register (the TDI ramp) – these CCD rows receive incrementally less exposure - but the diminution is small for a large field and sidereal TDI rates.

Since a productive image acquisition and detection pipeline has already been refined and optimized during a decade of MODEST operations, MCAT will implement this methodology for some of its GEO survey work. The method is expected to yield a 20th magnitude detection limit corresponding to approximately 10 cm diameter targets. Located at 167.6° West longitude, MCAT surveys a new longitude regime relative to MODEST (71° West longitude). In keeping with the goal of autonomous MCAT operations, development is now underway to expand the pipeline to include rapid and automated data reduction and follow-up capability. Orbits generated for those objects that MCAT can reacquire will be handed to MODEST where possible and will be key contributors to developing a GEO NDF.

Occasionally, when exploring specific regions of GEO phase space, it is desirable to survey along GEO latitude, longitude, or some combination thereof, rather than longitude alone. At these times, where field stepping is necessitated, the conventional still framing technique may be employed as MCAT traces linear or saw-tooth patterns in RA and Declination or in GEO latitude and longitude. The uniform exposure that still framing yields over the full field may also at times be desirable. A full evaluation will be performed comparing different techniques so that the optimum method is applied to a particular task.

SCM: Stare and Chase Mode

The advantages of a fully functional Stare and Chase mode (SCM) of survey operation are manifold. SCM offers the broadest possible acceptance window for orbital parameters. For example, SCM starting from a zenith staring position at Legan, accesses all objects with orbital inclinations greater than 8.98° and, absent telescope and detector constraints, at any altitude. Furthermore SCM combines the five phases of orbital object remote sensing - detection, discrimination, acquisition, tracking, observation – into one sequential stream – progressing from detection through detailed observation as one continuous

process in the shortest time possible. SCM is also well suited to autonomous operations. Population statistics can accumulate over time as each element of orbital phase space, allocated equal observing time, is evenly sampled without user intervention and without observational bias.

SCM has the disadvantage of being computationally intensive and therefore difficult to implement. The advent of desktop workstations capable of Giga Floating Point Operations per second (GFLOPS) and possessing gigabytes (GB) of physical RAM and terabytes (TB) of disk space, has made near real time SCM technically and economically feasible. The computational difficulty resides in target discrimination. The target must be quickly differentiated from a background field of static or streaked stars, and then the process must be repeated since successful prediction and reacquisition requires at least two independent target detections during field crossing to determine angular rate and position angle of motion. The process becomes increasingly demanding as altitude decreases. At lower altitudes, with faster angular rate targets, where both FCT and allowable time for reacquisition decrease, near real-time discrimination becomes essential to assure reacquisition. To facilitate the discrimination process the all sky stellar database discussed previously will be used conventionally to locate the celestial field

and then, astrometrically, the target within it. A more sophisticated approach will also be explored where the database will be used to generate a dynamic field template that conforms to the real field observed by the telescope pointing and motion. This template may be subtracted from the field to aid discrimination or used as real-time mask to minimize the image area that must be searched. These techniques remain to be tested and proven.

For the MCAT telescope and SI CCD detector combination, a maximum frame rate of one per second is a practical upper limit. This limits this combination to SCM above 2000 km altitude. Below that, an LC shutter is used to time resolve image motion by asymmetrically notching the target streak (or separating point like detections). Additionally, a small aperture wide field of view auxiliary telescope, with high speed sCMOS sensor, will perform initial detection and discrimination down to 200 km altitude for subsequent acquisition, tracking, observing by MCAT. The loss in light gathering ability for the auxiliary telescope relative to MCAT is partially mitigated by the high sensitivity sCMOS. The system will attain approximately 14th magnitude sensitivity (approximately 6 cm diameter at 200 km) in LEO, versus MCAT's expected 18th magnitude LEO detection limit (1 cm diameter at 200 km). The

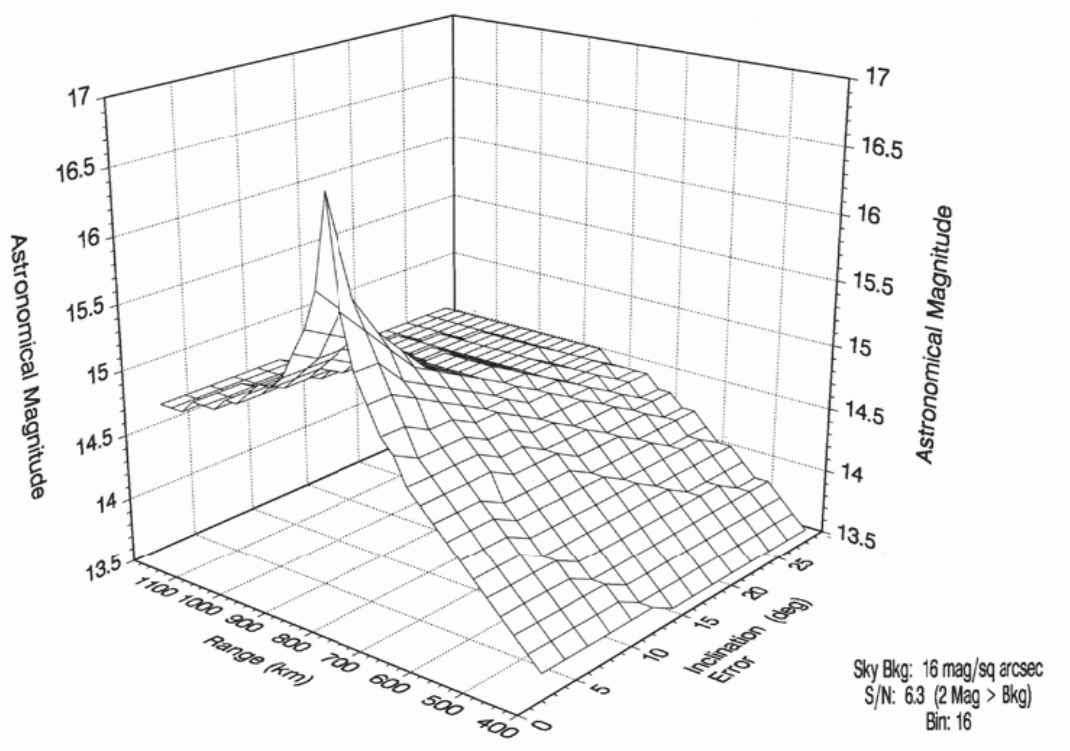


Fig. 7: Illustration of variations in detection sensitivity for targets on OSM. Maximum sensitivity occurs for targets moving at the telescope rate and direction (point-like image). Sensitivity diminishes for targets whose angular rate or inclination differs. MCAT will adjust midcourse to track objects that deviate by prescribed amounts from the initial OSM track.

expected advent of large format sCMOS detectors over the next 2-3 years will supplant CCDs for MCAT observations and obviate the need for MCAT's high speed shutter or auxiliary telescope.

Conceptually, SCM does not have to start from a staring position. It can begin from a sidereal track during GEO anti-solar point surveys or from an orbit track during Orbit Scanning mode (OSM). Once fully implemented and optimized it is expected that SCM will become the nominal operating mode for MCAT - the only variations being its starting state.

OSM: Orbit Scan Mode

Orbit Scan mode (OSM) can be viewed as functionally equivalent to SCM with the start state being an orbital track rather than a static azimuth and elevation or a RA and Declination celestial position. OSM detection capability is optimal for those objects whose orbital motion match the OSM track (Fig. 7) - and thus yield point-like images and maximum SNR. The mode is primarily intended for surveying under-sampled orbital inclinations or those in which fragmentations have occurred, but because of its inclination and altitude selectivity, performance is poor for objects with motions that deviate from the defined orbit track.

OSM efficacy can be improved significantly beyond its simplest implementation if SCM capability is enabled. SCM enables discrimination and acquisition of object that deviate slightly from the chosen OSM inclination or altitude. This broader acceptance window allows more fragments to be observed and importantly removes the phase space restriction from OSM. Additionally OSM with SCM capability can be used with the existing MCAT camera down to 200 km altitudes because the demand for rapid framing and discrimination is somewhat reduced if the telescope start state is already moving at LEO angular rates. (Broad surveys in terms of inclination and altitude acceptance still require the high-speed shutter or wide field auxiliary telescope for static or near-sidereal SCM). Operating in OSM mode incurs comparable computational challenges to static or sidereal modes. Two detections and discriminations are required to establish the new trajectory. The new position and velocity vectors, with requisite corrective acceleration, are calculated in the moving coordinate system, and the target is re-acquired. The greatest difficulty relative to pure SCM is the moving background field which has fewer reference stars and less accurate astrometry. The dynamic background field generator discussed previously may prove efficacious here. Figure 8 shows the detection limits expected from MCAT operating in OSM mode.

VI. CONCLUSION

Capitalizing on decades of observational and modeling experience, gained through a range of different instruments, observing campaigns, and

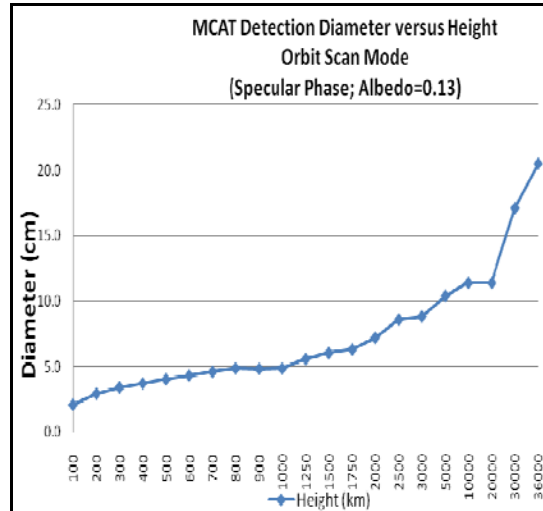


Fig. 8: Limiting detection diameter as a function of altitude for MCAT operating in Orbit Survey Mode (OSM). Though the sensitivity decreases at low altitudes due to shorter allowable exposure time, limiting diameter detection decreases due to the smaller range.

mathematical constructs, NASA has developed a new instrument and set of observing methodologies to carry it forward to next phase of orbital object environment discovery and characterization. MCAT represents the culmination of NASA's efforts thus far in the study of optical properties of the orbital object environment. The experience gained has yielded a telescope, mount, software, and strategy capable of tracking earth orbital objects at all inclinations and at altitudes from 200 km LEO to GEO and beyond. MCAT will discover new debris in under-sampled orbits and do so with a detection capability that exceeds that of any dedicated assets.

Importantly, MCAT incorporates an innovative autonomous strategy that maximizes the telescope productivity and minimizes operational labor and costs. Its hoped that, once refined and optimized, MCAT's SCM and OSM modes will be adopted by other groups to assist the global effort to better define the orbital object environment for the benefit of all space faring activities.

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