

The NASA Meter Class Autonomous Telescope: Ascension Island

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ABSTRACT

The Meter Class Autonomous Telescope (MCAT) is the newest optical sensor dedicated to NASA's mission to characterize the space debris environment. It is the successor to a series of optical telescopes developed and operated by the JSC Orbital Debris Program Office (ODPO) to monitor and assess the debris environment in (1) Low Earth Orbit (LEO), (2) Medium Earth Orbit (MEO), and (3) Geosynchronous Orbit (GEO), with emphasis on LEO and GEO altitudes.

A joint NASA – Air Force Research Labs project, MCAT is a 1.3m optical telescope dedicated to debris research. Its optical path and sensor yield a large survey fence at the cutting edge of current detector performance. It has four primary operational observing modes, two of which were not computationally feasible a decade ago. Operations are supported by a sophisticated software suite that monitors clouds and weather conditions, and controls everything from data collection to dome rotation to processing tens of gigabytes of image data nightly. With fainter detection limits, precision detection, acquisition and tracking of targets, multi-color photometry, precision astrometry, automated re-acquisition capability, and the ability to process all data at the acquisition rate, MCAT is capable of producing and processing a volume and quality of data far in excess of any current (or prior) ODPO operations. This means higher fidelity population inputs and eliminating the multi-year backlog from acquisition-to-product typical of optical campaigns. All of this is possible given a suitable observing location.

Ascension Island offers numerous advantages. As a British overseas territory with a US Air Force base presence, the necessary infrastructure and support already exists. It is located mid-way between Brazil and Africa at 7.93S latitude and 14.37 W longitude. With the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) asset in Mòron, Spain shutting down, this presents access to the sky from a unique latitude/longitude for an optical telescope. Constant trade winds from the SSE, originating from Africa, give promise to a steady laminar airflow over an island, a trait sought after to create stable atmospheric and good astronomical 'seeing' conditions with very low annual rainfall values. This combination of attributes created the necessary compelling argument to redirect MCAT to its final destination: Ascension Island.

1. INTRODUCTION

The Meter Class Autonomous Telescope (MCAT) is a 1.3m optical telescope designed to characterize the space debris environment. Operated by the Johnson Space Center Orbital Debris Program Office (JSC ODPO), it will be dedicated to the statistical and targeted study of debris in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO). MCAT's predecessors include a suite of highly successful optical telescopes that pioneered observing techniques and discoveries in the evolving orbital debris field [1]. This began with the small aperture Lenzar (1987-1989) and CCD Debris Telescope (CDT) (1990-2002) and progressed through Liquid Mirror Telescope (LMT) (1995-2002) and Michigan Orbital DEbris Survey Telescope (MODEST)¹ (2002-present). MCAT incorporates into its design and operation the cumulative experience acquired over the past 2.5 decades of optical

¹ MODEST is a 0.6m telescope located at Cerro Tololo Interamerican Observatory (CTIO).

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14. ABSTRACT

The Meter Class Autonomous Telescope (MCAT) is the newest optical sensor dedicated to NASA's mission to characterize the space debris environment. It is the successor to a series of optical telescopes developed and operated by the JSC Orbital Debris Program Office (ODPO) to monitor and assess the debris environment in (1) Low Earth Orbit (LEO), (2) Medium Earth Orbit (MEO), and (3) Geosynchronous Orbit (GEO), with emphasis on LEO and GEO altitudes. A joint NASA / Air Force Research Labs project, MCAT is a 1.3m optical telescope dedicated to debris research. Its optical path and sensor yield a large survey fence at the cutting edge of current detector performance. It has four primary operational observing modes, two of which were not computationally feasible a decade ago. Operations are supported by a sophisticated software suite that monitors clouds and weather conditions, and controls everything from data collection to dome rotation to processing tens of gigabytes of image data nightly. With fainter detection limits, precision detection, acquisition and tracking of targets, multi-color photometry, precision astrometry, automated re-acquisition capability, and the ability to process all data at the acquisition rate, MCAT is capable of producing and processing a volume and quality of data far in excess of any current (or prior) ODPO operations. This means higher fidelity population inputs and eliminating the multi-year backlog from acquisition-to-product typical of optical campaigns. All of this is possible given a suitable observing location. Ascension Island offers numerous advantages. As a British overseas territory with a US Air Force base presence, the necessary infrastructure and support already exists. It is located mid-way between Brazil and Africa at 7.93S latitude and 14.37 W longitude. With the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) asset in Maricao, Spain shutting down, this presents access to the sky from a unique latitude/longitude for an optical telescope. Constant trade winds from the SSE, originating from Africa, give promise to a steady laminar airflow over an island, a trait sought after to create stable atmospheric and good astronomical seeing conditions with very low annual rainfall values. This combination of attributes created the necessary compelling argument to redirect MCAT to its final destination: Ascension Island.

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operations at JSC. Once fully optimized and developed, the data rate could exceed 50 times that of the current MODEST operations.

2. THE NEW DESTINATION: ASCENSION ISLAND

Originally planned for the island of either Legan or Roi-Namur, part of the Kwajalein Atoll Islands, recent developments have led to a change in venue. The Ground-based Electro-Optical Deep Space Surveillance, or GEODSS, system of telescopes is the United States’ major tracking system for deep space (Fig. 1). This network consists of telescopes in Maui, Hawaii; Diego Garcia (Indian Ocean), and Socorro, New Mexico. A fourth optical telescope, though smaller in size, has been operating in conjunction with this effort until recently in Mòron, Spain. With the Mòron site closing, a significant gap in longitude exists between the New Mexico and Diego Garcia sites.

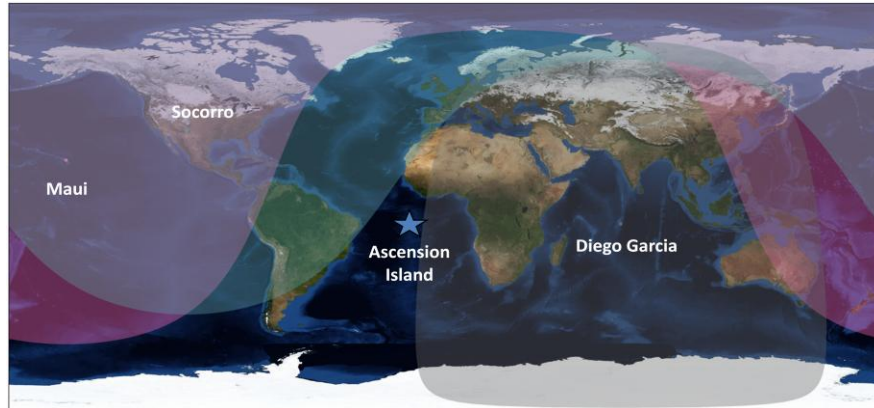


Fig. 1. Ascension Island will fill a longitudinal gap not attainable by the current suite of GEODSS sensors.

This longitudinal gap is well covered by placing a telescope on Ascension Island ($7^{\circ} 58'20''$ S, $14^{\circ} 24' 4''$ W), in the Atlantic Ocean. This location offers the benefits of location, weather, and infrastructure. The near equatorial location affords the opportunity to access under-sampled low-inclination orbits and new GEO longitudes.

Ascension Island is a volcanic, desert island, receiving only 7" of rain per year on average, yet the nearby ocean contributes consistent humidity (typically in the 60-75% range). To protect the telescope and instruments, a dry air purge will bathe the telescope, focus housing, and filters while the telescope is not in use. With consistent trade winds blowing from the SSE direction off Africa, the combination of an island location with consistent winds should create the smooth laminar flow sought after by all astronomical sites, which creates stable atmospheric ('seeing') conditions (see Sec. 6.1). In addition, this low population island has strict lighting limitations due to a population of nesting sea turtles that require the darkest skies possible. This results in skies that are also ideal for an observatory.

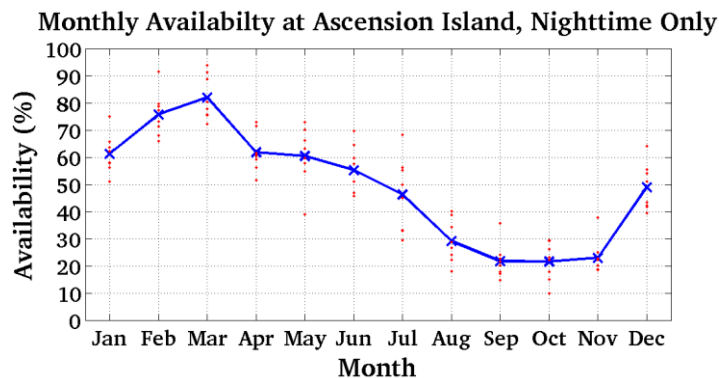


Fig. 2: An estimate of the percentage of clear nights available as a function of time of year derived from Meteosat Second Generation (MSG). Data are defined through a *Cloud Free Line of Site* (CFLOS) analysis where clear is defined as an optical depth < 0.1 (the limit of the sensors). Red dots indicate the average for the indicated month for one year and the blue Xs indicate the average of 8 years (2005 – 2012) for that month.

Fig. 2 shows the results of eight years of estimations of Cloud Free Line of Site (CFLOS) data collected by the Atmospheric Effects group at Northrop Grumman Corporation. Data were derived from Meteosat Second Generation (MSG) Imagery using a custom cloud retrieval algorithm. Horizontal resolution is 4km and temporal resolution is 30 minutes taken during the night (no daytime observations). Summer (starting in December) through fall in this southern hemisphere location offers the most favorable cloud-free conditions, with spring presenting poor observing conditions. Yearly CFLOS measured between 2005-2012 range from ~ 40-55% clear skies.

A British Overseas territory serving as the midway point between the UK and the Falkland Islands, Ascension is also home to the US Air Force 45th Space Wing, Detachment 2. Significant infrastructure and support exists and is expected to continue for the foreseeable future due to this presence. As such, maintenance and logistical support, along with a multi-million dollar, state-of-the-art secure radar facility where MCAT will be deployed, will provide an ideal setting for an autonomous telescope.

3. MCAT MISSION REQUIREMENTS

Debris poses risks to satellites and spacecraft launched by all countries and entities, military and civilian alike. Several events have brought the real threat of collisions, explosions, and thereby debris to the forefront of the community's attention: (a) the breakup of satellites at/near GEO, including the Russian Ekran 2 (due to a battery malfunction) in 1978, and the U.S. Titan IIIC Transtage in 1992 (perhaps due to unspent propellants at the time of the explosion); (b) the Chinese anti-satellite missile test that destroyed the Fengyun (FY-1C) satellite in LEO in 2007; and (c) the recent collision in LEO between the functional Iridium 33 satellite and the non-functional Kosmos-2251 in 2009. Damage to spacecraft due to impacts by debris can cause malfunctions or loss of life, whether that life is the functionality of a satellite or humans in the International Space Station. As such, understanding the debris environment has become a critical task for NASA and is the primary purpose of MCAT.

The orbits of "station-kept" satellites in geosynchronous orbit require routine burns to maintain an inclination of 0°. The orbits of uncontrolled debris at GEO are known to oscillate between 0-15° inclination over a 50 year period, a consequence of the gravitational influences of the Moon, the Sun, and the Earth's oblateness (J2 term). These uncontrolled objects oscillate about the stable Laplacian plane, which is inclined 7.5° with respect to the Earth's equator [2]. Consequently, statistical sampling of the belt of GEO debris requires observations at low declinations readily attainable by telescopes between ±30° latitude. At nearly 8°S, Ascension Island is ideally suited to this task as the GEO belt sweeps across the zenith at this location, offering consistently low airmass observational opportunities.

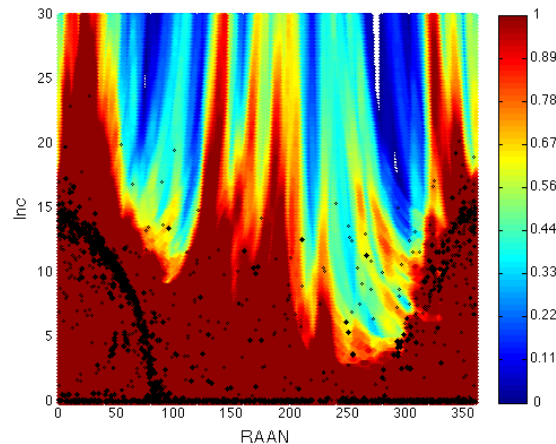


Fig. 3. MODEST coverage of the Inclination (Inc) versus Right Ascension of the Ascending Node (RAAN) orbital parameter space after 122 nights of observation in the period 2007-2009 [2]. Objects are statistically expected in the redder regions on the plot due to their orbital motions [3].

Fig. 3 shows the resultant probability Inclination vs. Right Ascension of the Ascending node (Inc vs. RAAN) coverage map obtained from 122 nights (~700 hrs) of photometric data obtained over a 3 yr period (2007-2009) [2]. Catalogued objects are shown as dark diamonds, while uncorrelated targets (i.e. debris) are shown as open

diamonds. The redder the color, the closer the probability is to unity, and therefore the greater the likelihood an object in that orbit will be detected. Via its GEO observing modes, MCAT is expected fully cover the GEO belt and at almost a full magnitude (0.85) fainter -improving the size detection limit by ~50%, or potentially fainter and thereby smaller size limits with longer exposure times, assuming favorable observing conditions (good seeing, limited atmospheric extinction).

4. INSTRUMENTATION

All instrumentation was designed to observe both fast-moving LEO as well as slow-moving GEO debris fields, and collect both metric and photometric data.

4.1 Telescope

Designed with a low latitude site and fast moving debris targets in mind, the 1.3m DFM telescope can easily and smoothly track LEO targets through the zenith. A modified Ritchey Cretien, MCAT is an f/4 reflecting telescope on a double horseshoe equatorial mount. It has the capability of slewing at a rate of 4°/sec with 10°/sec² acceleration, resulting in an angular movement of ~9° within 2.2 sec. This will allow for sampling 0° orbits at a range of 200km altitude in LEO.

4.2 Dome

Fast tracking with a telescope is only effective with an equally capable dome. The facility will be equipped with a 7-meter Observa-dome, the same manufacturer responsible for the domes erected by the GEODSS program, domes that have suffered no major down-time in 35 years. This high-speed tracking dome can rotate at a maximum angular velocity of 15°/s with an acceleration of 7.5°/s² yielding motion of 18° in 2.2 sec.

4.3 Camera and filters

A Spectral Instruments CCD optical camera will be attached to the telescope with two sets of broad-band photometric filters available for use in the 8-position DFM filter slide, including Sloan Digital Sky Survey (SDSS) g'r'i'z', and Johnson/Kron-Cousins BVRI filters (Fig. 4). The large format 4096 x 4096 CCD has 15um pixels. On this f/4 telescope, this equates to 0.677° x 0.677° (0.957° diagonal) field of view with 0.60"/pix. With a fused silica window to allow UV/blue photons through the system, the optical wavelength range is 3000Å – 1.06 μm. It is a Grade 1, e2v back-thinned, deep depleted CCD to improve the sensitivity for detecting faint objects, with a multi-port read-out design for fast frame-rates (0.1 – 2 MHz). The camera is a closed-loop Cryo-tiger cooling system (-100° C) with 2e-/s average read-noise (3e-/s max).

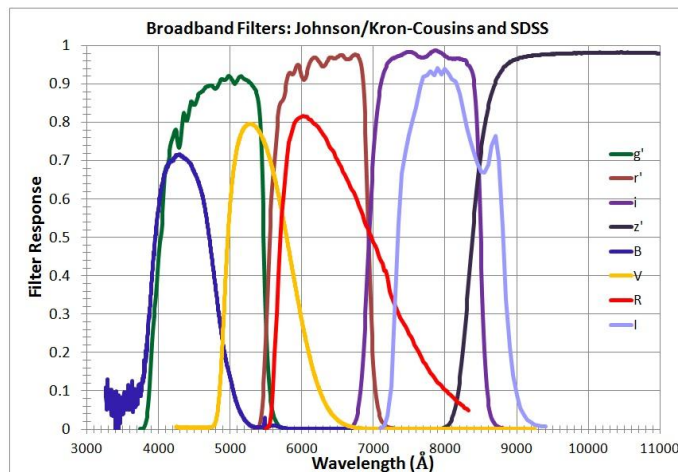


Fig. 4. Plot of the filter response for Johnson and Kron-Cousins BVRI broadband filters and Sloan Digital Sky Survey (SDSS) g'r'i'z' filters.

4.4 Weather Suite

The suite of weather systems are designed to detect rainfall while monitoring temperature, pressure, humidity, dewpoint, wind speed and direction . This includes two weather stations (Davis and New Mountain), and two

Optical Scientific, Inc. (OSI) rain sensors (one windward, one leeward). A FLIR infrared camera and a Boltwood cloud sensor will be used to monitor clouds. The Observatory Control Software (OCS) accepts constant input from the weather sensors to determine whether conditions are acceptable for observing and will close the dome and shut the system down when they are not.

5. COMMISSIONING AND CALIBRATIONS

Establishing a new observational program requires several critical stages: System Commissioning, Instrument Calibration, and Algorithm Testing/Thresholding. Each requires *time on the sky* and none can be bypassed. One must address fundamental questions about the nature of the instrumentation, their calibrations, and the algorithms used to reduce the data from the outset. Rigorously adhering to testing and operation standards and procedures ensures MCAT will produce trusted data at a predictable and reliable rate. Extensive collection efforts are required to provide this level of quality assurance.

5.1 System Commissioning

All telescopes require an initial testing and verification period during which time the behavior of the telescope and instruments are characterized, and the software systems are configured to optimize performance. Initial activities during this time include testing and verifying the functionality of all telescope and observatory systems, software systems, and network connectivity.² The static and dynamic performance of the telescope is determined while the optical collimation is assessed and fine tuned. Pointing and focus models are developed to include effects of flexure, thermal distortion, and wind loading to yield accurate pointing and target field positions.. Any new facility will undergo substrate and structure shifts and settling so a new model will be required monthly at first, then perhaps quarterly after the first year. Optical and detector collimation is similarly performed under clear conditions and is expected to require a few hours quarterly.

At a normal site, commissioning work for a new telescope typically extends throughout the first year as systems are shaken down, pointing models are refined, and seasonal effects are assessed. The fraction of night-time on-sky observations required drops from 100% initially to 10-20% as science observations are phased in. As an example, the 4m Canada-France-Hawaii Telescope (CFHT) on Mauna Kea required 2-3 months to perfect the pointing model and several years of refinement (such as improvement of dome seeing through thermal analysis and mitigation) to produce high-quality images . Weather is not expected to be as favorable at Ascension, and as such, the process will take longer to vet.

5.2 Instrument Calibration

In addition to activities associated with commissioning, there are ongoing tasks required to ensure data fidelity and integrity. Instrument calibration and periodic re-calibration are essential to providing trustworthy observational data for analysis. Periodic maintenance activities, such as mirror cleaning or recoating, require observing time for realignment and re-measurement of photometric zero points and astrometric field distortion. It is anticipated for MCAT that these baseline activities will require on the order of 10% of the available observing time, given typically clear weather, longer if poor weather prevails or systems integration issues surface. A typical high-quality telescope site offers 2000-3000 clear dark hours per year. Thus, the time needed for these baseline activities corresponds to ~200-300 hours/year.

5.3 Algorithm Testing/Thresholding

The complex testing, verification, and thresholding processes for each operational mode (see Sec 7) are anticipated to require extended effort. Clear skies are needed so that automatic target detection thresholds can be determined accurately. For LEO, cloud-free target trajectories are required to develop accurate tracking - requiring empirically determined image processing thresholds and precise in-frame or mount position astrometry so that the magnitude and extent of real-time motion corrections can be assessed and applied. Intensive efforts spanning approximately one year and requiring an estimated 200-300 hours of observation are needed to fully implement and vet all of MCAT's observational modes. Once achieved, MCAT will possess unique and powerful capabilities that maximize its productivity and with minimal user intervention.

² Initial integrated factory tests including telescope and system control software, telescope hardware (to the extent possible), and weather systems were completed successful in July, 2013.

6. MCAT CAPABILITIES AND DATA ACQUISITION

As NASA's dedicated optical observational asset, MCAT's objective is to observe space debris and provide substantial and timely data on the orbital debris population. With GEO observations as its primary mission, MCAT is expected to match MODEST coverage and productivity. Although its larger aperture (MCAT 1.3m; MODEST 0.6m) enables it to detect fainter objects with each exposure, its much smaller field (MCAT 0.68 x 0.68 deg versus MODEST 1.6 x 1.6 deg) requires a roughly 5.5x increase in sampling frequency. This should easily be achieved as MCAT will operate every clear night more efficiently, courtesy of the automation software (See Sec 7). In addition, MCAT's aperture advantage translates to improving the minimum size detection from 20cm to 13.5cm for objects in GEO (assuming Lambertian phase function, 36000 km range, and an albedo of 0.175), as shown in Fig. 5, for 5-second exposures (smaller sizes can be achieved with longer exposures or co-adding frames), assuming observing conditions equivalent to CTIO (where MODEST is located).

Since the debris population is continually evolving, the GEO orbital parameter space should be re-sampled two year intervals at a minimum, which would ensure high productivity levels for MCAT. Through the combination of both a fast-tracking dome and telescope, MCAT's contributions at LEO are expected to be substantial, especially given its efficient automated acquisition and processing modes. This assumes substantial *time on the sky* is available.

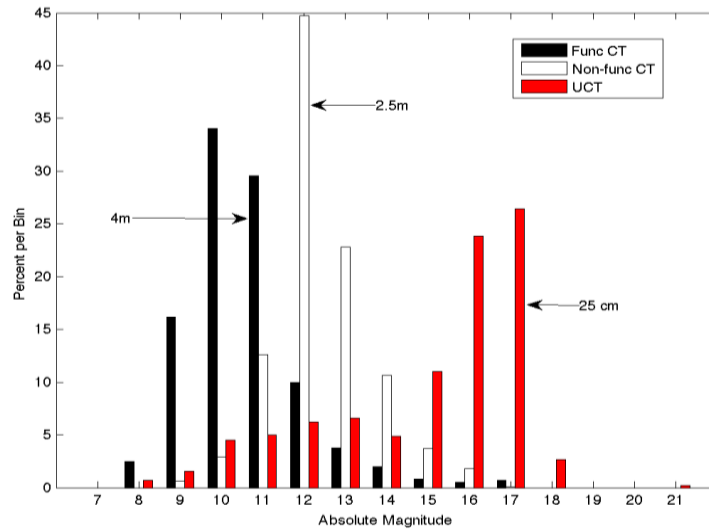


Fig. 5. Absolute magnitude and derived size distribution based on 2007-2009 MODEST observing [2]. MCAT will extend the detectable absolute magnitude range beyond 18 mag.

6.1 Seeing

For background-dominated observations, faint object detection diameter increases by 5% for every 10% increase in the effective seeing disk (i.e. image concentration as limited by atmospheric turbulence). The low altitude atmospheric contribution at a sea level site like Ascension yields an atmospheric coherence scale length (r_0) of order ~5-7 cm – implying seeing of order 1.5" or greater in V band. This will increase MCAT's limiting size detection by 50% relative to a better site at high altitudes (r_0 of 15-25 cm). Compared with 13.5 cm GEO detections possible from a 0.7" seeing site, MCAT on Ascension Island will be able to detect objects no smaller than 20cm based on seeing considerations alone if the anticipated seeing of 1.5" is correct. Laminar airflow resulting from the steady ESE trade winds may result in better seeing than anticipated and thus smaller minimum sizes detected.

6.2 Sky Brightness

As a rule of thumb, faint object detection diameter decreases 2.5% per 0.1 magnitude increase in sky brightness. Ascension sky brightness matches that of a good mountain site (21.3 mag/sq arcsec) under dark sky conditions (no moon). When the moon is up, sky brightness increases in all sites; however, the scattering of moonlight off of cirrus clouds would present an additional source of sky brightness. Modeling this contribution is complex and is wavelength dependent (sky brightness increases with decreasing wavelength in visual bands), but rough estimates can be made, ranging from 0.7 (in I) to 3.2 mag (in B) brighter at full moon vs. new moon [Error! Reference

source not found., 6]. On average in V, the sky may be ~1 mag brighter for typical lunar altitude and phase within seven days of full. The MCAT size detection floor will rise ~25% during this time, as is expected of ‘bright time’ observations at any observatory.

6.3 Location and Extinction

The altitude of the hill on which MCAT will be sited is ~350’ above sea level and roughly one mile from the ocean. At this altitude, the extinction in B is typically 0.5 mag, compared to 0.25 mag at 2635 m altitude (Cerro Paranal) [7]. A 0.5mag increase in extinction increases the smallest detectable size by ~30%.

The inland location on Ascension will eliminate the concerns regarding degradation due to direct ocean sea spray that was expected on Kwajalein (MCAT’s previously considered site) owing to the facility’s planned site in close proximity to the ocean (~2m altitude, ~30m from the shoreline). The acidic volcanic soil and dust present at Ascension is likewise expected to cause corrosion, but at a much slower rate. The low-altitude atmospheric aerosols due to sea spray are, however, expected to increase both extinction and scattering of moonlight. This is hard to quantify without photometry, but could be substantial. Sea salt aerosols are estimated to contribute 44% of the global optical depth at 500 nm [8]. 70% of the Earth’s surface is ocean, which increases this estimate to ~62% for a low-altitude site on an island in the ocean. Typical extinction from sea level could be larger by ~1 mag due to aerosols. Total extinction, then, may be on order 1.5mag due to aerosols and altitude combined, or a 78% increase in detection diameter compared to a high altitude site. Combining the 50% increase due to seeing with the 78% increase due to extinction, this would potentially result in a minimum size detection of 35.6cm.

Given the sky brightness and extinction losses, intensive study of individual debris pieces to determine spectral signature and thus material type are more appropriate for V, R and I bands than B, but significant insight into material characteristics can be gained by B-R and R-I colors. The broader g’ band of the Sloan Digital Sky Survey (SDSS) bands should yield higher short-wavelength signal-to-noise ratio (SNR) than the Johnson B filter, resolving this conundrum. Considering also the extensive standard star calibrations performed for the SDSS filters, the g’r’i’z’ bands will be the filter set of choice for MCAT.

7. OPERATIONAL MODES

MCAT’s primary goal is to statistically characterize LEO, MEO and GEO orbital regimes to better understand the debris environment by providing high fidelity data in a timely manner to protect satellites and spacecraft in orbit around the Earth. Toward this end, a fully automated software package (OCS) has been designed specifically for MCAT by Euclid Research to command the telescope and dome. MCAT hosts a suite of weather sensors to monitor rain, humidity, cloud cover, wind direction and speed; all sensors are controlled via the OCS and provide the capability to remotely close the dome and shutdown the telescope during unfavorable/dangerous observing periods. For each night, an input target/orbital parameters/standard star list is generated and uploaded into the OCS. The software determines the priority for observing based on visibility and/or priority based on observing modes (see below). Cloud cover is also analyzed and used to calculate the priority for observations (e.g. thin cirrus clouds are acceptable for astrometry). After a night of observing, the software will close the dome, park the telescope, and turn off all instrumentation. During the day, it performs a standardized data reduction procedure that results in a single text file including photometry of standard stars and detected objects, and necessary header information, which is then sent via Defense Satellite Communications System (DSCS) satellite to NASA ODPO for analysis.

MCAT’s unique capabilities have not been realized by any in any telescope dedicated to orbital debris to date. These include four sophisticated observing modes that involve automated detection, acquisition, tracking, and - via preliminary orbit generation and refinement – re-acquisition of both GEO and LEO targets. The automated sequence suite can occur from an initial static or tracking (TDI³ or slew) state, thus supporting the conventional Stare-Detect-Chase concept or the newer Orbit Scan mode where a particular orbital space is sampled.

7.1 GEO Survey/GEO Follow-up Mode

GEO orbital debris acquisition is a primary objective. Because debris generally transits all longitudes as it drifts in the [inertial] stable plane orbital space (~a fraction to 1 degree per day), Ascension’s specific longitudinal location is

³ TDI is Time Delay Integration - During the 5-s exposure, the charge on the CCD is shifted in reverse so that the debris objects are seen as a point source and the stars are seen as streaks.

not necessary for GEO Survey mode, but is necessary for target specific studies (Object of Interest mode). A complete GEO survey is achieved via sweep of inertial volume near GEO altitudes spanning inclinations that are expanded to 15° by solar/lunar perturbations (see Sec. 3). Patterned sweep is typically performed by counter-sidereal drift scan. In theory, the entire GEO belt can be observed, weather permitting, in a year. However, poor weather (e.g., clouds, high winds, high humidity) is inevitable and will prohibit some portion of observing time. With a dedicated asset, the entire GEO belt might be observable over ~ 2 years, given expected weather conditions.

This mode follows the method implemented by MODEST for surveying the GEO belt [2]. MODEST is a 0.6m telescope located at Cerro Tololo Interamerican Observatory (CTIO). This program is a successful and mature program implemented in 2003. A broad-R filter has been traditionally used by MODEST to maximize the signal-to-noise obtained in observations that can be calibrated photometrically.

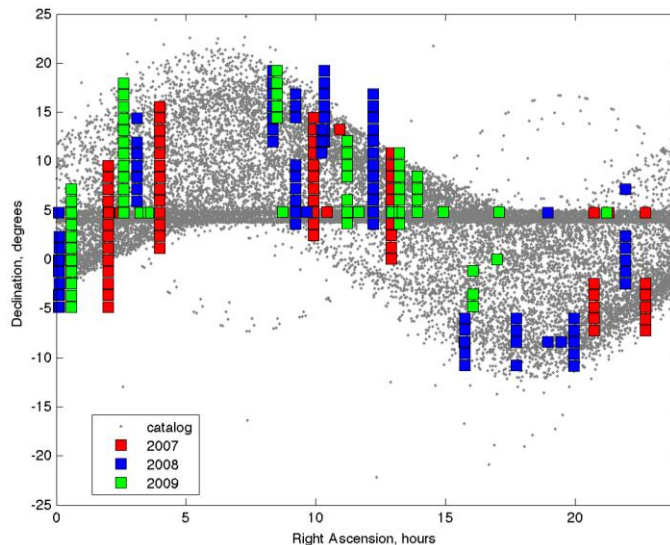


Fig. 6. MODEST daily motion for GEO objects plotted as Declination versus Right Ascension; filled coverage map for years 2007-2009 as view from CTIO, Chile [2]. Note the GEO belt is centered at 5° Dec as viewed from CTIO. Grey dots indicate catalogued objects with mean motions < 1.1 rev/day and $\text{Inc} < 17^\circ$. MCAT will observe similar fields in its Counter-sidereal TDI or GEO stare and chase operational modes.

Fig. 6 shows the MODEST field mapping of the GEO field at a snapshot in time. Grey dots indicate catalogued objects with mean motions < 1.1 rev/day and $\text{Inc} < 17^\circ$. Since MCAT's primary objective is GEO orbital debris acquisition, and all debris transits all GEO longitudes as it drifts in the [inertial] stable plane orbital space (\sim a fraction to 1 degree per day), a specific longitudinal coverage is not necessary for GEO statistical sampling. However, for targeted searches, longitude does matter.

Debris identified within the GEO survey may be the focus of Geo Follow-up studies to further investigate its properties including metrics and filter photometry (colors) using the suite of Johnson/Kron-Cousins or SDSS filters.

7.2 Catalog or Object of Interest Tracking Mode (LEO, MEO, GTO, GEO)

Detailed information or characterization of a specific object may be of interest, whether catalogued and designated a Correlated Target (CT) or not (Uncorrelated Target, or UCT). Filter photometry can be employed to characterize the light curve of objects (using one filter) to better understand their rotation/tumble rates as well as yield a coarse correlation with material type (using multiple filters; accurate color photometry requires simultaneous observations in multiple filters that eliminates any variations in brightness due to the object's tumbling motion, for which MCAT is not designed). In the event of a break-up or collision, MCAT affords NASA the ability to rapidly respond to the event and track the time evolution of the cloud of debris. This mode can be used for GEO, MEO, or LEO objects.

Other global sensors may also hand-off targets to MCAT (see Sec. 8.1) for better overall orbit determination. Through its unique longitude, MCAT can be used to support Space Situational Awareness (SSA) and the Space Surveillance Network (SSN) by providing astrometry, catalogue maintenance, or catalog metrics data to US

STRATCOM or the Joint Space Operations Center (JSpOC). Astrometric data can be collected with light cirrus present.

7.3 Orbit Scan Mode (LEO)

This search strategy exploits knowledge of the expected orbital motion of debris at a particular location, orbital inclination and altitude in LEO. It can be used to generate a ‘virtual object’ trajectory. Detected objects should then appear as (nearly) point sources against trailed background stars. The telescope track rate can then be adjusted to match the newly acquired object(s) rate if it presents any motion from one image to the next. This mode is similar to the methods applied in the GEO survey mode, and can be used for orbit determination of newly discovered UCTs.

7.4 Stare-Detect-Chase Mode (LEO)

This intensive search mode for LEO (similar to GEO follow-up mode) must utilize real-time, high speed image processing to track identified objects that have crossed the field of view of the telescope while in stare-mode. Specifically, the telescope initially tracks at sidereal or static rates (Stare). Once an object is detected, its streak rates can be used calculate new rate and direction for the telescope to follow (Detect). This method discriminates objects through brightness or rate of motion criteria where its orbital motion estimated from streak length and frame-to-frame detections. The object must be detected in at least two frames to determine direction of motion. The telescope is then tasked to track at the object’s calculated new position and rate (Chase).

8. COORDINATED OBSERVATIONS

Observations taken in conjunction with other assets can yield a whole new realm of information. After MCAT has been fully vetted, it could potentially coordinate its observations with other optical or radar telescopes.

8.1 Coordinated Optical Observations

If MCAT is employed in conjunction with other telescopes around the world, the suite of observations can be used to refine the orbits of individual pieces of debris whereby one telescope hands off coordinates to the next telescope in longitude. Here, the unique longitude of Ascension becomes a true asset. Objects would be viewed from Ascension at a different place in their orbit than they would at other longitudes. Clear skies (or very light cirrus) will be essential in accepting hand-offs from other telescopes. Multi-day GEO orbit determination and refinement is similarly weather-dependent.

In addition, if assets at a similar longitude were employed (e.g. in Tenerife), one could obtain observations with different aspect angles. Combining this information with range to the target, one might gain insight into the shape of the target to give intrinsic insight into the risks posed to GEO by the object.

8.2 Simultaneous Radar-Optical Observations

The holy grail of debris observations is understanding how observational quantities relate to actual size of the debris, and thereby risk to spacecraft. The NASA Size Estimation Models (SEM) of debris targets are based on radar observations, due to its ability to directly measure the radar cross-section (RCS) of a target. This is particularly effective when objects are either physically close or have an intrinsically high SNR. Due to the limited radar return (proportional to distance to the object, $1/r^4$), objects must either be close (LEO), or must be large and/or bright at radar wavelengths. The sensitivity of optical observations, however, varies only as $1/r^2$. Thus, optical measurements must be relied upon for observationally fainter objects, and is thus the wavelength of choice for observing GEO debris.

Creating an Optical Size Estimation model (OSEM) requires understanding how to translate optical brightness of an object to its size. Its brightness can increase with increasing size (whether physically larger or a larger portion of the sunlit side facing the detector) and/or albedo. Simultaneous radar/optical observations could be used to create a model that provides a more accurate means of translating optical brightness into size estimates. The C-band radar, co-located at Ascension, could potentially be tasked to obtain simultaneous radar and optical observations of targets with well-known orbits.

LEO objects moving quickly across the sky present a small window of acquisition; therefore they must have accurate orbits for a successful campaign. Objects at higher altitudes allow for a longer observing window, and less contamination due to star trails (applicable for the optical observations) because their relative motion across the sky

is slower, but will present a smaller Radar Cross Section (RCS) and thereby a smaller signal-to-noise ratio (SNR). This poses significant challenges, but could result in significant returns for understanding the actual sizes of debris.

9. CONCLUSIONS

NASA's Meter Class Autonomous telescope has the potential to vastly improve NASA's understanding of the debris environment, which is essential to ensuring the safety of all spacecraft in orbit around the Earth. The new destination of Ascension Island offers benefits ranging from location to weather to support. The unique latitude/longitude will fill a significant gap in the GEODSS network's coverage of the sky. From an astronomical perspective, the environment and weather is promising with limited rainfall, steady trade-winds producing laminar flow over the island and potentially stable 'seeing' conditions, and dark skies. Personnel and infrastructure support at this remote location will be critical for the success of an automated telescope.

System performance relies heavily upon proper commissioning, calibrating and testing/thresholding prior to full operations commences. A fully automated software suite has been developed to (a) control the dome and telescope, (b) assess weather conditions and determine whether to open and observe (or end operations for the night), (c) determine the most efficient observing plan for the night, (d) observe, and (e) reduce the data. Four major operational modes will be employed: (1) GEO Survey/GEO Follow-up, (2) Catalog or Object of Interest Tracking, (3) Orbit Scan, and (4) Stare-Detect-Chase. Finally, coordinated observations might be possible with either other optical telescopes around the globe, or potentially with the C-band radar at Ascension. Results will be sent via DSCS satellite and routed to NASA ODPO for analysis.

All this is made possible due to the marriage of sophisticated automated software, a suite of weather sensors, advanced instrumentation, a fast tracking telescope and dome, and a very dedicated team of engineers and scientists.

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