Deploying the NASA Meter Class Autonomous Telescope on Ascension Island

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ABSTRACT

NASA has successfully constructed the 1.3m Meter Class Autonomous Telescope (MCAT) facility on Ascension Island in the South Atlantic Ocean. MCAT is an optical telescope designed specifically to collect ground-based data for the statistical characterization of orbital debris ranging from Low Earth Orbit (LEO) through Middle Earth Orbit (MEO) and beyond to Geo Transfer and Geosynchronous Orbits (GTO/GEO). The location of Ascension Island has two distinct advantages. First, the near-equatorial location fills a significant longitudinal gap in the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) network of telescopes, and second, it allows access to objects in Low Inclination Low-Earth Orbits (LILO).

The MCAT facility is controlled by a sophisticated software suite that operates the dome and telescope, assesses sky and weather conditions, conducts all necessary calibrations, defines an observing strategy (as dictated by weather, sky conditions, and the observing plan for the night), and carries out the observations. It then reduces the collected data via four primary observing modes ranging from tracking previously cataloged objects to conducting general surveys for detecting uncorrelated debris. Nightly observing plans, as well as the resulting text file of reduced data, will be transferred to and from Ascension, respectively, via a satellite connection. Post-processing occurs at NASA Johnson Space Center.

Construction began in September 2014 with dome and telescope installation occurring in April through early June, 2015. Engineering first light occurred on June 2, 2015; scientific first light was achieved on Aug 25, 2015. Acceptance testing, full commissioning, and calibration of this soon-to-be fully autonomous system commenced in summer 2015.

1. INTRODUCTION

The population of debris orbiting the Earth is rising steadily with time. Breakups have been observed dating as far back as 1961 [1]. Notable GEO events include the 1978 breakup of the Russian Ekran 2 (battery malfunction), and at least two Titan transtage explosions/break-ups, one in 1992 (potentially from unspent propellant) and the other in June 2014. Several catastrophic explosions in LEO have resulted in thousands of pieces of debris, including the 2007 Chinese anti-satellite missile test that destroyed a Chinese weather satellite at nearly 900km.

The Meter Class Autonomous Telescope (MCAT) is a 1.3m optical telescope designed to characterize this space debris environment. Operated by the Johnson Space Center Orbital Debris Program Office (hereafter ODPO), it is dedicated to the statistical and targeted study of debris in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), GeoTransfer Orbit (GTO), and Geosynchronous Orbit (GEO).

From an observational perspective, the ODPO currently has access to telescopes on Mauna Kea with the 3.8m infrared UKIRT telescope as well as in Chile where the Michigan Orbital Debris Survey Telescope (MODEST; optical), Cerro Tololo 4.0m Blanco (optical), and Las Campanas Magellan (twin 6.5m optical/infrared) telescopes are located [Fig. 1]. Unlike UKIRT, Magellan, and the 4.0m, MCAT gives the ODPO year-round access to and full control of this telescope. Unlike MODEST, MCAT will be automated, allowing for data to be collected on every clear night of the year.

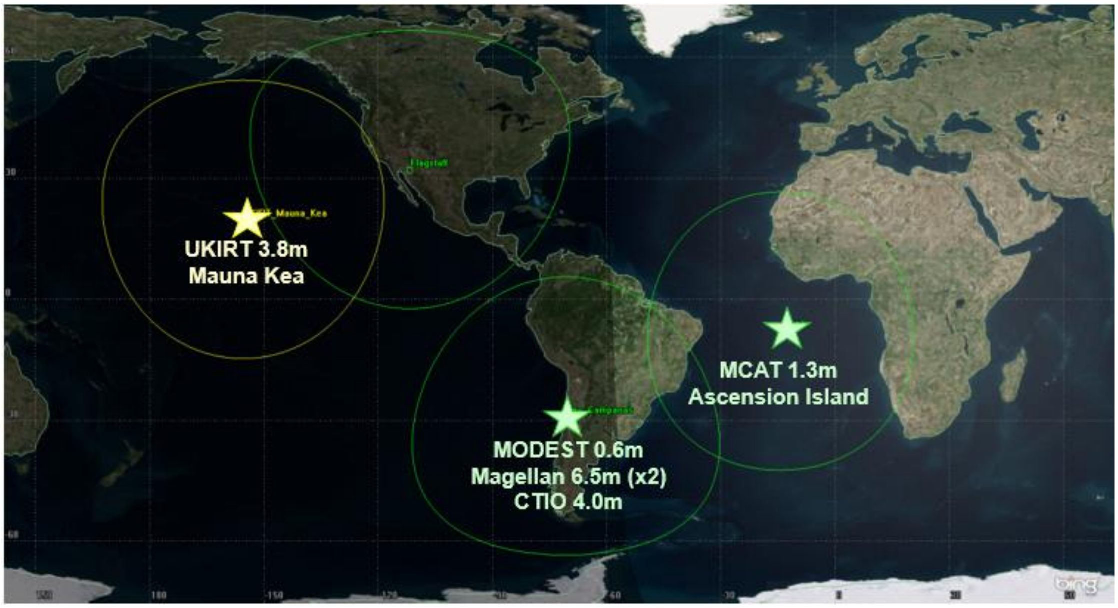

Fig. 1. Location of telescopes used by the Optical Measurements Group of ODPO. UKIRT is an infrared telescope on Mauna Kea, Hawaii. Both MODEST and the 4.0m Blanco telescope use optical instruments and are located at Cerro Tololo Interamerican Observatory in Chile. The twin 6.5m Magellan telescopes have both optical and infrared instrumentation and are located at Las Campanas Observatory. MCAT expands the sky coverage to a region not covered by other GEODSS or NASA telescopes.

2. DESTINATION: ASCENSION ISLAND

Ascension Island, located in the South Atlantic Ocean at (7° 58′20" S, 14° 24′ 4"W) was chosen for two prime reasons: (1) it is very well suited to fill a gap in on-sky latitude/longitude coverage by the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system of telescopes, and (2) it is one of the very few low latitude locations (<10º latitude) where the US has a presence. The 45th Space Wing, Detachment 2, shares responsibility for the Ascension Island Airfield (ASI) and was originally one of the possible landing sites for the Space Shuttle. NASA has a history of presence on Ascension, not only with the Shuttle Program but also formerly operated a telescope for tracking purposes for the Apollo program.

The observatory is located on the southern portion of the island on the US Air Force Base [Fig. 2] next to the secure Consolidated Instrumentation Facility (CIF). The control room is located inside the CIF, which could allow MCAT to conduct secure observations if desired. The needed power and communications requirements of other assets at the CIF facility have proven fruitful for MCAT, which benefits from the clean and reliable power as well as access to the DSCS Satellite network. Both are difficult to come by on islands as remote as Ascension.

MCAT's placement on the windward side of the CIF ensures that the steady trade winds blowing from the SSE pass over MCAT smoothly before any turbulence is created by the buildings [Fig. 3]. This location ideally blocks MCAT from the lighting of the small Royal Air Force and US bases and airfield nearby. Prior to 2014, all streetlamps on the US base were standard mercury lights with no attempt to block the light from reaching the sky. In 2014, all were replaced with high pressure sodium in downward-facing 'shoebox' style lights to minimize stray light from brightening the sky. This alone darkened the sky by 0.4 mag/sq-arcsec. Notably, MCAT is also next to the joint RAF/USAF airfield, which poses an additional light source on nights that aircraft are on the tarmac (generally a few nights per week). MCAT sits comfortably in the 'shadow' of the CIF. Thanks to thousands of migrating sea-turtles that use Ascension as a nesting site, the dark skies on Ascension are further protected to ensure hatchlings scramble to the sea instead of toward bright lights after hatching at night. On a moonless clear night, even with the airfield lights on, the sky brightness measures a respectable 21.3 mag/sq-arcsec, dark enough that the Milky Way dust lanes are magnificent. With the airfield lights off, the sky is 21.7 mag/sq-arcsec, rivaling the darkest major observatories in the world.

At a low altitude, high aerosol site like Ascension, an atmospheric coherence scale length (r_0) of order ~5-7 cm – suggests seeing of order 1.5″ or greater in V band. During the first week of commissioning of the first camera to be installed on MCAT (See Sec. 5), seeing measurements taken on during a 1-week period support this estimate, but data taken throughout the coming years will be necessary to determine average site conditions. An auxiliary 0.4m (16″) telescope installed on a platform next to MCAT [Fig. 4] will have DIMM seeing monitor capabilities (Differential Image Motion Monitor) to independently determine the seeing conditions.

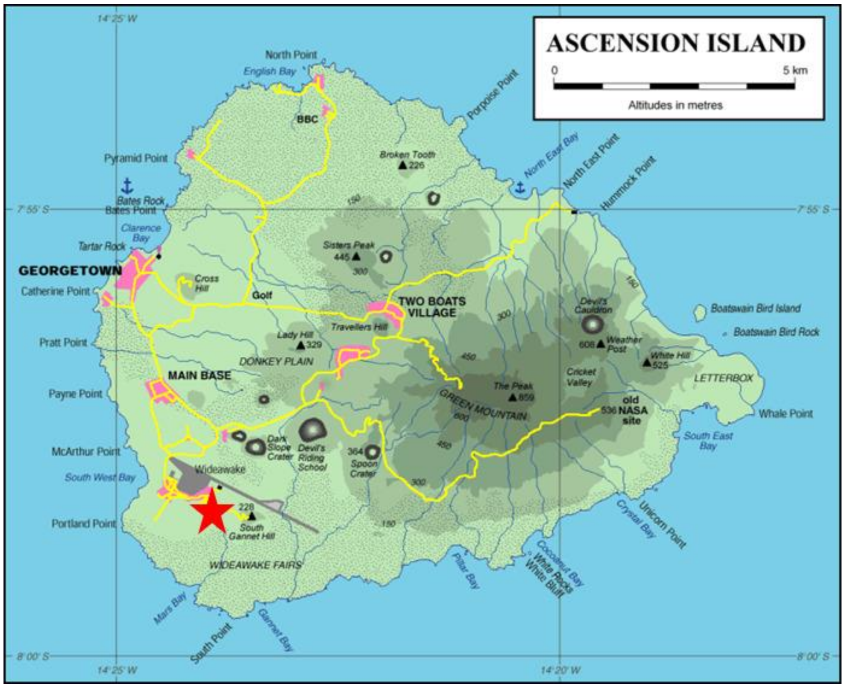

Fig. 2. The map of Ascension Island shows the location of the MCAT Observatory (red star). Located on the US Air Force Base and inside a secure area, MCAT sits on a hill 350′ above sea level and about a mile inland, which helps minimize sea spray but does not eliminate aerosols in the atmosphere.

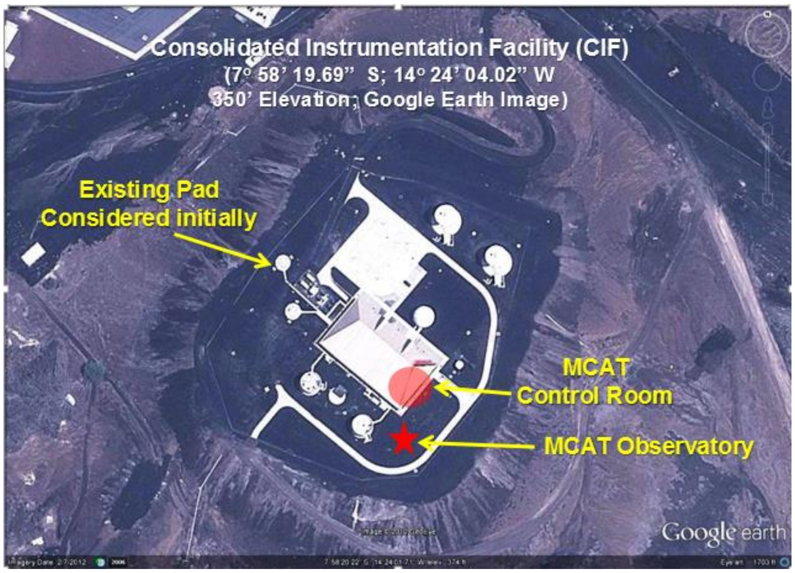

Fig. 3. Location of the MCAT Observatory. Steady trade winds prevailing from the SSE off the western coast of Africa ensure that a laminar airflow passes over MCAT before any turbulence forms from nearby buildings and structures**.**

Fig. 4. Construction of MCAT on Ascension Island. *Photo credit for the three full telescope images, Ben Hanna, Royal Air Force.*

3. MCAT INSTRUMENTATION

The programmatic and scientific goals of MCAT to track LEO and GEO including Low Inclination LEO (LILO) required a very unique set of instrumentation. The telescope and dome must be fast tracking to follow LEO. The mount of the telescope should be capable of tracking objects through the zenith without presenting a 'blind spot' nor requiring the flip of the telescope mount when it transits the meridian, which would cause a temporal gap in tracking LEO objects. The camera must be able to conduct survey imaging of portions of the geosynchronous belt every clear night with as wide a field of view as possible, but without undue stress on the telescope, and allow for astrometric and photometric data to be acquired. These requirements led to a unique combination of high-end instrumentation including:

(1) **TELESCOPE**: A fast f/4 double-horseshoe modified equatorial mount telescope designed exclusively by DFM Engineering for low latitude sites. This unique mount design eliminates both the blind spot at the zenith that is typical of German equatorial mounts as well as the meridional flip, allowing smooth, uninterrupted tracking across the sky. With a slew rate of 4°/sec and $10°/\text{sec}^2$ acceleration, the telescope can move ~9° within 2.2 sec. It easily tracks objects in LEO orbits.

(2) **DOME**: The dome is a 7-meter single-skin lightweight aluminum, fast-tracking Observadome with a wide 90″ aperture shutter. Utilizing friction-drive to allow rapid acceleration and deceleration, it is capable of rotating at 15º/s, easily matching any fast LEO passes tracked by the telescope.

(3) **SURVEY CAMERA**: A Spectral Instruments 1100S CCD is the prime camera used by MCAT. It has a Grade 1 e2v BI deep depleted astro ER1 coated chip which boasts > 90% quantum efficiency over much of the visible wavelength regime [Fig. 5]. On MCAT, the field of view is 41′ x 41′ (nearly 1º diagonally). The spectral range of the optical camera is 3000 Å – 1.06 μm. The camera is TDI[1] (Time Delay Integration) capable, ideal for nightly surveys tracking the Geosynchronous belt. TDI mode eliminates undue stress on the telescope by eliminating the need to re-center the telescope on fields repeatedly through the night, using the counter-sidereal scanning of the camera instead of the telescope to track at GEO rates.

(4) MECHANICAL SHUTTER: A Uniblitz shutter, model CS90HE (6-blade pupil shutter) with a Hall Effect sync sensor and two actuators for more reliable shutter closing. The Hall Effect sync sensor system allows the software to confirm the shutter has closed as these shutters have an average lifetime of ~500,000 cycles.

(5) **FAST FRAME-RATE CAMERA**: A Finger Lakes Instrumentation (FLI) MicroLine ML1050 boasts a very fast frame-rate (4 or 12 MHz digitization) with an electronic shutter. It was originally slated for use with a DIMM seeing monitor telescope. The CCD, a Trusense KAI01050 (1024x1024 pixels, 5.5μm/pix), is thermoelectronically cooled to down to 55ºC below ambient temperatures, yielding a dark current of 0.0002 e-/pix/sec at -35ºC. The quantum efficiency of the camera peaks at 50% in the visible [Fig. 6] and offers a field of view of 3′ x 3′ when deployed on MCAT. The mechanical shutter combined with SI survey camera cannot accommodate the necessary time sampling for lightcurve studies of debris that can tumble at rates as fast as 0.1 Hz. Fast time sampling, however, is the forte of this camera. The FLI ML1050 camera was the installed on MCAT in August 2015 while the SI survey camera was under repair.

(6) **FILTER SLIDE**: DFM Engineering designed a linear 8-position filter slide to accommodate a full suite of filters.

(7) **FILTERS**: A set of research grade Sloan Digital Sky Survey (SDSS) g′r′i′z′, and Johnson/Kron-Cousins BVRI filters are installed in the 8-position filter slide [Fig. 7]. Filters were manufactured by Custom Scientific with a sputtered coating. This coating is very robust in high humidity environments like Ascension, ideal for long-term spectral stability.

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. Given 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.

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[1] *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.*

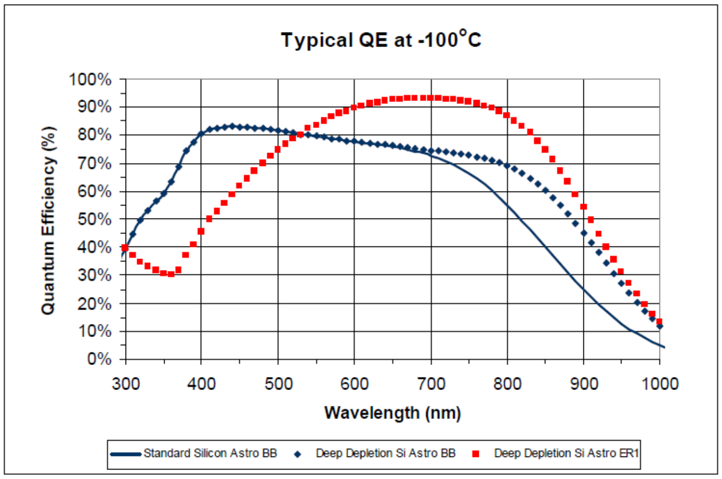

Fig. 5. Quantum Efficiency of an e2v BI deep depleted astro ER1 coated chip plotted in red. This is the CCD chip housed in the MCAT Spectral Instruments 1100S camera, which is optimized for GEO surveys.

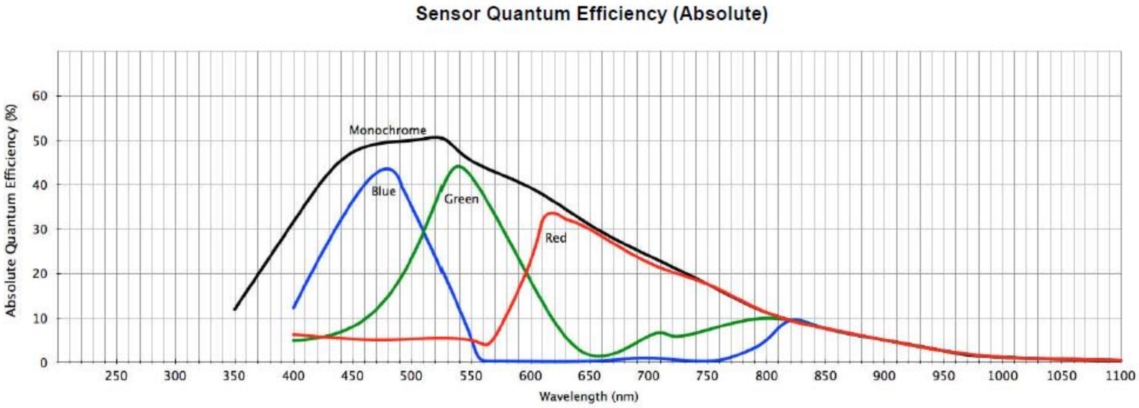

Fig. 6 Quantum Efficiency curve of the FLI ML1050 fast frame-rate camera.

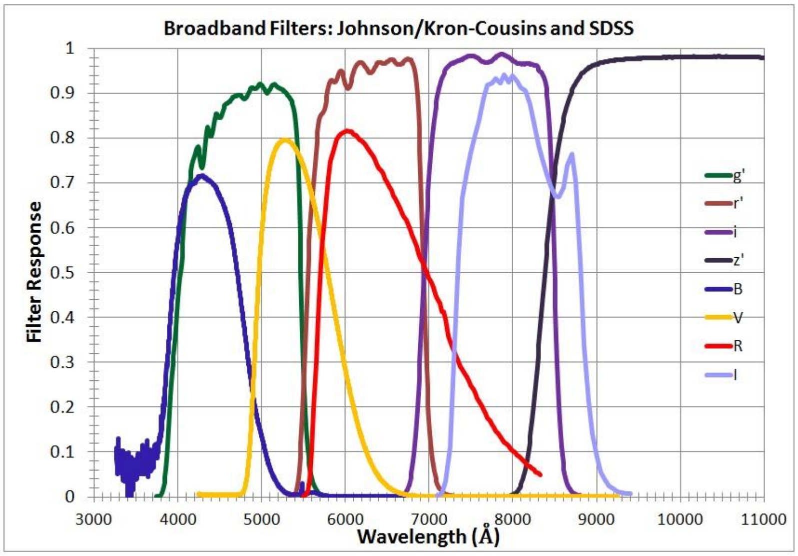

Fig. 7. Plot of the filter response for Johnson and Kron-Cousins BVRI broadband filters and Sloan Digital Sky Survey (SDSS) g′r′i′z′ filters.

4. MiniCAT AUXILLIARY TELESCOPE INSTRUMENTATION

Originally designed solely for a DIMM seeing monitor, a platform was erected on a structure next to and at the height of MCAT to monitor atmospheric stability and act as an independent health check for MCAT. This platform will now house a dual-purpose, high-end small telescope system, capable of acting as either a DIMM telescope or as a Raven-class system. It will be controlled by the same software as MCAT to observe simultaneously with MCAT using a different filter, or in concert with MCAT. It will conduct GEO Surveys, track LEO, MEO, GTO, or GEO objects, or play the role of ‘chaser’ when MCAT detects an object in Stare and Chase mode (or vice versa). Like Raven-class systems, the entire package is comprised of Commercial Off The Shelf (COTS) instruments.

(1) **Telescope and Mount:** An Officina Stellare RiLA 0.4m f/5.2 telescope is the basis of the system, designed in conjunction with an FLI ProLine PL4710 camera to result in a field of view that matches MCAT as closely as possible (this system 44′ x 44′; MCAT is 41′ x 41′ but with 2x better pixel sampling) [2].

The optical quality of this COTS telescope is excellent. The mirrors are made of low thermal expansion coefficient borosilicate glass and are coated with SiO_2 (quartz) protected enhanced aluminum (like MCAT’s mirrors) for longer-life and superior reflectivity. The primary mirror is supported by axial and radial supports to alleviate stress and prevent astigmatism. Light baffles and anti-reflective paint help minimize stray light.

An extra-low CTE carbon/aluminum athermal open truss optical tube assembly is very lightweight and sports a black shroud to protect the mirror. At the same time, the carbon-tube joints are designed to strengthen the assembly structure, frontal rings to strengthen secondary mirror support, and the truss designed to encourage thermal stability. It is a very well built COTS telescope whose fast focal ratio (uncommon in COTS telescopes) results in a distinctly advantageous wide field of view.

(2) **Mount:** The high-end Astelco NTM500 German Equatorial mount is long-lasting, very fast tracking and built with direct-drive torque motors. With a small, light-weight telescope attached, its industrial strength motors can complete the necessary meridional flip easily within 5 seconds. While this mount style does have a 2-degree blind-spot at the pole, on Ascension, that equates to a blind spot centered at 8 degrees above the horizon where the airmass limit and dome occultation prevents observing regardless of one’s desires. It touts micro-arcsecond encoders, accurate to 1″ RMS pointing with the Astelco pointing model, allowing for tracking accuracy of <1″ without an autoguider.

(3) **Dome:** A 7-foot AstroHaven clam-shell style dome allows for full-sky views without the need for dome rotation.

(4) **Camera and Focuser:** A Finger Lakes Instrumentation (FLI) ProLine PL4710 camera. Combined with the chosen camera, this system touts a 44′ x 44′ field of view, rivaling that of MCAT’s survey camera at 41′ x 41′. The Basic Midband Coated e2V Grade 1 sensor offers excellent quantum efficiency in the visible [Fig. 8] and has a built-in shutter. The system will utilize an FLI Atlas focuser.

(5) **Filter Wheel:** An FLI Centerline CL-1-10 FLI filterwheel has 10 filter slots available. Its symmetric design eliminates imbalances caused by asymmetric filter wheels.

(6) **Filters:** The same suite of filters used by MCAT (Sloan g’r’i’z’, and Johnson/Kron-Cousins BVRI) broadband filters, albeit manufactured by Astrodon, not Custom Scientific. The Astrodon filters have recently been redesigned with a new long-life coating.

This system, under good sky conditions, should be capable of detecting objects as faint as 16.5 magnitudes in R-band images in 10-seconds, assuming a sky brightness of 21.3 in V, 20.5 in R, and seeing of 2.5″. Potentially better seeing and darker skies will serve to improve the limiting magnitude of the system. In comparison, MCAT’s larger aperture ideally will reach nearly 19th magnitude in R-band in 5-seconds.

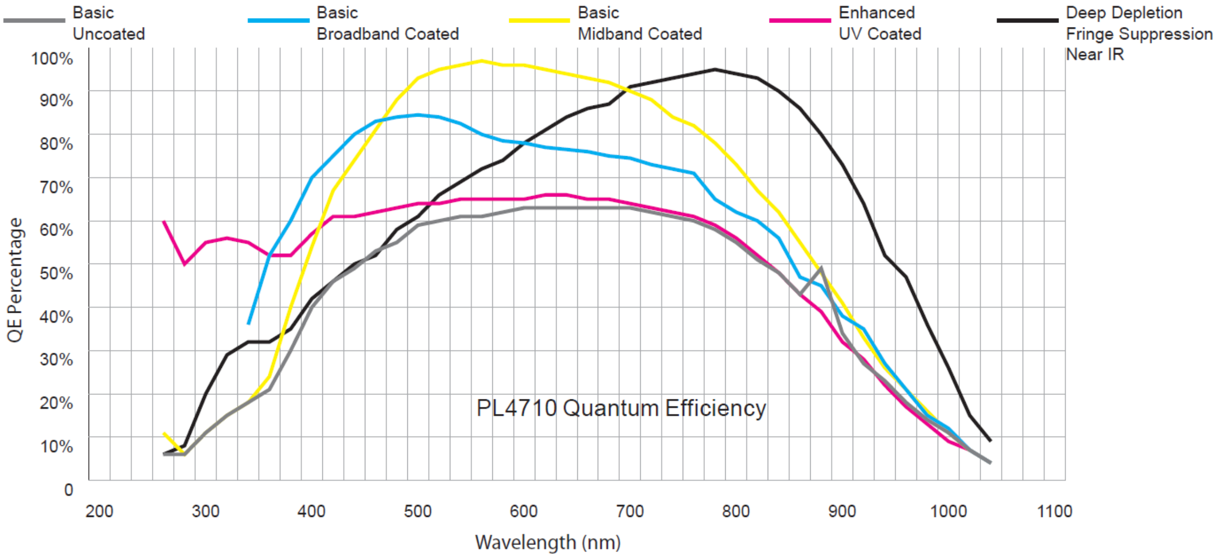

Fig. 8. Quantum efficiency curve of the Finger Lakes ProLine 4710 camera, to be used with the 16″ Officina Stellare telescope next to MCAT. The curve in yellow represents the QE curve of the Basic Midband Coated CCD chip.

5. Weather Suite

The suite of weather systems is designed to detect rainfall while monitoring temperature, pressure, humidity, dew point, 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 2 Boltwood cloud sensors will be used to monitor clouds. The Observatory Control Software (OCS) accepts constant input from the weather sensors to autonomously determine whether conditions are acceptable for observing and will close the dome and put the system into sleep mode when they are not.

The FLIR infrared camera has the best seat in the house. Mounted on the spider vein above the secondary mirror and thereby not occulting the primary mirror, the 40° field of view of the FLIR is always centered on the current MCAT field of view. Infrared images of the sky are taken every 30 seconds. They give infrared intensity, equivalent to sky temperature. A threshold setting below a certain level indicates whether the skies are photometric or not. Low clouds are warm, high clouds are cold, and photometric skies are somewhat colder, requiring some fine-tuning to determine the conditions of the sky. To first order, the values measured by the FLIR on known photometric nights, nights with thin cloud, and nights with thicker cloud will be determined to allow a correlation with infrared sky temperature and sky conditions.

An SBIG (Santa Barbara Instruments Group) All-Sky camera offers views of the entire sky simultaneously and is mounted on the platform next to MCAT where the auxiliary miniCAT telescope will be deployed in 2016. The images produced by the SBIG camera are translated into ASCII text by calculating sky brightness values (higher with thicker clouds) and creating a 2-D map of ASCII values to quickly determine whether the sky is clear, and if partially clear, in which direction the sky is clear for tasking the telescope. This method is effective for high, slow-moving clouds, but not for low, fast-moving clouds.

6. 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 (Observatory Control System hereafter OCS) has been designed specifically for MCAT by Euclid Research to autonomously control the telescope and dome and to continuously monitor the weather conditions to determine whether the conditions dictate closing the observatory. A tasking file is uploaded each night with a prioritized list of objects or fields and the desired observing mode for each.

OCS can employ four distinct observing modes for automated detection, acquisition, tracking, and – via preliminary orbit generation and refinement – re-acquisition of both GEO and LEO targets (for more information see [3]):

1. **GEO Survey/GEO Follow-up Mode**
   GEO survey is achieved via sweep of inertial volume near GEO altitudes spanning inclinations that are expanded to 15° by solar/lunar perturbations. Patterned sweep is typically performed by counter-sidereal drift scan, TDI, camera read-out mode.

2. **Catalog or Object of Interest Tracking Mode (LEO, MEO, GTO, GEO)**
   Characterizing specific objects of interest can be achieved by tracking objects with known orbits. Two Line Elements (TLEs) from spacetrack.org are translated to ephemerides, which are accepted by the telescope's control system for tracking objects at their orbital rates. MCAT and miniCAT can be controlled by OCS to obtain simultaneous observations in different filters, which ensures data are taken over the same range of that object's lightcurve, yielding true colors of the objects and a coarse correlation with material type.

3. **Orbit Scan Mode (LEO)**
   Orbit scan mode samples a particular orbital space by creating a virtual TLE that defines the anticipated orbital parameters of heretofore undetected objects.

4. **Stare-Detect-Chase Mode (LEO)**
   Stare-detect-chase mode is designed to discover new LEO objects by (a) tracking at sidereal or static rates (Stare), (b) detecting streaks, and using those streaks to calculate the rate and direction of the object (Detect), and (c) using that output to track the newly discovered object (Chase). The object must be detected in two or more frames to determine the direction of motion. Streak-length is used to estimate orbital altitude.

7. COMMISIONING AND CALIBRATIONS

Construction of the DFM 1.3m double horseshoe mount telescope was completed in early June [Fig. 4], and engineering first-light was accomplished on June 2, 2015. An engineering video camera was employed to fine-tune MCAT's physical alignment in altitude and azimuth, and a pointing model successfully resulted in an overall pointing error of 6.8″ RMS error, adjusted for easily by the DFM pointing model.

Upon connecting the cooling lines to the prime SI camera to MCAT, a hissing noise indicated the inevitable conclusion: the cooling lines in the camera had cracked, requiring that the camera be shipped back to the manufacturer for repair. This presented and unexpected opportunity to test the ML1050 fast FLI with an electronic shutter for lightcurve studies, expanding MCAT's scientific capabilities. Commissioning of the FLI ML1050 camera occurred during a two week period at the end of August through early September 2015.

Scientific first light was achieved with the FLI camera on August 25, 2015, imaging NGC 6302, a southern hemisphere planetary nebula known as the Bug Nebula. Tracking Earth-orbiting satellites was also confirmed on this night with the successful acquisition of the GOES 4 and 8 satellites [Fig. 9]. Over the ensuing week, MCAT was tested in sidereal and non-sidereal modes. Calibration data were collected, including standard star fields, flat fields, and linearity tests. MCAT and the dome easily tracked targets in all orbital regimes, LEO to GEO. However, an elusive encoder error in the Telescope Control System software causes satellites to migrate and intermittently jump across the field of view during observations. Ongoing investigations with DFM are being conducted to track down this issue.

A suite of LEO objects were tracked during this commission run, including SSN 00118, a fragment from the first known breakup of a satellite in Earth-orbit. On June 29, 1061, a US Ablestar stage deployed three payloads, Transit 4A, Injun, and Solrad3, though the latter two did not separate from one another [1]. The spacecraft did not vent its remaining 100kg of hypergolic propellant upon separation, and 77 minutes after orbital insertion, the spacecraft fragmented at an altitude of 990 km. Venting of all remaining propellant for future missions was recommended after a thorough investigation of this event. Initially 296 fragments were cataloged, and as of 2008, 181 were still in orbit. The Transit 4A rocket body, 1961-015C (SSN 00118) was tracked successfully on Sept 3, 2015 with MCAT. Two passes, ranging from 10-20 seconds in duration, were followed.

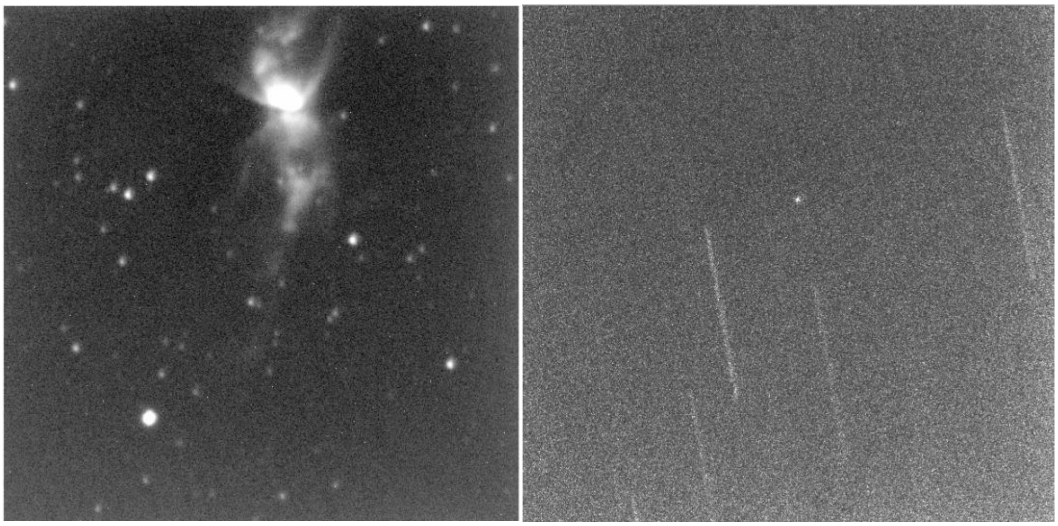

Fig. 9. First light images from MCAT with the Finger Lakes Instrument Microline ML1050 camera. On the left, NGC 6302, the Bug Nebula, a southern hemisphere planetary nebula. On the right, GOES 4 (Geostationary Operational Environmental Satellite). Images were acquired through non-photometric conditions.

Five additional pieces of debris from this breakup were also tracked, including SSN 00126, 00133, 00147, 00159, and 00548. Debris fragments were also observed from Titan (SSN 01684) and Atlas Centaur (SSN 00700) breakups. Rounding out the LEO observations were Gonets M07 (SSN 39251), Radio 8 (SSN12998), and COSMOS 1234 (SSN 12113). A GPS Navstar satellite in MEO (SSN 24876) as well as two GEO weather satellites (GOES 4, SSN 11964 and GOES 8, SSN 23051) demonstrated the capability to track these orbital regimes.

8. CONCLUSIONS

MCAT is located on Ascension Island in the South Atlantic Ocean, ideally suited for sampling low-inclination LEO orbits (LILO) in what was once a geographic blind-spot for ground-based telescopes employed by the US to track debris. With a fast-tracking, 1.3m telescope and dome, MCAT is capable of tracking LEO, MEO, GTO, and GEO in four major operational modes. These include: (1) GEO Survey/GEO Follow-up, (2) Catalog or Object of Interest Tracking, (3) Orbit Scan, and (4) Stare-Detect-Chase.

A 0.4m Raven-class COTS system will be deployed on a platform at MCAT's height, next to MCAT. With an equally fast-tracking mount and a clam-shell dome, this telescope can be run simultaneously or in concert with MCAT, using its own set of filters that match those used by MCAT. This offers an extremely enticing capability of collecting data in two different wavelength regimes simultaneously, allowing true colors to be determined as both telescopes observe the object through identical rotational/tumble phases.

During the initial MCAT commissioning phase, 11 LEO objects, one MEO, and two GEO objects were observed, demonstrating the ability to easily track a multitude of earth-orbiting objects at all regimes. Designed to be fully automated, MCAT software is built to monitor weather, intelligently observe only when conditions allow, observe in four distinct modes, process data, and output a file with detected objects each night for further analysis at NASA JSC. 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.

9. REFERENCES

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