NASA's Orbital Debris Optical Program: ES-MCAT Updated and Upgraded

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ABSTRACT

The 1.3m ES-MCAT telescope (or MCAT for short) now has a proven capability for observing objects from Low-Earth Orbit (LEO) out to Geosynchronous (GEO) orbit, and the ability to run all systems autonomously. A GEO survey, the initial focus for MCAT, will commence in late 2019 to map out the current state of the GEO population as input for the ORbital Debris Engineering Model (ORDEM 4.x). This survey will statistically sample the GEO belt (0 to ~15 deg orbital inclinations) to detect both known and unknown targets. If a break-up occurs, additional surveys of the break-up field can be followed for discovery and investigations of daughter debris fragments from the parent satellite. Discovery can be accomplished by tracking orbits near to and including the parent object's orbit. Targeted observations of debris can be taken with a suite of broadband filters for characterizing individual objects by rate-tracking their known or calculated orbital elements (Two-Line Element sets, TLEs).

Several modifications and upgrades have been made to the instrumentation and systems originally installed in 2015 and are reported here. In 2018, MCAT's primary mirror was recoated with a high-end protected, enhanced silver by the ZeCoat Corporation. The CCD chip was replaced in the Spectral Instruments camera with a broad-band antireflective coated chip. The automated weather systems have been modified from the original system, removing some weather sensors and installing replacements that are better suited to Ascension's weather and environment. A new 2.5-m ObservaDome replaced the Astrohaven dome on the nearby tower platform that will house an auxiliary 0.4-meter telescope. Finally, in 2019, the Observatory Control System was upgraded to 2.0 which includes additional flexibility for automating data collection and reduction. With these updates completed, MCAT is now well on track to reach Full Operational Capability (FOC) in 2019 for its survey, rate-track, and TLE tracking capabilities.

1. INTRODUCTION

ES-MCAT, the Eugene Stansbery – Meter Class Autonomous Telescope (historically called MCAT) was deployed on Ascension Island, and achieved first-light in June 2015 [1, 2 ,3, 4]. Ascension Island is a British overseas territory located in the South Atlantic Ocean midway between Brazil and Africa (7° 58' S, 14° 4' W, 350' elevation). ES-MCAT, a joint NASA-Air Force Research Labs (AFRL) project, is located on the U.S. Air Force base (45th Space Wing, Detachment 2) near the Ascension Auxiliary Air Field (AAF). Ascension was chosen because: (1) its near equatorial latitude ensures that low-inclination LEO (LILO), GEO and GTO target orbits pass overhead; (2) it fills a gap in longitudinal coverage of the GEO belt that is not covered by other US ground-based telescopes (GEODSS in particular); (3) its remote location provides very dark skies for astronomical observations, very important for small, faint debris; and (4) its infrastructure and personnel on the island allow for long term logistical support and maintenance.

The primary ***observing goal*** for MCAT is to statistically characterize under-sampled orbital regimes, with emphasis on monitoring the GEO debris belt to determine the distribution function of debris. The prime ***objective*** is to monitor and assess the orbital debris environment by surveying, detecting, and tracking orbiting objects at all orbital altitudes: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geo Transfer Orbit (GTO), and Geosynchronous Orbits (GEO). MCAT can also be used to track and characterize a Resident Space Object (RSO), defined here as an artificial object orbiting Earth, whose orbital elements are known. As a dedicated NASA asset, MCAT can be tasked for rapid response to break-up events after they have occurred, and is intended to become a contributing sensor for the Space Surveillance

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Fig. 1. The John Africano Observatory (JAO) is a joint NASA-AFRL facility that includes: (a) the 1.3-meter MCAT telescope, installed in the larger 7-meter ObservaDome on the left, and (b) a 0.4-meter Officina Stellare telescope that will be installed in the new smaller 2.5-meter dome on the tower platform on the right.

Network (SSN) for the purposes of Space Situational Awareness (SSA). MCAT is expected to make a valuable contribution to our understanding of the orbital debris environment around Earth for years to come.

The ES-MCAT telescope is a 1.3m f/4 DFM Engineering optical telescope with a 7-meter ObservaDome, both fast-tracking to easily accommodate tracking debris at all orbital altitudes. The custom Euclid Research Corp. Observatory Control System, OCS software queries and controls all functions of the observatory, including autonomously monitoring weather and system health, conducting all observations, and processing the data. Ultimately, the optical data products are incorporated into the ORbital Debris Engineering Model (ORDEM), which is used by satellite designers and operators to estimate the OD impact risks on their vehicles in Earth orbit. ORDEM provides information on debris impact rate as a function of size, material density, impact speed, and direction along mission orbit [5].

2. INSTRUMENTATION

The John Africano Observatory (JAO) comprises the 1.3m MCAT telescope facility, the 0.4m telescope Benbrook tower facility, the weather mast, and the control room within the Consolidated Instrumentation Facility (CIF). The full suite of instrumentation within JAO was previously discussed at AMOS [2] but has undergone some modifications, which we report here.

2.1 Survey Camera: SI Camera, now with a *broadband* anti-reflective coated e2v chip

In May 2018, the camera was sent back to the US for servicing. At some point, the original Grade 1 e2v BI deep depleted astro ER1 antireflective coated 4k x 4k chip (Fig. 2, red curve) suffered from failures that ultimately rendered that CCD completely non-functional, unreadable from any ports. Fortunately, a deep depleted astro broadband (BB) coated 4k x 4k e2v chip (Fig. 2, blue curve) was available at no cost to replace the original CCD. The astro BB anti-reflective (AR) coated chip is now installed in the SI camera, and is in service on the MCAT telescope. This chip is more sensitive in the blue than the astro ER1 coated chip, but less sensitive in the red where debris tends to be brighter, though not strictly (e.g. aluminum is fainter in the red due to the broad absorption line ~800nm). The intent for MCAT is to use either the Johnson/Kron-Cousins R, or preferably the well-calibrated Sloan Digital Sky Survey (SDSS) r′ filter. The BB AR coating on the current chip will affect the limiting magnitude in each filter, improving it in g′ and B, but for the case of the filters in the red end, it translates to decreasing sensitivity and thereby MCAT will not detect

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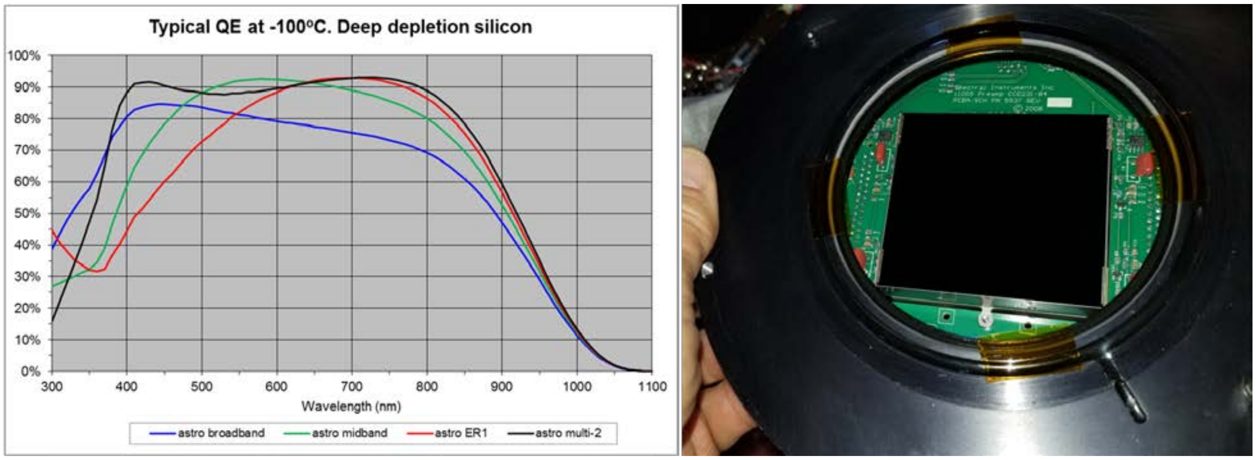

Fig. 3. Left: Quantum Efficiency curves for the CCD chip installed on MCAT from Dec 2015 to May 2018 (astro ER1) in red, versus the CCD installed in December 2018 (astro broadband/BB) in blue. Right: the new 4k x 4k chip installed in the Spectral Instruments camera on MCAT.

objects as faint in the red as it would have with the original chip. Fortunately, a newly coated mirror (See Sec. 3 below) has more than made up for this decreased sensitivity compared with the fully integrated system with the old CCD and old mirror coating.

3. PRIMARY MIRROR: Coating and Cleaning

3.1 ZeCOAT re-'aluminization' for primary mirror: Enhanced Protected Silver

MCAT is the proud recipient of a newly re-coated primary mirror. As with all visible telescopes with front-surface coated optics, periodic re-coating of the mirrors is required. Major research observatories typically strip/recoat mirrors every 1 to 5 years. With the harsh sea-level environment MCAT is exposed to, it was determined in late 2017 that this maintenance was due. With the telescope nearing completion of testing planned for the Initial Operational Capability (IOC) phase, timing was ideal to recoat in preparation for attaining Full Operational Capability (FOC), anticipated for fall of 2019.

The coating requirements included:

(1) Optimization for the360nm – 1µm wavelength range
(2) Minimum of 90% average reflectivity across the SDSS g′r′i′z′ filter bandpasses
(3) Minimum 90% reflectivity from the central hole of the mirror to within 5% of the outer edge of the mirror
(4) A reflective layer thickness of 1000 Å +/- 10%
(5) A protective topcoat applied to withstand the corrosive environment

Given how severely the coating degraded in the months following the discovery that it was starting to degrade (a quick degradation like this is apparently normal once it begins) led to extensive investigations into choosing a coating, coating vendor, and stringent environmental tests for the new coating as Ascension is known to be a very corrosive environment, and cost/schedule effects are significant given there is no coating facility on Ascension, requiring the mirror be shipped back to the US for recoating.
These tests included the following Mil-STD (defined to achieve standardization objectives by the DoD), and ISO (International Standards Organization) standard tests and guidelines:

(1) Adhesion – tape tests: ISO-9211-4: Test 6.2.1
(2) Abrasion – no scratches/streaks: ISO-9211-4, moderate abrasion test 5.2.2
(3) Physical – Free of physical defects, such as no flaking, peeling, cracking, blistering: ISO-211-4, section 8.5 Evaluation
(4) Cosmetic – free of stains, smears, discolorations, streaks, hazy/cloudiness: ISO-211-4, section 8.5 Evaluation

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(5) Environmental and physical durability

a. Cleaning Durability – with acetone, ethyl alcohol, and a mild detergent: MIL-C-48497A
b. Humidity tests
c. Water solubility test (ISO-9211-4)
d. Salt solubility test (ISO-9211-4)
e. 24-hour salt-fog corrosion test (MIL-STD-810G_CHG-1.pdf, Method 509.6)
f. Acid Corrosion test (ISO 9022-12-1 Chemical Durability Environmental test; or MilStd810G, Method 518.2)
g. Alkaline Corrosion test (ISO 9022-12-2, ISO 10629: Chemical Durability Environmental test)

Test and Inspection for Optical Quality (MIL-PRF-13830B) included Surface Quality Inspection Methods No.1 and 2 for both the reflective and topcoat(s) layers (Back lit and front lit inspections). Many of the environmental tests were conducted on a suite of witness samples, with additional witness samples purchased for purposes of deploying them on the telescope. These witness samples will experience the same environmental conditions throughout the years as the fully installed 800-lb mirror, but are much easier to ship back to the US for analysis if needed in the future – something desired when the original coating degradation was identified. And finally, the new coating also needed to be chemically strippable for future recoating efforts.

In May 2018, the NASA MCAT optical team traveled to Ascension Island to remove the 800+lb, 1.3-m (52-inch) primary mirror from the telescope, and shipped it to the ZeCoat Corporation in Torrance, California. ZeCoat coated the mirror with an *enhanced, protected silver,* multi-layer coating with reflectivity meeting/exceeding the > 90% requirement across the entire visible spectral band pass (360 – 1000 nm), and > 95% *average* total reflectivity. Not only is the performance significantly better than protected aluminum (MCAT's original coating), but the extensive environmental tests demonstrated this proprietary silver coating is also much more durable. Originally patented by Lawrence Livermore National Labs [6], the coating was re-developed by Dave Sheikh/ZeCoat for NASA, employing an ion-assisted evaporation process for easy application to meter-class mirrors [7]. This coating was previously applied by ZeCoat to the 1.44-m Kepler Space Telescope as well as JPL's Moon Mineralogy Mapper spectrometer mirror. Notably, ZeCoat's enhanced, protected silver coating passed ALL tests and requirements laid out and discussed herein. Protected aluminum witness samples generated by ZeCoat that were tested, however, did not pass the salt solubility/salt fog tests. Notably, protected aluminum, though a different formulation that was applied by a different vendor, originally coated the MCAT mirror.

In December 2018, the NASA MCAT team returned with DFM Engineering's Ian Huss (DFM designed, built, and installed MCAT), for the week-long process to carefully reinstall the mirror into the mirror cell and hoist it up to the telescope. The mirror was aligned, mechanically/laser collimated, and collimated on-sky. Initial tests indicate that MCAT's performance with the new silver-coated mirror now exceeds its previous best performance with the original aluminum coating. Further tests to quantify this are forthcoming.

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Figure 5: The 1.3-meter, 52-inch 800 lb mirror suspended in the recoating chamber at ZeCoat before coating (left) and after recoating was completed (right).

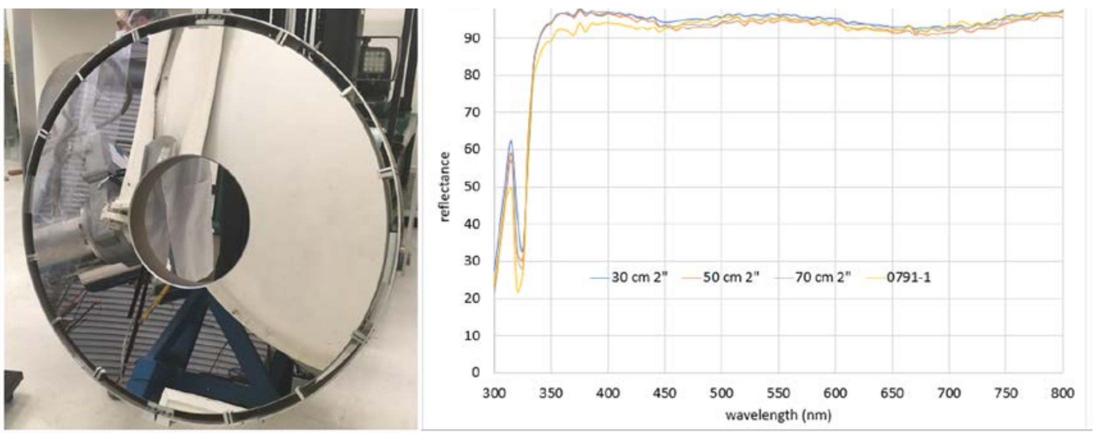

Fig. 4. Left: The MCAT mirror with its new enhanced, protected silver coating. Right: The reflectance curves, including: YELLOW: the originally proposed coating, BLUE, RED, GREY – actual final reflectivity as measured from witness samples that were coated in the chamber with the MCAT mirror. The throughput demonstrates the superior and uniform coating across the entire surface.

Fig. 6: Cleaning the mirror with First Contact® polymer spray. Left: Primary mirror fully coated. Right: Peeling off the dried polymer.

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3.2 Mirror Cleaning

The most effective way to increase the lifetime of any mirror coating is to keep it clean. With this in mind, the MCAT mirror is now cleaned each time the team travels to the island for any maintenance trip (roughly 3 times/year). Because Ascension is a sea-level environment, MCAT is exposed to salty humid conditions (typically 65-80% humidity). Such conditions are not well suited for weekly cleaning with CO_2 snow, as is often done at very dry and high altitude professional observatories. This is because in humid environments, CO_2 snow ice can cause condensation of water (from the humid air) on the mirror surface, which leads to water streaks on the mirror. Worse, if that humidity is laden with salt water, salty deposits could encourage degradation or damage of the thin molecular protective coating on the mirror.

Cleaning a mirror with a solution of soapy water is also undesirable for MCAT. The volcanic dust of Ascension Island is very sharp edged. Even dragging optical cleaning cloths very lightly along the surface as one does with this technique could scratch the outer protective coating on the mirror.

In contrast, neither condensation of water nor scratches are a significant risk with the alternative approach used on MCAT. Here, a polymer spray is applied to MCAT's mirrors for cleaning, called First Contact®, trapping the dirt within it (Fig. 6). To prepare for the polymer, everything surrounding the mirror must be covered in plastic as the liquid polymer spray will stick to everything, and is not easily removed from the black anodized surface that covers MCAT's mirror doors, nor from the black tube assembly in the central hole of the mirror, nor does one want this inside the mirror cell on the sensitive counterweights supporting MCAT. Once it is completely protected, a spot-remover pre-treatment is sprayed on the mirror to help dissolve any salty deposits on the mirror (imagine cleaning your windshield after spending a few days at Oceanside beaches). Before the pre-treatment dries, the reddish colored liquid polymer is sprayed onto the mirror. Several coats are applied, allowing a few minutes of drying between each polymer coat. The coating thickness can be gauged based on the pinkish color of the polymer, appearing nearly clear if it is too thin, but becoming darker pink as more coats are applied. This is allowed to fully dry and cure over the course of several hours (or preferably overnight), trapping any dust/dirt particles into the dried polymer. Once cured, one simply peels away the polymer with the trapped dirt, much like removing plastic wrap (e.g. Saran wrap) from the surface.

4. WEATHER SYSTEMS

The observatory is designed as a fully autonomous facility. The first line of defense in protecting the telescope and instruments lies in the ability to constantly monitor the changing weather conditions and above else, ensure that the dome closes when conditions deteriorate below defined thresholds. The suite of weather systems in place is designed to detect rainfall while monitoring temperature, pressure, humidity, dew point, wind speed, and wind direction.

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.

Thresholds/limits that trigger the observatory to close, as well as to re-open are currently (in 2019) set:

(1) Rain – any sensor that detects rain triggers closing
(2) Wind – both wind gusts and average wind speed limits to close and a lower threshold to re-open
   a. GUST: close limit set to ≥ 20 m/s (45 mph)
   b. GUST: re-open limit of ≤ 15 m/s (33 mph)
   c. AVG: close limit set to ≥ 15.6 m/s (35 mph)
   d. AVG: close limit set to ≥ 13.4 m/s (30 mph)
(3) Dew point/condensation monitor:
   a. Close limit ≤ 1.67 C degrees,
   b. Must increase to ≥ 2.78 C degrees to re-open.
(4) Humidity – above a certain humidity level
   a. Close limit of ≥ 90%
   b. Re-open limit of ≤ 85%

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In all cases, the weather conditions must drop below and stay below the re-open limits for a certain period of time (set currently to **20 minutes**) to ensure that the weather has become stable enough to warrant opening the observatory again, preventing open/close/open/close in minute-by-minute increments.

Two weather stations of each type are installed to deliberately ensure redundancy in the event of any hardware or software failures. Weather stations include: (a) Davis Vantage Pros (T, P, wind speed/direction, humidity, rain), (b) Optical Scientific, Inc. (OSI) rain sensors, and (c) ASE Rain Sensors. Previously installed Boltwood cloud sensors and the New Mountain weather station did not withstand the harsh corrosive environment of Ascension and have been removed, replaced by the ASE rain sensors and a second Davis station, respectively.

The condensation monitor was designed to ensure dew does not form on the mirrors and potentially corrode the mirror coatings. The monitor includes three thermocouples attached to the primary mirror, which is connected to an Advantech ADAM unit powered by a Rhino power supply, and the Davis ambient temperature and humidity readings. The temperature difference between the primary mirror and dewpoint is noted above.

In addition, cloud cover is estimated by a small FLIR infrared camera installed on the spider vein above the secondary mirror, ensuring that the view seen by the MCAT camera is always within the FLIR field of view. The camera estimates opacity of the atmosphere to quantitatively monitor sky transparency conditions when data are taken, necessary for properly calibrating the brightness (photometry) of detected objects. See [2, 4] for more details.

Figure 7: Left: The weather mast is located 75 ft upwind from the observatory. Right/top: The Davis Vantage Pro (black cylinders with anemometers) and one of the OSI rain sensors (above left Davis station) are at the height above ground of the MCAT telescope. Right/bottom: the ASE rain sensors are installed about 1/3 up the mast.

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5. 2.5-meter OBSERVADOME INSTALLATION

Next to the MCAT telescope is a tower platform that was originally designed to house a differential seeing monitor (DIMM), and as such, designed so that the height above ground level of the DIMM to roughly reflect the height of MCAT above ground level (roughly 18-feet above ground). The tower itself is designed to minimize vibrations given its initial primary purpose of independently monitoring the seeing conditions, which could be affected by vibrations translated through the tower structure. The height above ground also ensures both telescopes experience the same level of ground-layer turbulence for accuracy in estimating seeing by two separate systems.

With the purchase of a fast-tracking, upgraded research grade Astelco mount and 0.4m Officina Stellare telescope, a new dome was purchased with the goal of better protecting the telescope. The system will now be housed inside a bi-parting shutter dome (versus the previous clamshell dome design) that is also fast tracking (up to 25 deg/s slew) with for the purposes of observing LEO debris. This 2.5-meter ObservaDome was installed by ObservaDome in August, 2018 on the platform by MCAT. This is essentially a smaller version of MCAT's dome, though a different control system, the ACES SmartDome controller, is installed on the 2.5-m dome to open, close, and turn the dome. [8]

ObservaDomes are designed to withstand some of the most extreme environments. They're fabricated out of non-corrosive aluminum and in this case, also painted to withstand the very harsh UV environment experienced at 8-deg south latitude. Flashings and seals along the aperture doors and ring wall keep the instrumentation inside safe even from heavy rains. As rains on Ascension typically pop up suddenly, that the bi-parting doors close in a matter of seconds is of great importance for keeping the telescope and all other equipment inside dry and safe. Though the MCAT weather system autonomously monitors weather with its extensive weather system, this small dome is additionally equipped with its own individual ASE rain sensor attached to the dome and monitored by the ACES SmartDome controller. This is important because if communication between MCAT and this separate facility is lost, the ACES smart dome will both monitor rain from its own rain sensor, and is also set to close if comm is not re-established with MCAT prime within the time period defined by the user.

Also, an HVAC system was installed to minimize corrosion of the instrumentation inside the little dome when it is closed. Like with the large dome, relays are triggered when the dome opens/closes to ensure that the air conditioning is turned ON when the dome is closed, and OFF when the dome is open. As with all telescopes, the goal is for the telescope to experience the same conditions as the outside world (equilibrated temperature and pressure) to minimize seeing degradation (atmospheric turbulence induced 'smearing' of the objects detected) while open and observing, but to keep it dry to minimize corrosion, which is aided significantly by the HVAC system. Details on the telescope, mount, camera, and filters for this system can be found in [2].

Fig. 1. The new 2.5m ObservaDome, left, installed in August, 2018. Like the 7-meter dome for MCAT, this smaller version is fully capable of fast-tracking debris at all orbital regimes, from LEO to GEO.

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6. OBSERVATORY CONTROL SYSTEM SOFTWARE, VERSION 2.0

The OCS master software, developed by Euclid Research Corp, is custom software that queries and controls all functions of the observatory, including the full suite of hardware, instrumentation, and the software controlling each system. It is designed for maximum autonomy in data collection and processing. This requires the master software to be the eyes and brain that typically is fulfilled by an on-site observer

In early 2019, an upgraded OCS 2.0 software control system was installed on MCAT and fully tested/vetted. Upgrades to the software include:

(1) In-frame calibration for photometry
(2) Defining photometric detection quality
(3) Astrometric solutions calculated for each image using streaked stars
(4) Improved calculations for photometric and astrometric uncertainties
(5) Logging and reporting weather downtime and cloud cover statistics

A full overview of the software control system, data reduction and processing, and operations will be presented in the first International Orbital debris Conference (IOC) in Housto, Texasn in December 2019.

7. SUMMARY

NASA's orbital debris telescope, MCAT, having undergone a suite of updates in hardware and software, is now well on track to reach Full Operational Capability (FOC) in 2019 for its survey, TLE and rate-track capabilities. Upgrades to the system include both hardware and software changes. After the original ER1 anti-reflective coated e2v CCD chip was permanently damaged during attempted repairs, a replacement broadband anti-reflective coated e2v CCD chip was installed in our prime research camera by Spectral Instruments.

The old protected aluminum coating on the primary mirror that had severely degraded was stripped off and coated with a protected enhanced silver coating, originally developed by Lincoln Laboratories and modified by ZeCoat, yielding > 95% average reflectivity across the visible bandpass utilized by MCAT. A procedure to clean the primary mirror has been established that minimizes or eliminates the sharp-edged volcanic dust on Ascension from being dragged across the mirror and scratching the surface. Here, First Contact® polymer spray is sprayed over a pre-treatment spray, allowed to dry, and peals away the dirt and grime from the mirror.

Mods to the weather system include removing the less corrosion resilient Boltwood cloud sensors as well as the New Mountain weather station, and replacing them with two ASE rain sensors and a second Davis Vantage Pro weather station. The Astrohaven clamshell dome was removed from the tower platform next to MCAT and replaced with a 2.5-meter ObservaDome with a quick-close bi-parting shutter doors and fast-tracking in azimuth. Designed to withstand extreme environments, which Ascension has proven itself to be, it is a smaller version of the 7-meter MCAT dome with an independent control system that is slaved by the master Observatory Control System, OCS software, now upgraded to 2.0.

With these upgrades, MCAT is now well suited to begin its first full GEO survey.

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