NASA's Orbital Debris Optical Program: ES-MCAT Nearing Full Operational Capability (FOC)

S. M. Lederer[1], C. L. Cruz[2], B. A. Buckalew[2], P. Hickson[3], R. Alliss[4]

[1]NASA Johnson Space Center, Orbital Debris Program Office
[2]JETS/Jacobs
[3]University of British Columbia/Euclid Research
[4]Northrop Grumman Corporation

ABSTRACT

The NASA JAO/ES-MCAT (Eugene Stansbery Meter Class Autonomous Telescope) Facility is nearing Full Operational Capability, or FOC. ES-MCAT is now fully capable of autonomously running all observations, including: (a) monitoring weather and closing when conditions are not safe, as well as halting observations when conditions are not suitable (e.g. too cloudy) for operations, (b) start-up/shut-down nightly tasking, (c) collecting calibration data and survey or TLE-tracked data, and (d) processing all collected data, including on-chip photometry and astrometry calibrations using the GAIA star catalogue. The processed data are then further analyzed at NASA Johnson Space Center to correlate detections with known objects in the Space Surveillance Network (SSN) catalogue.

MCAT can collect data of specific objects with known orbits or can search for objects with orbits similar to those of spacecraft or rocket bodies that have recently broken up. However, the primary goal for ES-MCAT is to survey the geosynchronous (GEO) belt to provide a statistical sample of the GEO debris environment for both engineering models for spacecraft designers and long-term environment evolutionary purposes. The approach for sweeping the sky to statistically survey GEO has been investigated and updated from past surveys taken by NASA and will be reported, herein referred to as the Candy Cane method.

ES-MCAT's optical performance and the limiting magnitude for the full optical system will be discussed. An analysis used to determine which filter to use for GEO surveys (SDSS r′) includes combining the reflectivity of the primary and secondary mirrors, transmission of the field corrector and CCD window, and the quantum efficiency of the CCD detector, resulting in throughput of the full optical path. This throughput is then combined with the expected typical transparency of the atmosphere at ES-MCAT's altitude/location for the Sloan Digital Sky Survey (SDSS) g′r′i′z′ and Johnson/Kron-Cousins BVRI filters to yield expected relative throughput.

1. INTRODUCTION

The John Africano Observatory (JAO) was built for the 1.3m optical telescope, ES-MCAT, and is located on Ascension Island in the south Atlantic Ocean, roughly half way between Brazil and Africa – in the middle of nowhere, next to nothing, where thousands of Brazilian sea turtles take 3 years to migrate to, and lay their eggs. For astronomers, that's good news. It means there is a concerted effort on the part of the island as a whole (because everyone loves baby sea turtles), and Ascension Island Conservation in particular, to maintain very dark skies so as to not lure the baby turtles inland after they hatch. This has excellent consequences for maintaining dark skies for an observatory intent on detecting very small, and therefore very faint orbital debris, very far away. There is also a constant presence by the USAF, now the US Space Force 45th Space Wing and their contractors, and all the benefits therein for a remote observatory – a source of power and a safe location for the telescope on the base, with a workforce that can be contracted for any troubleshooting that requires hands-on help. Fold in that the Geosynchronous belt, or GEO as we refer to it, is high overhead at Ascension's near-equatorial location (just shy of 8°S latitude) which means observing conditions always place the GEO belt at a very low airmass in the sky (astronomer speak for 'since you're looking straight up, you're looking through a much thinner slab of air than if you're pointed more toward the horizon'). This is good because more of the light you're trying to detect makes it through to your detector – less chance of it being absorbed by the atmosphere if it travels through less atmosphere, after all. This is where the story of ES-MCAT – Destination Ascension, began.

2. GEO SURVEY FULL OPERATIONAL CAPABILITY (FOC)

Full Operational Capability (FOC) is achieved when a system has completed its development phase and is ready to be employed and maintained to meet its operational need. For ES-MCAT, that will mean it has a proven capability to safely and autonomously take GEO survey data, process the data, and transmit the results to NASA JSC. "Safely" invokes a myriad of requirements, both hardware (HW) and software (SW), to monitor weather and the observatory itself with a clearly laid out hierarchy of what to do when something goes wrong. It also includes testing that hierarchy each time a SW or HW change is made. Here we discuss an overview of what all that means and what it takes to get there – to FOC that is.

JAO/ES-MCAT (or ES-MCAT) has undergone rigorous testing, and completed Verification and Validation (V&V) of all hardware, software, and analysis tools. Of particular note, an updated/upgraded version of the Observatory Control System Software, OCS 2.1 (by Euclid Research Corp.) has been installed, debugged, tested, and undergone V&V for every single command and functionality – and there are hundreds. (See [1], [2],[3], and [4] for more details on OCS operations, including weather monitoring, data collection, reduction, calibration, and analysis, especially if you'd like to see a little math that explains how we calibrate and analyze the data.)

2.1 Autonomous Operations: Putting the A in ES-MCAT

With a telescope dedicated to collecting debris year-round, ES-MCAT's autonomy is now fully functional. For a truly autonomous observatory to operate all aspects that an astronomer would normally perform on-site, many system redundancies, power back-ups, remote functionality, monitoring and failure responses via software must be put in place. The hardware and software must complete an intricate dance of actions and communication, listening to and commanding tasks of each system to make it possible to allow the system to collect the required data while minimizing risk to the instrumentation and facility (that's the 'safely' part in action).

Nearly all powered instruments and equipment are plugged into PDUs (Power Distribution Units) to allow remote power cycling from Houston, or OCS to power cycle equipment when a reboot is detected as necessary. In turn, all PDUs are generally powered through a UPS, and the power draw optimized to ensure a minimum of 20 minutes of powered time, more than enough to shut down the observatory (which takes ~5 mins, including ~30 sec to close the dome shutter) if the observatory line power is lost. The intentional exception to these rules is a small single-board computer (SBC), connected to line power directly to ensure that OCS has a way to infer that power is down, via comm loss with the SBC. Specifically, after 3 unanswered pings from the SBC, it triggers the failsafe script to close the dome, park the telescope, shut down the observatory, and put the system into a *failsafe* state. It also generates an alert posted on the control computer at NASA JSC so users will investigate the failure before allowing normal operations to resume. *Failsafe* state ensures the dome will not be opened until a user intervenes and manually resets the system to one of the operational states once the issue is diagnosed and resolved. Likewise, OCS monitors an entire suite of other possible failures (e.g. other power or comm, telescope, camera, dome, or weather sensor issues, etc.). The most egregious is a failure of the dome shutter closing when called to close. In this case, the dome azimuth (a separate motor drives the turning of the dome than the dome aperture doors) is turned to face the open slit leeward (i.e. anti-windward) and the telescope pitched forward with the nose buried into the protected portion of the dome, allowing the large D-beam telescope support structure to physically block and protect the mirror and camera; and the mirror door covers closed. One of the advantages of Ascension weather is that the wind very consistently blows from the same direction (trade winds from the SSE, from Africa), so we know which direction is safest to point the dome toward in this scenario.

As the final back-up to all the software monitoring and failure-mode scripts, the Ascension Island Security team drives by ES-MCAT 4x daily, and knows what to watch for (e.g. dome open in the day, any indication that the telescope is open during rain) and each security guard has been trained to manually close the dome and contact NASA as well as our on-island contractor if there are any suspicious issues. Critically, there is one fully trained contractor on-site, and she knows the facility, telescope and instrumentation well. She conducts the weekly, biweekly, and periodic maintenance that requires a physical presence, as well as trouble shooting of all systems (IT, power, comm, telescope, dome, weather, etc) with remote aid from the optical team at NASA when needed. She is the eyes, ears, and (yes) nose that catches what software cannot monitor – "that doesn't look right, sound right, or smell right" are all important diagnostic tools for a complex system. The key to all of this is: Better safe than sorry. It's better to conservatively close the dome and wait for the NASA team to investigate the concern than to risk damage.

Bad weather poses one of the riskiest autonomous challenges. The top-surface silver coating on the primary mirror can be damaged by salty moist air condensing (through rain or dew) on the mirror. In a tropical sea-level environment like Ascension, corrosion of the mirror or anything metal (like the rolled steel Hour Angle (HA) drive surfaces that allows the telescope to move East/West) is a constant concern – shipping an 800lb, 1.3m (i.e. 52” in diameter) piece of glass across the Atlantic to the US for recoating the primary is no small task (cost, schedule, and risk-wise) if the primary mirror coating is damaged by salt water. Finding weather instrumentation that can withstand the corrosive environment of Ascension and detect the very light rain that is so common there, with reliability, has been yet another learning experience. Weather instrumentation (as of 2020) includes 2 Davis Vantage Pro weather stations, 3 ASE rain sensors (great for detecting the lightest of rain), and one OSI rain sensor (only effective for larger droplets of rain, and not as useful on Ascension – the second one has already failed). Boltwood cloud sensors previously installed have a short lifetime on the island due to their propensity for corrosion of their metal prong sensors, so after several replacements in the first several years, have been removed from the weather suite. (For further details on weather limits set – meaning when the dome should be closed, and then when reopened, which are a different than the close limits to allow weather to stabilize a bit – and instrumentation, see [1].)

2.2 Data Collection – Getting down to Business

In addition to monitoring the observatory health, status, and weather, OCS is also designed to actively operate each night’s identified and prioritized observations. A *start-of-night* script begins by checking weather, and if acceptable, opening the dome around sunset. The telescope mirror doors are also opened and telescope drives turned on. To minimize seeing effects from the additional air turbulence, the dehumidifiers, air conditioning and dry air purge (blowing on the telescope mirror, drives, and filters) are turned off – all these systems are on when the dome is closed to mitigate corrosion everywhere inside the dome.

For each night, a program file is uploaded for OCS to direct the telescope on the specific observations to be taken on that night. The *sequenced* state directs OCS to step through the program file. Generally, a program file consists of calibration data (biases, flats, standard stars) and debris data, which may include GEO survey data or targeted observations (e.g. for characterizing individual objects, scanning an orbit after a break-up event, etc.). The set of biases and, for each filter planned for the night, a set of flat field frames are taken at the start and end of each night, during twilight. Standard star fields taken with the telescope tracking at sidereal rates (*sidereal track,* or *ST* mode) are observed at the beginning and end of the night. These allow us to check focus and monitor with time how dirty the mirror is, the latter based on the resultant zero-point variability of the standard star data (as the mirror gets more dirty and/or degraded, it effectively adds an additional source of extinction to the zero-point of the data).

When data are taken from sites with consistently clear skies (e.g. Chile, or Mauna Kea; NOT Ascension), one typically uses independent standard star images collected throughout the night over a range of airmasses for calibrating data directly, to convert from instrumental magnitude (below the atmosphere) to calibrated apparent magnitude (above the atmosphere). The frequent variability of clouds forming/dissipating locally on Ascension has dictated that on-chip photometry for each individual image is necessary to accurately calibrate the brightness of our detected objects (see below and [2], [3]). The advantage is that cloud cover affecting that particular image is directly calculated. The disadvantage is that because debris moves at a different rate than stars, the calibration stars are streaks – signal from the star falling on more pixels means more noise affecting the SNR (signal-to-noise ratio) of the star. For Ascension, the image-to-image cloud cover variability is much worse than the added ‘streak noise,’ so the on-chip calibration approach wins over the standard astronomical approach for ES-MCAT.

Finally, debris observations are taken, composing most of the time spent each night, at least on a good night. GEO survey operations are conducted using the *rate track (RT)* mode, assuming GEO objects are moving at 15.014″/s in Right Ascension relative to the stars. For those with experience observing, this rate should be familiar – it’s the rate stars move. We set the telescope to move the opposite direction but same rate, which is essentially equivalent to turning the telescope motion off (without having to then risk mucking up other observations with drives off). The purpose should be clear: GEO objects orbit at the same rate the Earth rotates, thus are essentially stationary in the sky (save any perturbations affecting objects that are not station-kept). Data of known debris objects use the *object/orbit track (OT)* mode to follow their orbital two-line-elements (TLEs), which dictates their relative motion in the sky.

Collecting said data is entirely dependent upon weather conditions on Ascension, which is typically very seasonal, but has been fairly consistent from year to year. We conclude this subsection with insight into how often we can open the dome to actually take data, based on satellite based cloud climatology (Fig. 1). The cloud database is derived from the European Meteosat Second Generation geostationary satellite. A pixel level cloud analysis was performed using the visible, near and longwave infrared channels over Ascension Island. Results indicate a seasonal variation in the amount of clouds but very little inter-annual variability [5].

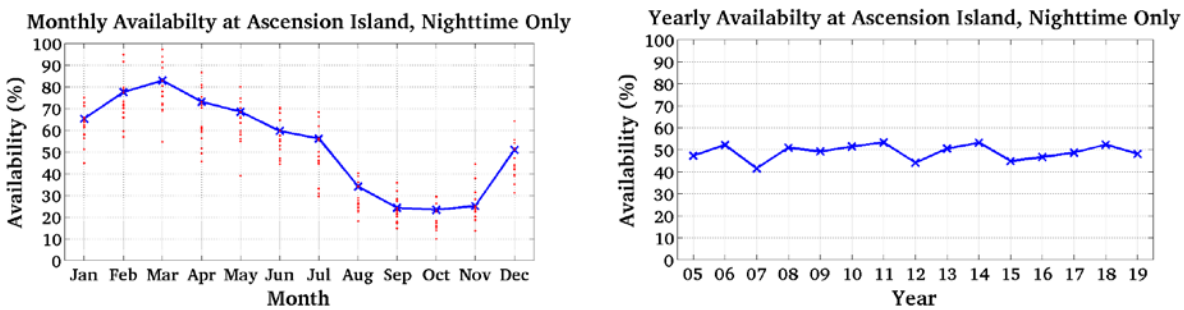

Fig. 1: (a) Monthly mean cloud freeness (blue x's) and individual months cloud freeness (red dots) between 2005 and 2019. Cloud freeness is generally higher during the summer months (Jan.) and lower in the winter. (b) Yearly cloud freeness between 2005 and 2019 indicates very little inter-annual variability and averages around 50% [5].

2.3 Data Reduction and Analysis – Turning Raw Images into Useful CALIBRATED Information

After ES-MCAT completes observations for a night, the data are then processed by OCS. During the day, OCS conducts standard data reduction steps typically applied to astronomical optical images. This includes applying a suite of calibration steps to the images, and then finding the debris. Let's step through all the processing.

2.3.1 Calibration: Biases, flats and darks (except the darks aren't needed) – the basics

A master bias image (the median image from 11 zero-second exposures) is subtracted from each raw image. This is the underlying steady-state signal an electronic sensor like a CCD has (because who wants to use photographic plates? No one. If you don't even know what that is, lucky you. You'll have to trust us on that).

The image is then normalized by the master sky flat field created for each filter (predominantly the SDSS r′ for GEO survey mode; see Sec. 3.1.2 for how we decided on r′). Flats are needed to remove all the junky features, like dust doughnut ghost images, or flaws in the chip that would make an image of a perfectly featureless illuminated surface (like the sky at twilight) appear uneven or show features. One can use a white screen attached to the dome for dome flats, but the twilight sky is a much better, even more evenly illuminated surface. Like the bias frames, a median from 11 flats of a given filter are used for each master flat.

MCAT's CCD is cryogenically cooled, so "darks," used to subtract contributions of 'signal' from warm electronics, (which, if present, increases with exposure time, especially for electronically cooled sensors) are not needed for the primary Spectral Instruments 1110 camera in use with ES-MCAT. Simply put, at -110°C, there just aren't enough electrons generated by the CCD 'warmth' to require this step.

2.3.2 Calibration: Photometric – How bright is it? And Astrometric – Where is it?

The Johnson-Cousins (BVRI) and SDSS g′r′i′z′ filters allow us to properly calibrate the data for surveys, light-curve and material analyses. The extensive (1.7 billion measurements) exquisitely calibrated Gaia catalogue ensures that if the sky is clear enough, there will be observed star's streaks on each image that can be used for photometric and astrometric calibrations. As noted earlier, stars show up as streaks on data when the telescope tracks at the expected debris rates. Because the stars are streaks, uncertainties in both photometry (brightness) and astrometry (where is it) are not as small as they would be if they were point sources, but are still well within acceptable limits, due to Gaia's fantastic data (see [2] and [3] for more details). Typically, individual star trails can be measured and calibrated to an accuracy of 0.1 - 0.2 mag. The median difference between the instrumental and Gaia magnitudes for each star is used to determine the magnitude zero-point correction for the image, typically with an error of 0.03 - 0.05 mag (this varies based on number of stars analyzed, whether trailed or not, and how trailed if so (e.g., LEO vs GEO trail lengths differ).

To convert from simple ‘counts/s’ measured by the SI CCD camera, images are first divided by the exposure time. The images are cleaned of cosmic rays and convolved with a high-pass filter to remove large scale variations from clouds. Star are identified using the Gaia catalogue for the in-frame photometry & astrometry, and then removed. The software then searches for point-source detections of candidate debris objects, logging the Right Ascension (RA) and Declination (Dec)[1] location and brightness (in magnitudes) of every detected object.

Next, photometry *(phot)* files are produced for each calibrated debris data image. It includes the FITS header information and relevant information for each detected object in that image. The FITS information provides, e.g. exposure time, date/time of observation, pointing of the telescope for that image (field center), airmass, which filter was used, and the cloud density at the start/end of the exposure (from the FLIR camera). The FLIR values essentially measure the cloud opacity during the exposure, and are approximately equal to the atmospheric extinction for values that are less than 4.0. If the FLIR value is greater than 4.0 at the expected start of the exposure, the telescope waits until it has dropped below 4.0 to take data to avoid taking a lot of bad, cloudy data, following the mantra: Bad data are worse than no data. However, if the FLIR value rises above 4.0 during the observation, there is no good way to stop the observation mid-exposure, so the data are still taken and the end FLIR value noted in the header for NASA to decide later whether to use or, preferably, discard the bad data.

A line of data for each detected object in that image is also included in the *phot* file. Each detection includes the ICRF (International Celestial Reference System) RA and Dec coordinates, apparent magnitudes, zero points, etc. The OCS zero points are the values that the software uses to convert ES-MCAT’s instrumental magnitudes to the proper apparent magnitudes – the magnitude corrected for extinction due to the atmosphere. Zero points are filter dependent.

Finally, the stars observed on each image allow for an astrometric (where it is) solution for each image, which includes position offsets, rotation, anamorphic distortion (changes in image scale in RA and DEC), and sheer. This is a fancy way of saying we take great care to be sure the astrometry is as accurate as it can be. This astrometric model is then used to transform instrumental (apparent) coordinates of all objects to true coordinates. Typically, the residual astrometric error for ES-MCAT has been found to be less than 0.2 arcsec (not including telescope pointing errors).

2.3.3 Data processing – Which of these objects is just like the other?

Now armed with a set of detections (logged in the *phot* files), the system then must *match* each of the objects for each set of images taken. It computes where the first detected object should fall in subsequent images based on their expected motion and checks those locations. Depending on the weather, up to 7 images may be taken of each field center pointing. For a detection to be taken seriously, there is a minimum requirement of 4 detections of a given object from 4 separate images to ensure it is not a false detection. False detections are commonly from cosmic rays, residuals left from star trail removal, or bad pixels, though pre-processing steps by OCS are applied to clean and therefore minimize these effects. Once *match* links moving objects together, based on their expected motion on the sky, *merge* then cross-checks forward/backward across the images to link all possible object sets that go together. For example, if you have one set matched in frames 1-3, and another in frames 5-7, *merge* checks to see if those might be, in fact, the same object. If so, it merges them into one complete set. Finally, to help us, the *composite* command generates postage-sized clips of each detected object to make it easy for a human to view what OCS deemed a detection to allow manual reviews of the efficacy of OCS (*Fig. 2*).

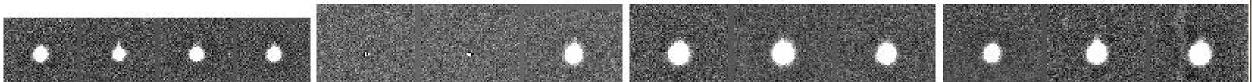

Fig. 2. Composite images from matched/merged sets of detected objects. The second set is spurious as the first two images can be seen to be defects. In fact, only the first set shown here would be accepted as a true detection as it has at the minimum required 4 detections within the set.

[1] RA and Dec are the celestial coordinates corresponding to the Earth’s longitude and latitude, projected on the sky.

3. MCAT PERFORMANCE: HOW FAINT CAN WE SEE?

3.1 Optical System Throughput – How much light makes it through?

Now that we have a working system, we can ask the question: How good is ES-MCAT? We need to know so that we can figure out what SHOULD have been detected (if it was visible in the sky) versus what WON'T be detected, because it's below our threshold. First, we note that ES-MCAT's complete optical system is composed of multiple components. These components include: the primary mirror, the secondary mirror, the field corrector, CCD camera window, the CCD detector, and the available filters. The full system throughput calculates the theoretical response of ES-MCAT's complete optical system from a given light source with the use of different band pass filters (*Fig. 3*).

3.1.1 Transmittance/Reflectance of Optical Components – Assessing Each Component in the Light path

For the field corrector, CCD window, and filters, the response is represented by transmittance, or the ability for each component to transmit light through them. For the CCD, this response is measured by quantum efficiency (QE), or its ability to convert photons of light (reflected by the debris in space) into signal (counts). Finally, for the primary and secondary mirrors, the response is measured by reflectance. All values are dependent on wavelength and have a range between 0 and 1. The response values were gathered for the components between the wavelengths of 390nm and 980nm, which cover the visible light spectrum and part of the near infrared spectrum, and the range of wavelengths encompassed by our SDSS filters. These values were provided by the manufacturers ([6][7][8][9][10]).

Both fused quartz (but with different anti-reflective coatings), the field corrector [8] and CCD window transmittance [9] rival each other for the best performance at nearly 1 from 400nm to just shy of 800nm where the field corrector performance begins to drop off. The primary mirror, coated with an enhanced protected silver by ZeCoat, has an average reflectivity of >95% across this bandpass (and >90% from 360 – 400nm) [7]. The secondary mirror has a different coating, enhanced aluminum from L&L Optical Services, Inc., who also produced the field corrector [8]. The secondary has >90% reflectivity from ~400-700nm, and stays above 80% across the bandpass. Finally, the SI Camera astro broadband e2v CCD chip, cooled to -110°C, has a better quantum efficiency at the blue end than the red.

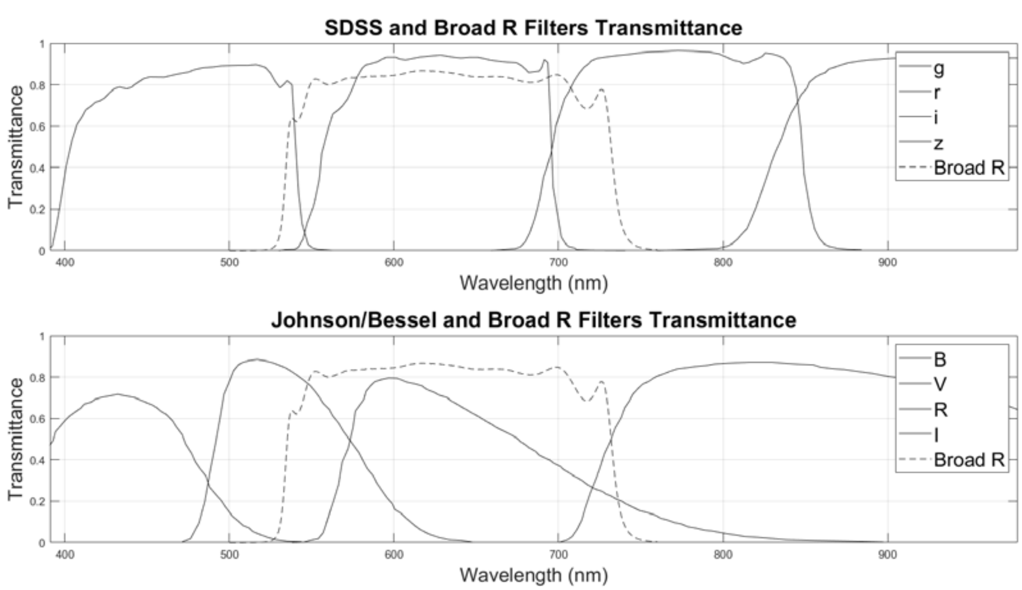

Fig. 3. Transmittance of the SDSS g'r'i'z' and the BVRI filters. For historical purposes, the broad R filter used for past GEO survey observations for NASA, using the MODEST telescope in Chile, is also included (MCAT does not have a broad R filter). The STSS r' filter has been selected for conducting GEO observations (see Sec. 3.1.2)

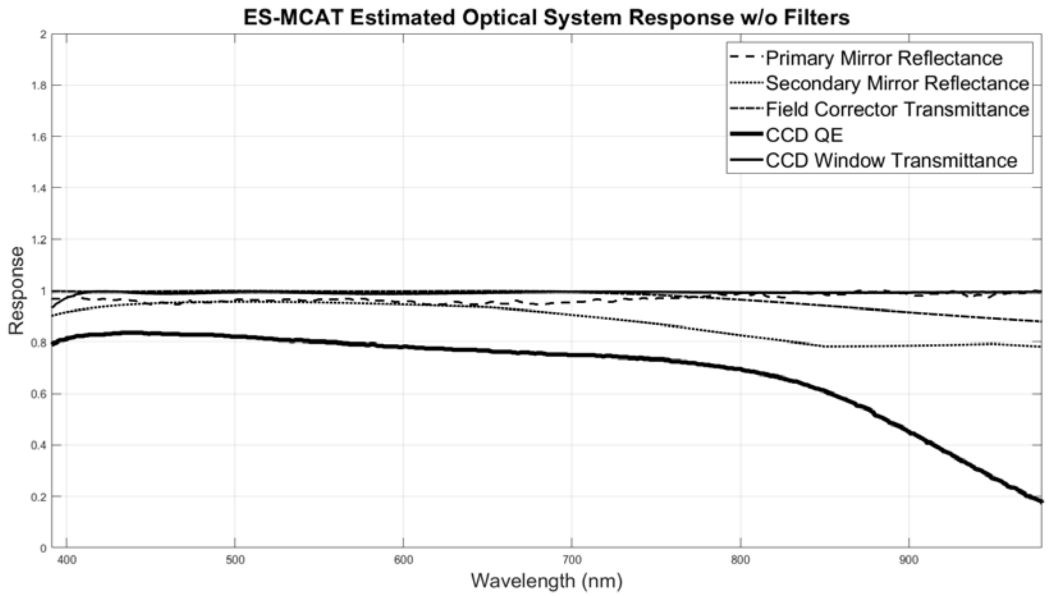

Fig. 4. Response of each optical component in the light path. From highest to lowest at 900nm, are the primary mirror reflectance (enhanced protected silver) and CCD window transmittance, followed by the field corrector transmittance, the secondary mirror (enhanced aluminum), and the astro broadband e2v CCD quantum efficiency.

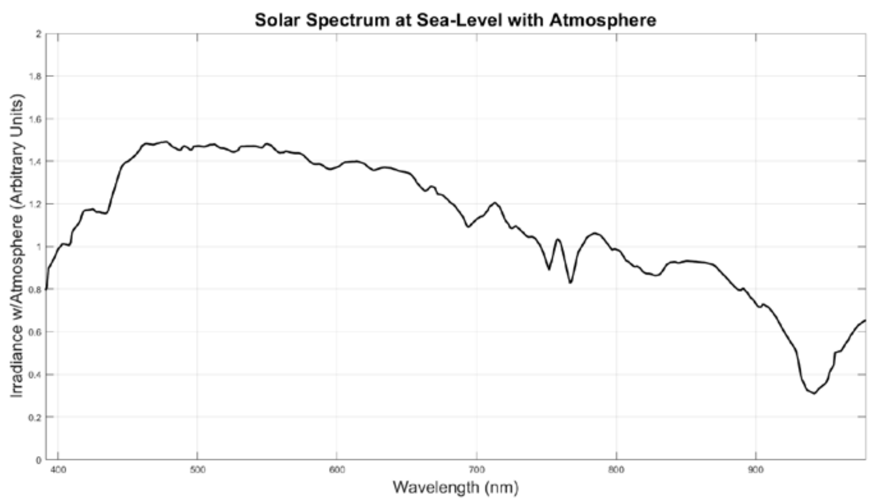

Fig. 5. The average Solar Spectrum in irradiance/flux units, from 390-980nm at sea level [12][13][14].

The light source used in this model is the solar spectrum (absorption due to Earth's atmosphere included), because the primary light source for orbital debris optical measurements is reflected sunlight (there is some Earth-shine as well, but that is neglected for the purposes of this exercise), which passes through the Earth's atmosphere on its way to the CCD sensor. As with all data, the response of the solar spectrum can vary, and thus an average from several data sources was calculated (see [12][13][14]). Each spectrum was separately linearly-interpolated between the wavelength regions of interest and were then averaged together to yield the result shown in *Fig. 5*.

3.1.2 MCAT Optical Throughput Calculation – Putting it All Together

Using a similar calculation process to the MODEST (Michigan Orbital DEbris Telescope) throughput [15], each component's response was linearly interpolated for the different optical filter band passes (SDSS, Johnson/Bessel Cousins, and Broad R filters). The interpolated response data for all components were then multiplied together so that the entire optical system would be represented for each filter. Finally, this result was integrated to give the total system response for each filter in arbitrary flux values. These results are adequate, as only the comparative values between each filter are of interest.

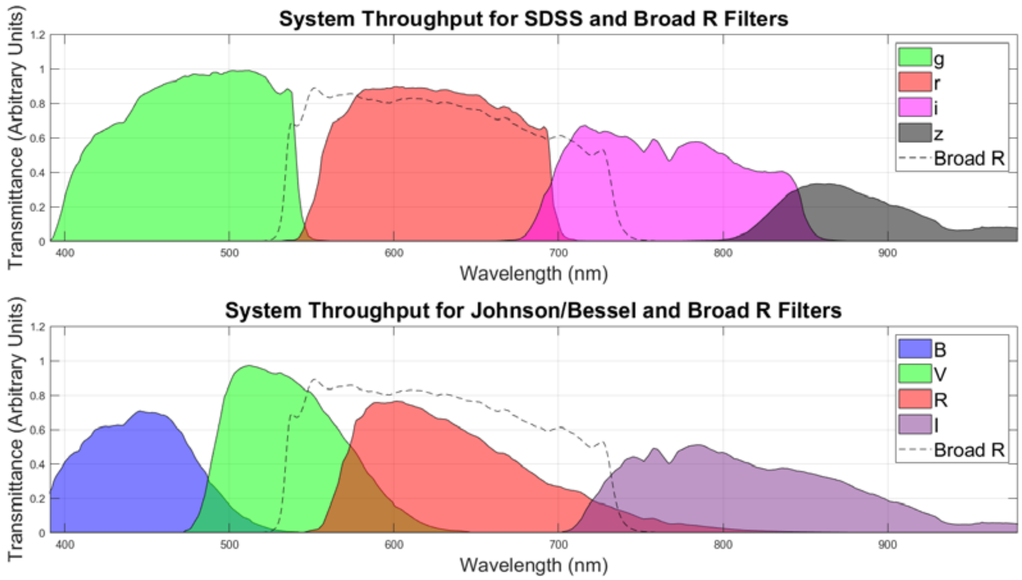

Fig. 6. Full system throughput is shown for each filter bandpass. This includes all optical components and the effects of the solar spectrum (the source of reflected light from debris objects).

Filter	Flux (Arbitrary Units)
g'	**118 ± 1.36**
r'	**116 ± 1.35**
i'	82.8 ± 0.998
z'	30.9 ± 0.560
B	56.0 ± 1.04
V	81.6 ± 1.23
R	89.7 ± 1.22
I	75.5 ± 0.855
Broad R	146 ± 1.49

Table 1: Relative throughput flux for each filter, with all optical components and atmospheric effects applied. The g′ and r′ filters are close contenders.

The throughput from the optical components discussed above must next be combined with the expected typical transparency of the atmosphere at ES-MCAT's altitude/location for the g′r′i′z′ and BVRI filters. The shape of the total system throughput response is dominated by the solar spectrum and the CCD quantum efficiency (the other component's curves are quite flat). These results helped inform which filter should be used to achieve the highest signal-to-noise ratio (SNR) on average for this specific optical system, assuming a similar amount of flux coming from debris at each waveband (which of course isn't always going to be the case). As shown in *Fig. 6* and *Table 1*, the SDSS g′ and r′ filters have the highest relative flux value throughput and are within each other's uncertainties. The reflectivity of materials that compose debris vary greatly across the visible bandpass – some are brighter toward the blue end, others toward the red end, and others are fairly flat, or vary greatly across the entire bandpass. So how do you choose? We opted to take test data with ES-MCAT of a variety of debris objects at GEO – meaning let's put it to the test doing what it will actually ultimately observe. These studies, combined with the consideration that data taken with past optical telescopes for NASA's ODPO were centered on red bandpasses (for better future comparison with ES-MCAT data), supported r′ as the filter of choice for ES-MCAT.

4. GEO SURVEY STRATEGY: THE CANDY CANE METHOD

Now that we have everything working, data that can be taken autonomously, and a facility that can be monitored and kept safe if failures occur, the million-dollar question is: What's the best way to take the data? Much testing and strategizing has occurred in recent years on approach. What is known is this: GEO objects are meant to orbit directly above the equator at an inclination (or INC) of ±0.1°. This narrow geostationary band is seen in *Fig. 8* as those densely packed horizontal lines, projected onto the sky[2] at Dec ~5° from CTIO [16], Chile, 30° latitude (*Fig. 8a*), and at Dec ~1° from Ascension, latitude ~8°S (*Fig. 8b*).

A satellite has to forcibly nudge itself to stay in the geostationary belt, and often (can be yearly, monthly, weekly, or even daily, depending on the type of thrusters used [17]), to maintain that orbit. This is what they call being 'station-kept' and those nudges are called station keeping maneuvers. Why? Well, when an object (like a piece of debris) in a GEO orbit is left to its own devices, its uncontrolled orbit will begin to oscillate, much like a top, taking 50 years to slowly oscillate, increasing to an INC peaking at about 15° over the first 25 years, and then slowly back to 0° inclination over the next 25. They oscillate around the stable Laplacian plane, which is inclined 7.5° with respect to Earth's equatorial plane and is due to combined forces from the oblateness (squashed'ness) of the Earth, solar, and lunar perturbations. For a few objects, their behavior will mirror this, decreasing instead of increasing in INC, seen clearly on the left plot in *Fig. 8* as those object doing their own separate 'I'm down when you're up' dance.

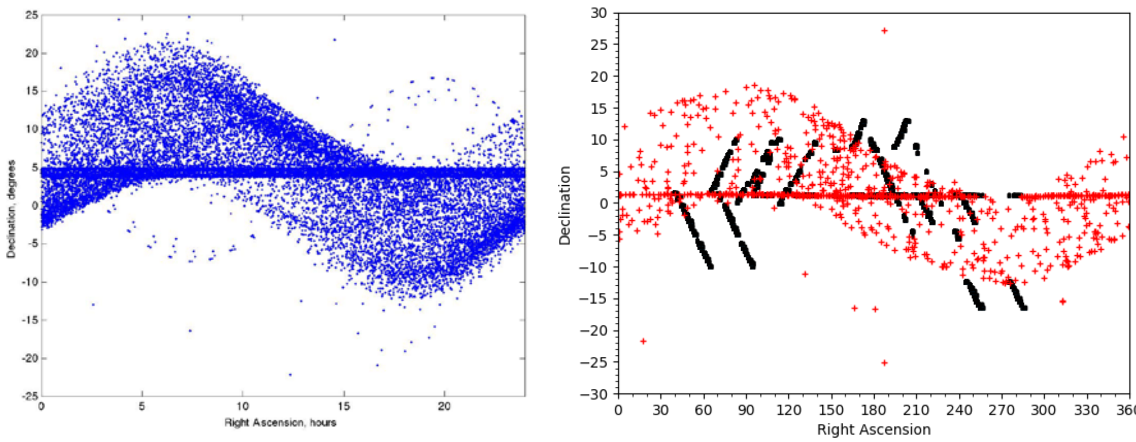

Fig. 7. (a) Daily motion for GEO objects ([16]) demonstrate how the oscillations of the orbital inclinations translate to location on the sky. This view is from CTIO in Chile, and thus the GEO belt projected onto the plane of the sky is at a higher Dec than from Ascension – seen in (b). (b) Each black square represents where ES-MCAT's field of view intersects the GEO belt on a given night. Pointings outside the GEO belt are purposeful to search for unknown debris not currently catalogued (referred to as 'uncorrelated targets') and therefore not yet known to exist.

For MODEST, the telescope was pointed as close to the anti-solar point as possible. During equinoxes, when the Earth's shadow fell on the antisolar point, the telescope pointed at a position leading the shadow, and in the second half, trailing the Earth's shadow. For a given run, fields stuck to one RA (unlike ES-MCAT), and move up or down only in DEC (those pointings would look like vertical lines of boxes if plotted in the right-hand plot, instead of the diagonal lines). Because neither autonomous nor remote operations were possible, all observations were taken via traditional observing, meaning NASA personnel and their contractors got to travel to Chile, to Cerro Tololo (generally a 24-hour adventure, each way), to take data with this telescope like traditional astronomers, and thus selectively went during the best lunar phase – during coveted 'dark time', meaning around new moon (e.g. new moon night ±5 nights for an 11 night run), when neither the moon was in the way physically, nor brightened the sky much.

With ES-MCAT, we have investigated whether there might be a more efficient way to collect data, to minimize how long it will take to sample the GEO belt in a statistically significant way, over about a 2-year period. With 100% access to ES-MCAT's schedule, every clear night that's feasible can be used, not just when we are on-island (excellent since it takes 36 to 60h to travel there and then back). However, we must still avoid the week around full moon (full

[2] The geostationary belt would be projected at Dec values below 0° from northern locations.

moon night ±3 nights, for a week per month) when the moonlit bright sky would wash out contrast to detect the interesting smaller debris anyway. This leaves about 21'ish nights per lunar cycle, weather permitting (see *Fig. 1*).

The survey strategy defines where to point the telescope in RA and Dec space each night, as specified in the nightly tasking file. For ES-MCAT, two RAs per observation night are defined as one hour in RA before and one hour after Earth's shadow – thus the RA pointing shifts from one night to the next to maximize the solar phase angle (again, maximum observable illumination) and results in the diagonal lines in *Fig. 8* that we internally refer to as the Candy Cane approach. The DECs for one set of images per night are on the geostationary portion of the belt (0deg INC), the rest survey off the geostationary portion (INC = 0), but in or near the GEO belt. The Dec pointing is shifted each day (roughly one field-of-view, or FOV) until the entire height of the GEO belt is observed (see *Fig. 8*). This process is repeated as the Earth's shadow changes throughout a year.

To assess where to point and how that affects the GEO belt coverage, a python "TieDye" program (owing to its colorful output plots) was developed that estimates the likelihood that any object that might pass through a specific set of orbital parameters, will be detected, defined as expectation value. Specifically, it considers how the pointing of the telescope translates into coverage for inclinations of 0 – 30°, and Right Ascension of Ascending Node (RAAN)[3] of 0 to 360°. A GEO survey is considered 'complete' when all field centers the telescope points toward yield expectation values of 0.3 or greater for orbits that translate on an INC*sin(RAAN) vs. INC*cos(RAAN) plot as a circular area centered at (7.5, 0) with a radius of 7.5 (recall that orbits are expected to wobble with inclinations of 0 to 15deg). If a given object is expected (on average) to be observed once, its expectation value would be 1; if it is expected to be observed multiple times, then > 1, and if multiple pointings are expected to detect it, then <1, meaning likely to be undetected or under detected. Through experimenting with the TieDye code, the Candy Cane method was determined to be an efficient method for a complete GEO survey.

5. SUMMARY

ES-MCAT is nearing official FOC and is collecting data autonomously. In practice, this requires setting up a suite of hardware and software to constantly monitor the observatory facility and instrumentation as well as the local weather for clouds, humidity, dewpoint, and rain. The OCS software is setup for this monitoring task, to autonomously close down the observatory or (if a failure occurs) put it into a *failsafe* state when needed. That software directs the observing run that an astronomer would otherwise orchestrate: Open the observatory at the appropriate time if weather allows, collects all the data needed (calibration and debris data for us), close the observatory at the end of the night (or when weather dictates closure), and start the data reduction at daybreak. Data reduction includes calibration and finding objects of interest. Due to the very variable weather on Ascension (rapidly forming/dissipating clouds), on-chip photometry and astrometry calibration is applied to the data, using the GAIA standard star catalogue (DR2 release in use as of 2020).

The performance of ES-MCAT has now also been assessed for the optical components. Assessment of the optical throughput, combining transparency, reflectivity, or quantum efficiency performance for each individual optical component, indicates that the SDSS g′ and r′ filters achieve the best performance. Given the historical data collections for NASA debris surveys has focused on red filters, ES-MCAT will use the SDSS r′ for its GEO survey data.

Finally, a new GEO survey strategy has been developed – the Candy Cane method. Here, we choose the RA that corresponds to ±1 hour from Earth's shadow (1 hour leading the shadow prior to midnight, and 1 hour trailing the shadow after midnight) and step up or down in Dec each night. Pointings concentrate within orbits ranging from Inclinations of 0–15° from the equatorial plane, but occasionally include orbits outside this to ensure we don't fall prey to "If we don't look there, then surely it doesn't exist because someone said it shouldn't be there." While theory and models guide us, our ultimate goal is for the data to speak for itself.

[3] The reference plane for GEO is the projection of the Earth's equator onto the sky (the celestial equator). Each debris object has an orbit that can be coincident with this plane (inclination = 0) or inclined to this plane. How 'tilted' the orbit of the object is defines the inclination of the orbit, or INC. Then, consider that inclined orbits will cut through the plane of the celestial equator at two RA's in the sky; again, RA is just longitude on the earth projected onto the sky. Then RAAN, or Right Ascension of Ascending Node, is the RA where the orbit cuts upward through the celestial equator plane. RAAN is undefined when INC=0. All very fancy way to define orbits.

6. REFERENCES

[1] Lederer, S.M., Buckalew, B., Hickson, P., and Cowardin, H.M. NASA's Orbital Debris Optical Program: ES-MCAT Updated and Upgraded, *AMOS Technical Conference Proceedings, Maui, HI,* 2019.

[2] Hickson, P. OCS: A Flexible Observatory Control System for Robotic Telescopes with Application to Detection and Characterization of Orbital Debris, *First International Orbital Debris Conference, Sugarland, Texas*, 2019.

[3] Lederer, S.M., Hickson P., and Buckalew, B. NASA's Orbital Debris JAO/ES-MCAT Optical Telescope Facility on Ascension, *First International Orbital Debris Conference, Sugarland, Texas*, 2019.

[4] Lederer, S.M., Hickson, P., Frith, J.M., B. Buckalew, B., and Cowardin, H.M., NASA's Optical Program on Ascension Island: Bringing ES-MCAT to Life as the Eugene Stansbery-Meter Class Autonomous Telescope (ES-MCAT), *AMOS Technical Conference Proceedings,* 2017.

[5] Alliss, R.J., "Ground Site Diversity Studies using the Laser Communications Network Optimization Tool (LNOT)", International Conference on Space Optical Systems and Applications (ICSOS) Proceedings, 2019.

[6] Custom Astronomy Filters, Custom Scientific, https://customscientific.com/research_astronomy.html, 2020.

[7] Saadia, J. and Sheikh, D., ES-MCAT 1.3 Measurement and Testing Results, ZeCoat Corporation, 2018.

[8] LaRue, R., private communication, 2020.

[9] Rodenburg, K., private communication, 2020.

[10] E2V Technologies Limited, Spectral Response at 173K, 2006.

[11] Lederer, S.M., Vavrin, A., Cowardin, H.M., Matney, M., Anz-Meador, P., Hickson, P. Integrating Orbital Debris Measurements and Modeling – How Observations and Laboratory Data are used to Help Make Space Operations Safer, *AMOS Technical Conference Proceedings, Maui, HI*, 2018.

[12] http://www2.oberlin.edu/physics/Scofield/p268/library/Ch-03%20Sunlight.pdf

[13] https://www.researchgate.net/publication/271891094_Design_and_Fabrication_of_an_Albedo_Insensitive_Analog_Sun_Sensor

[14] https://www.newport.com/t/introduction-to-solar-radiation

[15] Rodriguez, H., Mulrooney, M., and Barker, E., "Optical Properties of Multi-Layered Insulation", *AMOS Technical Conference Proceedings*, 2007.

[16] Abercromby K.J., Seitzer, P., Barker, E.S., Cowardin, H.M, and Matney, M.J., Michigan Orbital Debris Survey Telescope (MODEST) Observations of the Geosynchronous Orbital Debris Environment, Observing Years: 2004-2006, NASA TP- 2010-216129, 2010.

[17] Decoto, J, and Loerch, P., Technique for GEO RSO Station Keeping Characterization and Maneuver Detection, *AMOS Technical Conference Proceedings, Maui, HI*, 2015.