NASA's Orbital Debris JAO/ES-MCAT Optical Telescope Facility on Ascension Island

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ABSTRACT

The NASA Orbital Debris Program Office has a long-standing optical program begun over three and a half decades ago in 1984, designed to observe the Earth-orbiting environment with optical telescopes. Photometrically calibrated optical data provides a statistical sample for input to NASA models of the debris population for understanding the current and future debris environment around the Earth. Tracked objects and orbits allow for analysis of break-up events. Both known (correlated target in the SSN catalogue, or CT) and unknown (uncorrelated target, or UCT) objects are of interest to better understand how to protect current spacecraft and design more robust future operational satellites, and advise on how policies and practices can lead to protecting the environment itself for future generations.

In 2015, a joint NASA JSC – Air Force Research Labs (AFRL) project culminated in the installation of the 1.3-meter Eugene Stansbery Meter Class Autonomous Telescope, ES-MCAT (a.k.a. MCAT) on Ascension Island. This DFM Engineering designed telescope provides nearly five-times greater light-collecting power than its predecessor, the 0.6-m MODEST telescope, and faster tracking capabilities by both the telescope and the 7-m ObservaDome. This allows for all orbital regimes to be easily within reach, ranging from low Earth to geosynchronous orbits. Extensive testing and commissioning activities of this custom system led to successfully reaching Initial Operational Capability in 2018, and the facility is currently on track to reach Full Operational Capability.

The John Africano Observatory (JAO) comprises the primary 1.3-m ES-MCAT facility, the adjacent tower platform with a 0.4-m telescope, a sophisticated suite of weather instruments, and custom software by Euclid Research for autonomously running the entire system, including monitoring the weather and hardware, tasking all components, and collecting, processing, and analyzing the data. The mission of JAO and MCAT will be discussed, including survey and tracking tasking, a full discussion of data calibration, and both optics and weather-dependent performance.

1. INTRODUCTION

ES-MCAT, the Eugene Stansbery – Meter Class Autonomous Telescope (or MCAT) was deployed on Ascension Island, and achieved first-light in June 2015 [1, 3, 4, 5, 6]. 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, Fig. 1). 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), Geosynchronous (GEO) and GEO Transfer Orbit (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; (3) its remote location provides very dark skies for astronomical observations, particularly important for small, faint debris; and (4) its infrastructure and personnel on the island allow for long term logistical support and maintenance.

1.1. MCAT Goals

MCAT's prime goal is to statistically characterize Low Earth Orbit (LEO), Medium Earth Orbit (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. The initial focus is to conduct a GEO survey to characterize the orbital debris risk to GEO satellites, followed by characterizing the debris environment in under-sampled orbits such as LILO. GEO survey data is expected to be used with a future Orbital Debris Engineering Model (ORDEM) release. Ref. [1] details how measurements and modeling work to improve spacecraft designs, and better understand the debris environment.

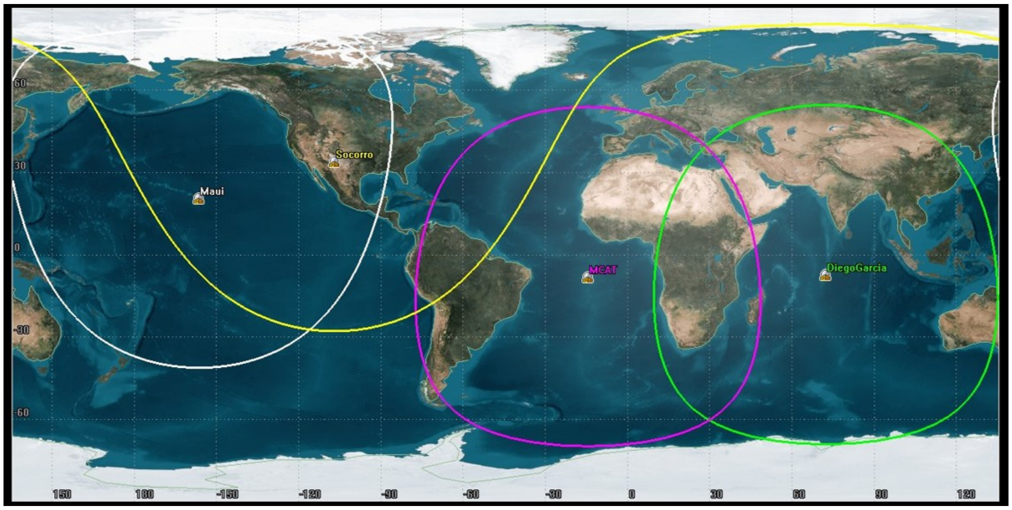


Fig. 1. MCAT's Field Of Regard (in magenta) fills in a gap that is not covered by GEODSS sensors located in Hawaii (white), New Mexico (yellow) or Diego Garcia (green).

1.2. MCAT Objectives

The prime *objective* of MCAT is to monitor and assess the orbital debris environment by surveying, detecting, and tracking orbiting objects at all orbital altitudes: LEO, MEO, GTO, and 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.

The following objectives are designed to meet the goals and prime objective laid out above:

1. Determine the distribution function (#, size, type) for the GEO debris field – *This is achieved through a sweep of the inertial volume near GEO altitudes spanning inclinations from 0 – 15° expanded by solar/lunar perturbations (about the Laplacian stable plane). A patterned sweep is typically performed by either counter-sidereal drift scan (TDI) by the camera, or rate-tracking by the telescope at GEO rates.*

2. Determine the distribution function (#, size, type) for the LILO debris field – *Either a static survey or an orbit scan survey can be conducted for this objective.*

3. Rapidly respond to break-up event – *Monitor the time evolution of a debris cloud following a break-up event. By tracking the orbit of the parent body, and similar expected orbits for daughter fragments near pinch-points, daughter fragments can be detected [7]. This can be achieved for any orbital regime given the hardware/software capabilities of MCAT.*

MCAT is intended to become a contributing sensor for the Space Surveillance Network (SSN) for the purposes of Space Situational Awareness (SSA). To accomplish this, metric observations described herein will be shared with Air Force Space Command (AFSpC). When approved by NASA, the facility may also participate in Joint Space Operations Center (JSpOC) follow-up or hand-off activities for observing specific RSOs or break-up events.

2. OPERATIONS

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. The Euclid Orbital Debris Processor (ODP) software correlates RSOs with SSN catalogued objects. Ultimately, the data are incorporated into the ORDEM model, an engineering model designed in part to describe the population of debris in Earth-orbits, ranging from LEO to GEO. For more details on how MCAT is operated by OCS, see [8].

2.1. GEO Survey/RT Tracking

The prime goal for MCAT is to monitor the GEO debris population. With this in mind, MCAT is typically run in a Rate-Track (RT) mode that sets the telescope to track at typical Geosynchronous rates where every star is detected as a streak of the same length running in the same direction (see Fig. 2 below). Alternatively, the telescope can track sidereally and allow the CCD chip to do the tracking work via a counter-sidereal drift scan called Time-delayed integration (TDI) where the CCD shifts the image at a counter-sidereal rate as it takes data to offset the telescope's sidereal rate motion. The effect is the same in both cases: GEO debris objects are point sources, which maximizes the signal detected and minimizes the noise by limiting how many pixels compose each detected object. Any non-GEO debris (or asteroids or comets) would be streaks of different lengths and orientations. GEO survey is achieved via sweeping through the inertial volume near GEO altitudes spanning 0 – 15° inclinations regime (see also [7]).

2.2. TLE Tracking: Object of Interest or Orbit Scan/Breakups

The telescope also has the capability to track objects with known orbital elements. Space-track.org, as of Oct 2019, contains 23,000 objects with Two Line Element (TLE) orbital parameters of sufficient quality for 17,000 to be publicly released [9].

When additional information is desired for specific RSO targets, especially if it's expected to have suffered a break-up event (e.g. fragmentation, collision, explosion), MCAT is capable of tracking the parent object of interest to collect astrometric and photometric data. To discover daughter fragments, OCS can calculate the expected orbital motion of a 'virtual object' and track at that rate to detect new objects. With a suite of observations, OCS can also estimate an orbit determination of newly discovered targets (see Sec 4.3 below for more details).

3. CALIBRATIONS

All data are processed by OCS to produce calibrated data, which are then analyzed by OCS to find RSOs, and by ODP to correlate to SSN objects (see also [8]).

In early 2019, an upgraded OCS 2.0 (hereafter, OCS) software control system was installed on MCAT and fully tested/vetted. Upgrades to the software include such features as

(1) Automatic queue processing of acquired data
(2) In-frame calibration for photometry and astrometry
(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

In-frame calibration for both photometry (brightness) and astrometry (positions) are calculated using stars in the Gaia Data Release 2 (DR2) catalogue [10].

3.1. Pre-processing

Raw images first must have either the master bias frame (zero-second exposure) subtracted, or a master dark frame whose exposure time matches the exposure time of the data image. A master image results from the median average of typically 11 frames collected in the same way (all bias, all flats, etc.). Then a master flat field for the appropriate filter is applied (divided out). Finally, cosmic ray tracks are removed by median filtering and any background variations due to clouds passing through the field are removed. This does not eliminate atmospheric extinction, however (see Sec. 3.2).

3.2. Photometry

MCAT has a suite of broadband filters, including the Johnson-Cousins (BVRI) and the Sloan Digital Sky Survey, g′r′i′z′ that are employed to collect photometric data for surveys, light-curve and material analyses.

The Gaia DR2 catalogue included a mind-numbing number of sources for calibration purposes, including ~ 1.7 billion sources with G-band data, and nearly 1.4 billion sources with the G_{BP} and G_{RP} band passes. For photometric calibration, only stars brighter than G_{BP} and $G_{RP} < 18.0$ are used. The Gaia filters band passes are as follows:

(1) G: unfiltered (white) light, 350-1000nm
(2) G_{BP}: blue photometer, 330 – 680 nm
(3) G_{RP}: red photometer, 640 – 1000nm

The mean photometry uncertainties for G: 0.3 mmag (G < 13); 2 mmag (G = 17); 10 mmag (G = 20).
Mean photometry uncertainties for G_{BP} and G_{RP}: 2 mmag (G < 13); 10 mmag (G = 17); 200 mmag (G = 20).
Uncertainty for two-parameter astrometry (position only) is 1 – 4 mas.

In-frame photometry of MCAT data is calculated through the following steps:

(1) The brightness of stars in the image are measured. When tracking at any rate other than sidereal (e.g. rate track, GEO, TLE tracking), the stars will be streaked on the image.
(2) Instrumental magnitude, m_{inst} of each star is calculated

$$m_{inst} = m_0 - 2.5 \log_{10}(Flux) \quad (1)$$

where m_0 is a constant (filter dependent) and estimated from data taken under clear sky conditions.
(3) Stars in the Gaia catalogue are identified and matched with the observed stars.
(4) MCAT filter bandpasses are estimated using the Gaia G, G_{bp}, and G_{rp} magnitudes through the transformations given in [11] for both Johnson-Cousins and Sloan Digital Sky Survey (SDSS) filter sets.
(5) The median difference between observed and Gaia magnitudes (transformed to match each MCAT bandpass) is computed for all matched stars to yield the zero-point correction for a given image. This zero-point then necessarily includes the effects of extinction due to atmospheric scattering, clouds, etc. for that image.
(6) Using the calculated zero-point, *Z*, the instrumental magnitude of all detected objects (stars or debris) are calibrated to yield apparent magnitude, *m*:

$$m = m_{inst} + Z$$

Parameters logged by the object detection and photometry algorithm include: Object number in the frame, position in pixels (x, y) and arcseconds (RA, Dec), apparent magnitude (extinction corrected), major and minor axis (important for streaked objects/stars), position angle of the major axis (degrees N through E), signal-to-noise ratio (SNR), and the number of pixels above the detection threshold.

3.3. Astrometry

The Gaia catalogue includes nearly 1.7 billion measurements for astrometry calculations. OCS uses only stars brighter than G < 18.0 for calibration purposes. The typical uncertainty in two-parameter astrometry (position only) for the Gaia DR2 release is 1 – 4 mas.

To calculate astrometry, OCS considers that the image may be slightly offset in telescope pointing (apparent coordinates) with respect to absolute position (true coordinates) in the sky. It first conducts a 2-D search for stars expected in the FOV of the image (given the telescope pointing of the center of the image's field) to find initial pointing offsets. It then fits a six-parameter astrometric model, using a least-squares analysis.

$$X' = A + BX$$

where *X* is a vector containing the instrumental right ascension (RA) and declination (Dec) position, *A* is a vector containing the position offsets, and *B* is a 2x2 matrix including rotation, anamorphic distortion (changes in image scale in RA and DEC), and sheer. This astrometric model is then used to transform instrumental (apparent) coordinates of all objects to true coordinates. Typically, the residual astrometric error for MCAT has been found to be less than 0.2 arcsec (not including telescope pointing errors).

Parameters reported in the calibrated files include: matrix *A* parameters (axis 1 and 2 offset), the four matrix *B* parameters, RMS error in RA (arcsec), RMS error in Dec (arcsec), and RMS position error (arcsec).

4. ORBITAL DEBRIS PROCESSING AND DATA ANALYSIS

Most of the data analysis is done by OCS on-island. The final step of correlating the matched objects (see below) with the Space Surveillance Network catalogued object's SSN #, is completed at NASA Johnson Space Center by the ODP software. *Detect*, *match*, *orbit* determination, and *correlate* are described below.

4.1. Photometric Detection

Both stars and RSOs must be detected within the images to calibrate the data in-frame. For GEO survey through either GEO or rate track, recall that the stars appear as streaks and the objects appear as point-sources for all objects moving at GEO rates (Fig. 2), or near point-sources for objects moving in orbits sub-GEO or super-GEO.

Cleaned images for object detections: The OCS *detect* algorithm employs image deconvolution to sharpen the image and limit confusion in crowded fields. This is done by modeling the image as a sum of components having the shape of the point-spread function (PSF) of the image being processing. The model components are then analyzed to identify and measure all individual objects in the image that exceed a specified SNR threshold.

Streaks: OCS uses the signal processing technique called *matched filtering*. This works well for detecting star trails in GEO or RT images that are tracking at the RSO rate as the stars are all the same length (computed from the telescope track rate, the known sidereal (star motion) rate, and exposure time) and streaked in the same direction on-frame, allowing for a template to be easily created with the expected intensity profile of the star trails. This template is then convolved with the image containing the star trails and results in estimates of both the star's flux and the position of the peak of each star trail within the convolved images. This yields astrometric and photometric solutions, which are applied to objects detected in the cleaned images noted above (note: *detect* does not search for RSOs in the convolved images – those are used only for calibration). For further details, and another example of the application of matched filtering to detect streaks in images see [8] and [12].

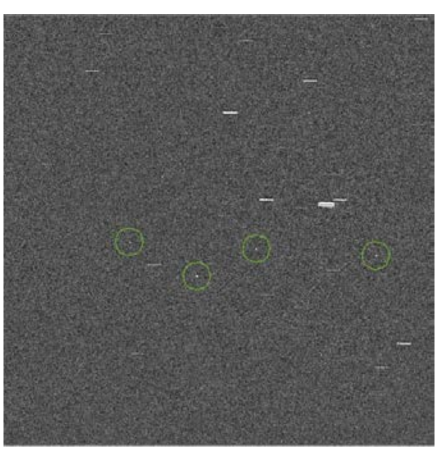
<u>Parameters logged by *detect* include</u>: photometric parameters (*Z*, extinction coefficient), mean FWHM (arcsec), object detect threshold, minimum SNR (Signal to Noise ratio), RMS background noise (in ADU), and the isolation radius (in pixels).

4.2. Match: Finding Moving Objects

Once a list of detected objects is created, and photometrically and astrometrically calibrated, the program *match* is run to identify detected objects on one image that correspond to those on other images, based on their motion in the sky, to determine which might be the same RSO observed multiple times. To accomplish this, the *match* routine will start with the first object detected for a given night, and computes the angular velocity it would have with all the detections from the next image. If the computed velocities matched with any object in the second image fall within the 'acceptable' range (e.g. expected rates for GEO objects), then *match* extrapolates where the RSO would fall in subsequent images and if a detected object is identified within those parameters, it is matched with the first two detections that were used to calculate the RSOs trajectory. The same check is done for all subsequent detections in the first image. After all detections in the first image are complete, it starts with all unmatched objects in the second image and runs the same sequence with subsequent images, until all possible combinations are exhausted.

The final lists of matched objects are cross-checked forward and backward by the *merge* program to link all RSOs that are likely the same object. To prevent false-detections, e.g., from residual cosmic rays, a minimum of 4 detections from 4 separate images must match to be considered a positive MATCH. This number was determined from studies done previously by this office, designed to improve data quality. Figure 2 below shows examples of 3, 4, and 5 matches. Currently, OCS requires a minimum SNR of 6.0 for detect, and 7.0 for match. The minimum SNR thresholds are correlated directly to the faint limit detection, and inversely to the statistical completeness and error rates (false positives increase as SNR decreases with attempts to reach fainter limits, without increasing exposure times).

<u>The output OBJECT file for each matched RSO includes</u>: the frame number in which the RSO was detected, RA, Dec, epoch of coordinates, apparent magnitude, date, time, and filter.



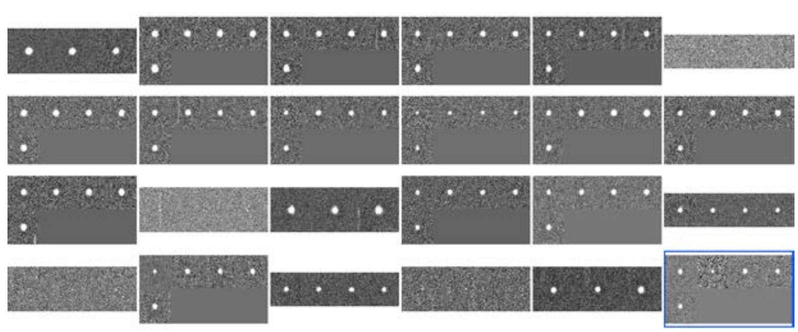


Fig. 2. LEFT: A group of RSOs detected at GEO orbits with short star streaks in MCAT's 41″ x 41″ field of view.
RIGHT: Thumbnail image views of 3, 4 and 5 matched RSOs.

4.3. Orbit Determination

After objects are matched to one another, *orbit* calculates the orbital parameters of the object. It is initially assumed that the object is in a circular orbit given two observed positions and times. A circular orbit is assumed as the arc of the orbit observed by MCAT is not long enough to determine the eccentricity of the orbit outright. Initial orbital elements are computed directly and the corresponding TLE is determined. This TLE is propagated via the SGP-SDP algorithm, and the observed positions are compared with those predicted by the TLE. The TLE is then refined iteratively using Metropolis-Hastings Markov-Chain Monte-Carlo (MCMC) optimization.

In the cases where stars or cosmic rays might have been matched to RSOs, the errors to orbital fits will increase. Thus, when a poor orbital fit results, OCS attempts re-fitting the orbit without the first matched object to see the results; then without just the second, and so on, until a good fit is found. The same can be done rejecting 2 of the matched objects in a set (trying all combinations again), presuming there are still 4 or more matched objects after the rejections.

4.4. Correlate

Once the TLEs are estimated, the ODP software is used to compare the orbital elements against the objects in the SSN catalogue. If an RSO correlates with an object in the SSN catalogue, it is logged as a “Correlated Target” or CT. If not, then it is logged as an Uncorrelated Target, or UCT.

The output BestGuess file includes: Date and time, frame, epoch, object ID, SSN#, instrumental and absolute magnitude (absolute for GEO survey defined as the magnitude if the object were at 36,000 km), and observed orbital elements (mean motion (MM in revolutions/day), inclination, Right Ascension of Ascending Node (RAAN)), and predicted best-fit orbital parameters (MM, range, eccentricity, inclination, RAAN).

ODP also logs (a) RSOs that were detected, but may have fallen on a bad location on the chip (e.g. the edge, or too close to a star, (b) objects moving faster or slower than the expected GEO rate, (c) objects where the catalogued SSN TLE is > 30 days old, or (d) an object that was expected to be observed based on the SSN catalogue, but not seen by MCAT (e.g. it was too cloudy to detect fainter objects, etc.).

5. PERFORMANCE

With the previous protected aluminum coating on the primary mirror, which was less reflective across all visible wavelengths compared with the current silver coating, but the original e2v chip with an astro ER-1 coating that was more sensitive from 550nm – 1.0 µm, a V-band limiting magnitude of 20.64 ±0.12 was achieved with a 5-second exposure with a SNR of 3 (meaning barely detected with a 30% error). With the protected, enhanced *silver* coating on the primary (with no change to the coating on the secondary) and the replacement broadband coated e2v chip [6], initial estimates from data suggests and improvement of roughly one magnitude in detectability.

OCS requires that it achieve an SNR of 6.0 for *detect*, and 7.0 for *match*. For 5-second exposures, with all else equal, this would relate to V magnitudes of roughly 19.9 and 19.7 for the old coating under clear skies.

It was estimated that debris as small as 20-35 cm in GEO should be detectable, weather and RSO albedo dependent [2]. With the new primary coating (see next) and slightly better seeing than expected, it is anticipated that MCAT will beat this, but only with clear skies.

5.1. MCAT Optics Throughput

MCAT’s fused silica field corrector transmits the full 300nm – 1.06 µm bandpass, which is limited by the response of the CCD camera. The secondary mirror is coated with protected aluminum, which typically reflects to >90% across the entire 300nm to > 1.06 µm bandpass. Though the MCAT reflectivity curve for M2 has not been specifically reported to NASA, this is consistent with measurements using a hand-held reflectometer. The primary mirror was coated in late 2018 with an enhanced, protected silver by ZeCoat with an average reflectivity of 95.5% from 360 – 1000nm (notably, this coating is ~99% reflective to beyond 25 µm with 2-5%, dips near 2.5 and 10 µm) [6, 13, 14]. The broadband antireflective coated e2v chip in the Spectral instruments camera cuts on at about 40% QE at 300nm and cuts off at 40% QE about 920nm. The SDSS g′r′i′z′ filter band passes range from about 380nm to 1.08 µm and are expected to be the prime photometric bandpasses used. For comparison, BVRI covers roughly 370nm to 910nm, but are much less square in their transmission curve and not as well calibrated as the SDSS filters. Combined, MCAT’s effective wavelength range is roughly 380 to 920nm.

6. WEATHER

Estimating the total observable hours requires monitoring both weather variables that require dome closure (humidity, dewpoint, wind average, wind gusts, rain) as well as cloud opacity. In dome-closure scenarios, the weather conditions must drop below and stay below the re-open limits for a certain period of time (*weather_close_time* 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. In all cases, re-open limits are stricter than the initial close limit, e.g. close is required at humidity ≥ 90%, but must drop to ≤ 85% for 20 minutes before a re-open is allowed. Close/re-open limits in 2019 are set as follows: Wind gust: 45/33 mph; wind average: 35/30 mph; dew point: 1.67C/2.78C. Rain detected by any sensor triggers a close as well, and sensors must be dry for the weather close time before opening [6]. Thus far, dome closure limits alone have translated to allowing MCAT to open 40% of the time.

In addition, an infrared FLIR camera, installed at the end of the telescope optical tube assembly, monitors cloud opacity when the dome is open, and no images are taken when the calculated FLIR cloud opacity surpasses the opacity limit. Over the 5 month period shown in Fig. 3, assuming 8 hours represents a full night of GEO data, clouds decrease our stats from 40% to ~34% up time. The graph also shows the difference in opportunity to collect data during the rainy season (Aug – Nov/Dec) versus the dry season (Jan – July'ish), which mirrors the Cloud Free Line of Sight (CFLOS) monthly averages observed for Ascension from 2005 – 2012 [1].

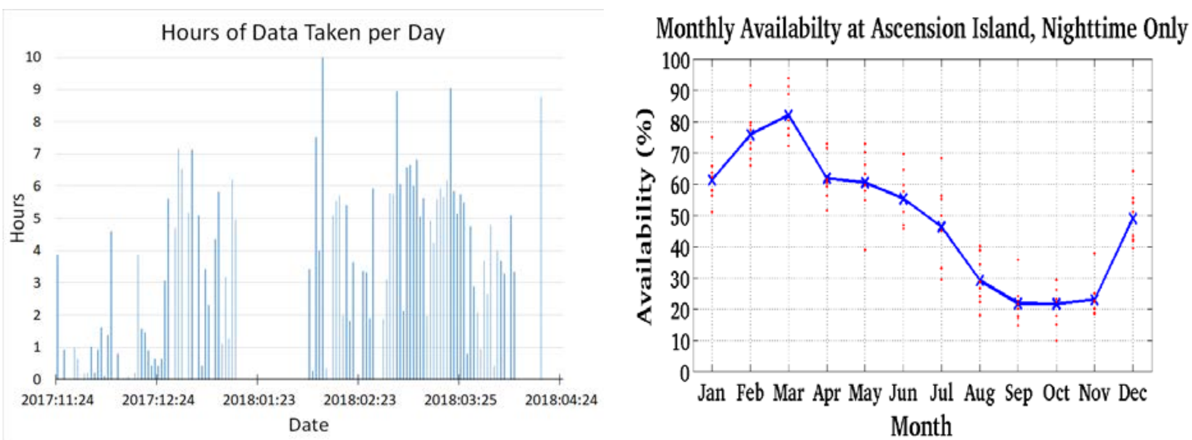


Fig. 3. (Left) Hours of data taken for a given date from 2017 Nov 24 until 2018 Apr 24. (Right) Cloud-free Line of Sight (CFLOS) where clear is defined as an optical depth < 0.1 (the limit of the sensors). Red dots indicate the average for the month for one year and blue Xs indicate the average of 8 years (2005 – 2012) for that month [*1*].

7. SUMMARY

The 1.3-m MCAT telescope is designed to monitor and assess the orbital debris environment by surveying, detecting, and tracking orbiting objects at all orbital altitudes. MCAT primarily collects data in a GEO Rate Track mode for surveying the GEO belt for debris, but is also capable of tracking TLEs to characterize objects of interest or surveying for debris after a break-up event.

The OCS 2.0 software collects, reduces, and analyzes the data while monitoring the weather, all autonomously. After collecting the data, the pipeline first preprocesses the data with master bias/darks and master flats. Due to the variable weather, in-frame calibration for photometry and astrometry is performed by analyzing the brightness and positions, respectively, of Gaia stars located in each individual image to produce astrometric and photometric solutions per image. This way, cloud opacity variations from one image to the next are accounted for, as is necessary given the rapid weather/cloud changes that accompany Ascension Island. The *Detect* and *match* algorithms find RSOs and link them from one image to the next. The *orbit* determination algorithm then finds a best-fit orbit. Finally, ODP correlates the output RSO observations with objects in the SSN catalogue.

Ascension Island offers challenging weather conditions, resulting in roughly 34% observational time for surveys, but with a newly coated, high performance protected silver coating on the primary mirror, performance of MCAT's detect capability now exceeds expectations. ES-MCAT is expected to make a valuable contribution to our understanding of the orbital debris environment around Earth for years to come.

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