NASA's Orbital Debris Optical and IR Ground-based Observing Program: Utilizing the MCAT, UKIRT, and Magellan Telescopes

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ABSTRACT

Characterizing debris in Earth-orbit has become increasingly important as the growing population of debris poses greater threats to active satellites each year. Currently, the Joint Space Operations is tracking > 23,000 objects ranging in size from 1-meter and larger in Geosychronous orbits (GEO) to 10-cm and larger at low-Earth orbits (LEO). Model estimates suggest that there are hundreds of thousands of pieces of spacecraft debris larger than 10 cm currently in orbit around the Earth. With such a small fraction of the total population being tracked, and new break-ups occurring from LEO to GEO, new assets, techniques, and approaches for characterizing this debris are needed.

With this in mind, NASA's Orbital Debris Program Office has actively tasked a suite of telescopes around the world. In 2015, the newly-built 1.3m optical Meter Class Autonomous Telescope (MCAT) came on-line on Ascension Island and is now being commissioned. MCAT is designed to track Earth-orbiting objects above 200km, conduct surveys at GEO, and work with a co-located Raven-class commercial-off-the-shelf system, a 0.4m telescope with a field-of-view similar to MCAT's and research-grade instrumentation designed to complement MCAT.

The 3.8m infrared UKIRT telescope on Mauna Kea, Hawaii has been heavily tasked to collect data on individual targets and in survey modes to study both the general GEO population and a break-up event. Data collected include photometry and spectroscopy in the near-Infrared (0.85 – 2.5μm) and the mid-infrared (8-16μm).

Finally, the 6.5-m Baade Magellan telescope at Las Campanas Observatory in Chile was used to collect optical photometric survey data in October 2015 of two GEO Titan transtage breakups, focusing on locations of possible debris concentrations as indicated by the NASA standard break-up model.

1. INTRODUCTION

Throughout the last sixty years, the population of artificial debris in orbit around the Earth has grown substantially as the rate of spacecraft launches has grown to meet the demands of humankind. Threats to active satellites has grown at an alarming rate as collisions, explosions, and fragmentations (generally referred to as 'break-ups) have created an environment that requires constant surveillance and frequent avoidance maneuvers to prevent future collisions, which would further contribute to the growth of the debris field. There have been five International Space Station maneuvers between October 2014 and August 2016 due to 8-14 cm debris, one maneuver against an intact body and one shelter-in-place protocol.

To this end, the Joint Space Operations is tracking over 23,000 objects ranging in size from 1-meter and larger in geosychronous orbits (GEO) to 10-cm and larger at low-Earth orbits (LEO). Roughly 17,000 of those are classified as debris, which includes all man-objects not serving a useful purpose in orbit around the Earth (e.g. non-functional intact spacecraft or rocket bodies; debris shed or catastrophically created from a break-up). Model estimates suggest that there are hundreds of thousands of pieces of spacecraft debris larger than 10 cm currently in orbit around the Earth, and >100 million smaller than 1cm.

As such, understanding the orbital debris population in Earth-orbit has been the prime goal of NASA's Orbital Debris Program Office (ODPO). A suite of ground-based telescopes have been tasked by NASA's ODPO for this purpose, including the Meter Class Autonomous Telescope (MCAT), the United Kingdom Infrared Telescope (UKIRT), and one of the Magellan telescopes all shown on (Fig. 1).

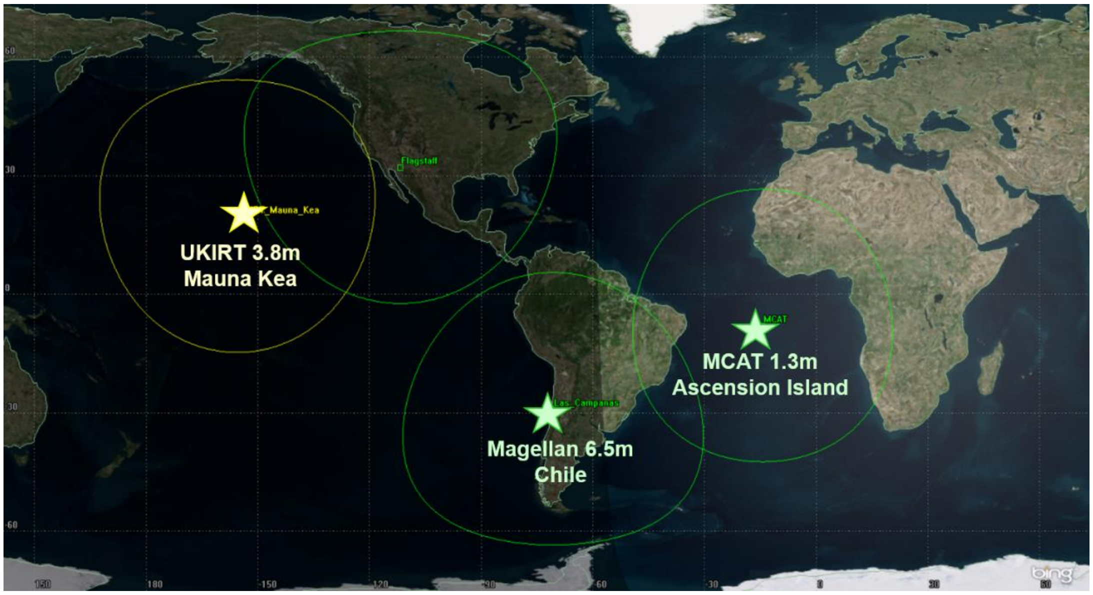

Fig. 1. Ground-based telescopes tasked by NASA's ODPO.

2. MCAT: METER CLASS AUTONOMOUS TELESCOPE

MCAT, the Meter Class Autonomous Telescope, is a DFM Engineering optical 1.3m telescope with a double-horseshoe mount design that allows smooth tracking through the zenith. MCAT is located on Ascension Island, midway between South America and Africa, in the Atlantic Ocean at (7° 58′20" S, 14° 24′ 4"W), which fills a gap in the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system of telescopes. This low latitude location is ideally suited for studying Low Inclination LEO debris (LILO). MCAT's fast tracking telescope mount and fast-tracking Observadome allow debris objects to easily be followed in orbits ranging from low-Earth (LEO) to Geosynchronous (GEO) altitudes without interruption. Tracking capabilities for a Correlated Target (CT) is shown in Fig. 2 for both LEO (left) and GEO (right). The trails seen in these two images are caused by stars streaking as MCAT tracks at the expected motion of the debris. For an overview of expected performance of MCAT on Ascension, see Lederer et al. [1, 2].

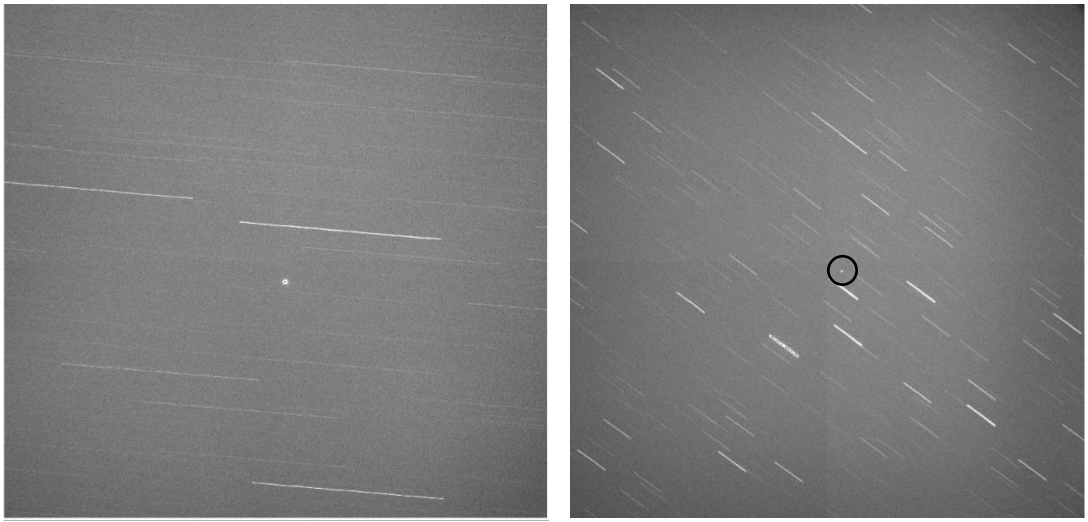

Fig. 2. Data taken with MCAT via Object Tracking mode that tracks at the object's rate as indicated by TLE (two-line element) orbital parameters. Exposure times of 5 seconds were used for both images. On the left, a LEO is tracked, resulting in longer start streaks. Tracking a GEO object (right) yields shorter star-streaks.

Instrumentation on MCAT includes an optical Spectral Instruments CCD camera with a 4k x 4k chip with 4-port readouts and Time Delay Integration (TDI) readout capability, and a 41′ x 41′ field of view. TDI mode aids in conducting GEO surveys by counter-sidereal scanning with the camera, eliminating the need to reposition the telescope after every integration, and thereby alleviating undue stress on the telescope drives [3]. With typically 1000 images expected during a full night of survey, "GEO survey" will be the primary imaging mode. Broadband filters used with this camera include a set of research grade Sloan Digital Sky Survey (SDSS) g′r′i′z′ filters, and Johnson/Kron-Cousins BVRI filters that are currently installed in the 8-position DFM designed filter slide.

MCAT has undergone telescope and instrument commissioning over the past year, including testing all operational modes. The primary goal of MCAT is to statistically characterize GEO and LEO orbital regimes to better understand the debris environment by providing high fidelity data in a timely manner for input into models with the ultimate goal of protecting satellites and spacecraft in orbit around the Earth. Toward this end, MCAT will take data in four data collection modes, including (1) GEO survey/GEO follow-up, (2) Catalog or Object of Interest Tracking at all orbital regimes (LEO, MEO, GTO, GEO), (3) Orbit Scan, which allows for the equivalent of GEO survey mode in LEO, as well as tracking expected orbits of fragments following a break-up in any orbital regime, and (4) Stare-Detect-Chase (Fig. 3) to discover UnCorrelated Targets (UCTs). (See Lederer et al. [2] for more details).

Fig. 3. The Stare-mode is designed to detect UCTs. Streak length is measured and, combined with exposure time, used to estimate the orbital altitude of the detected object (s). Thus, while searching for LEO was of prime interest in creating this mode, objects at any altitude could feasibly be detected.

A Raven-class commercial off the shelf (COTS) telescope is poised to be installed on a tower platform next to MCAT in December, 2016. The James R. Benbrook Telescope (JRBT), named after a former orbital debris colleague, is designed to complement the observations of MCAT. The telescope is comprised of a 0.4m Officina Stellare optical tube assembly supported by an Astelco German equatorial mount. A Finger Lakes Instruments (FLI) camera and focuser will be used with this telescope.

This telescope will be used in two configurations. In the first, it will essentially be tasked like a small version of MCAT, a.k.a. "miniCAT", Here, an FLI Proline PL4710 2k x 2k camera with a 44′ x 44′ field of view was chosen to match as closely as possible the 41′ x 41′ field of view of MCAT. The system also utilizes the FLI Atlas focuser, and an FLI Centerline CL-1-10 filterwheel with 10 slots available for filters. Like MCAT, an equivalent suite of filters (g′r′i′z′ and BVRI) will be utilized to allow observations to be photometrically calibrated. In the miniCAT configuration, the telescope can be tasked using any of the four data collection modes noted above for MCAT. It can take data in tandem with MCAT, for example in a Stare-Detect-Chase mode where it initially detects an object, and MCAT follows up with chasing the target to better characterize it, or the two roles can be reversed. It might also be used in parallel with MCAT, for example, in GEO survey mode whereby both telescopes are observing the same portion of the sky, but using different filters to yield simultaneous filter photometry.

This system will also be capable of operating as a DIMM (Differential Image Motion Monitor) when a 2-lens mask is installed on the optical tube. A DIMM allows the seeing to be measured independently of the telescope and system used to measure seeing for accurate assessments of the atmospheric stability. In the DIMM mode of operation, a fast frame-rate FLI MicroLine ML1050 1k x 1k camera will be attached to the FLI focuser.

3. UKIRT: UK INFRARED TELESCOPE

The United Kingdom Infrared Telescope (UKIRT), is a 3.8m infrared (IR) telescope, with capabilities in both the near-infrared (0.86 – 5.0 µm), or short and mid-wave IR (SWIR and MWIR), as well as the mid-infrared (8 – 25 µm) or long-wave IR (LWIR), where thermal emissions are detected. UKIRT is located on Mauna Kea, Hawaii. With arguably some of the clearest and driest skies, Mauna Kea is an ideal location for an infrared telescope. It often boasts very low humidity levels (the few-percent level is not uncommon). Associated precipitable water vapor values are considered to be "dry" (tau < 0.09) roughly 65% of the year, with monthly averages ranging from >50% to over 80% [4]. Dry conditions are necessary for quality thermal infrared observations. Seeing values, an indication of atmospheric turbulence, are < 0.55-0.6 arcsec in JHK and <0.37 arcsec in the N-band (11.7 µm) during70% of the year and can be as low as under 0.2 arcsec in any of these bands on an excellent night.

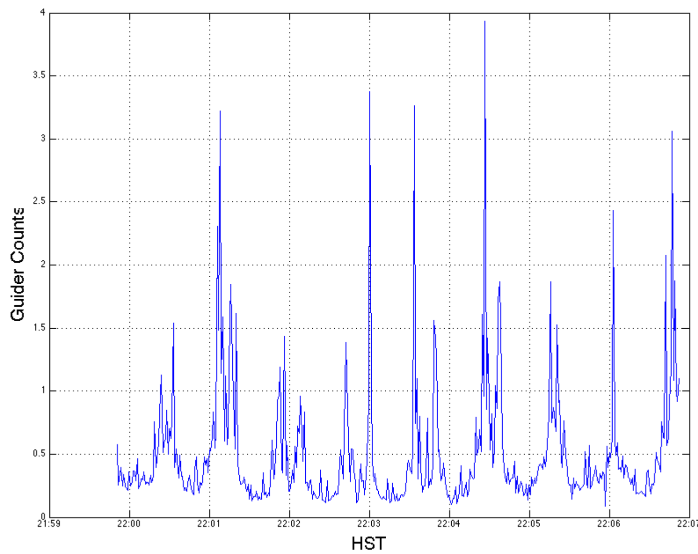

Fig. 4. A seven minute trace from a visible band guider tracking the debris object, in this case a rocket body, demonstrates the tumbling motion and variation in brightness (~0.1 to 4 x 10^4 counts) on short timescales.

A dichroic tertiary mirror allows visible light to be transmitted to UKIRT's autoguider. In all cases, UKIRT used the autoguider to lock onto the target object directly to ensure it did not drift out of the slit or shift locations appreciably on the array during data collection. Ephemerides are calculated by applying SGP4 (Simplified General Perturbations propagator) to TLEs (two-line elements defining the object's orbit) available on spacetrack.org. UKIRT's TCS (Telescope Control System) interfaces directly with the SGP4 code to calculate the ephemerides of the object. Visible photometry from the guider can also be saved to study the tumbling or rotational motion of an object (e.g. Fig. 4).

WFCam is a Wide-field imager, with a unique 4-array design with its autoguider centered within the field of view of WFCam [5]. Four 2048 x 2048 pixel HAWAII-2 arrays collect data at near-infrared wavelengths. Each array spans 13.65′ x 13.65′, resulting in an image 0.75º x 0.75º after a 4-shift sequence is completed. The 18 µm pixels yield 0.4″/pixel resolution on the sky. The set of WFCam broadband filters (ZYJHK) covers 0.83 – 2.37µm. [6].

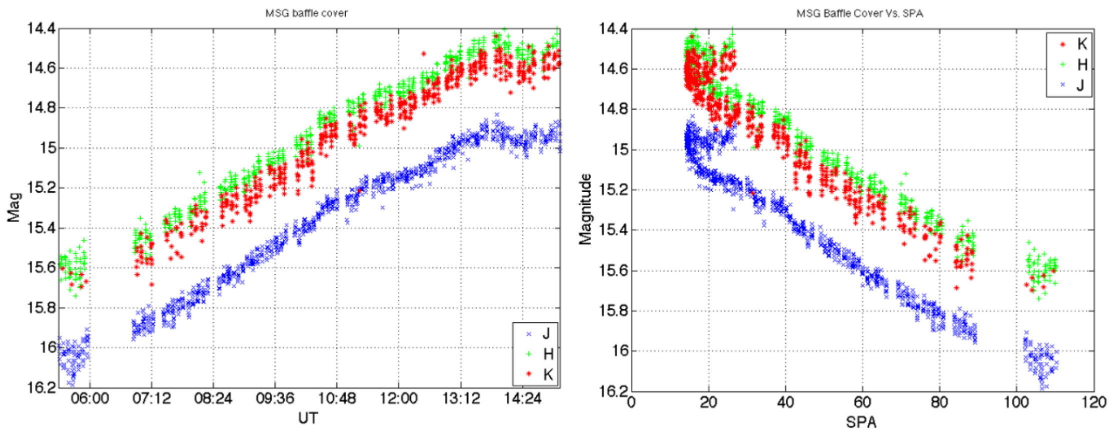

Fig. 5. WFCam data plotted as the magnitude of the MSG (Meteosat Second Generation) baffle cover versus Universal Time, UT (left) and Solar Phase Angle, SPA (right) in J, H, and K near-infrared bands. The tumbling motion is indicated by the vertical spread in data points.

WFCam data of a suite of objects have been taken over the past three years, with an example shown of the MSG baffle cover in Fig. 5. Magnitude versus Universal Time, UT (left) maps into magnitude versus solar phase angle, SPA (right). The 3σ uncertainty in magnitude is ± 0.1 mag, less than the observed spread in magnitude. The variation of the rotational/tumbling motion is indicated by the vertical spread in magnitude. The MSG spacecraft released both a cooler cover and a baffle cover (Fig. 6). Further discussion of WFCam data of both covers were discussed in a previous AMOS meeting [4].

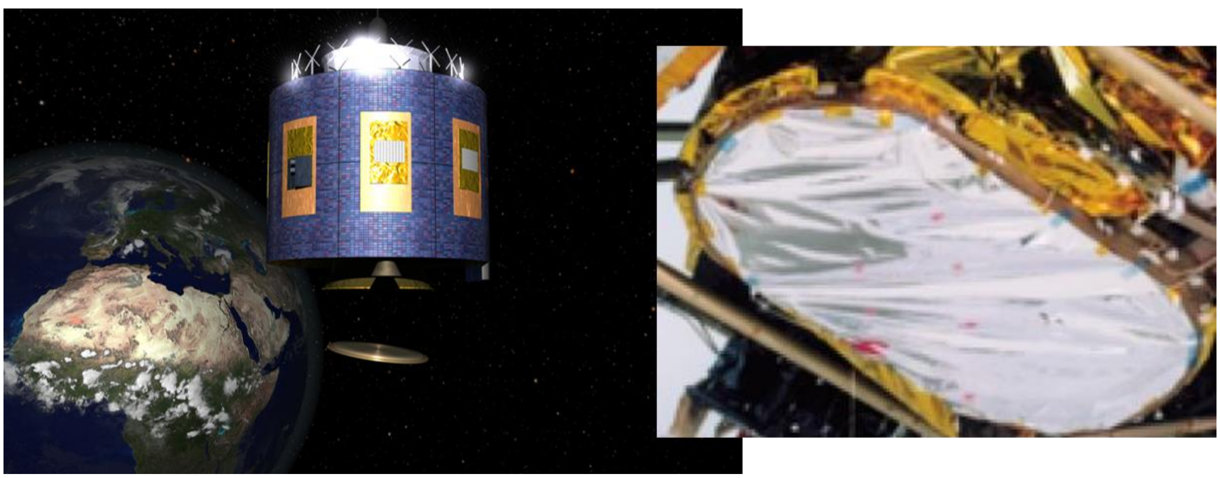

Fig. 6. Artist rendition of Meteosat Second Generation (MSG) satellite releasing the circular cooler cover (left) [7]. Its oblong baffle cover is shown on the right [8].

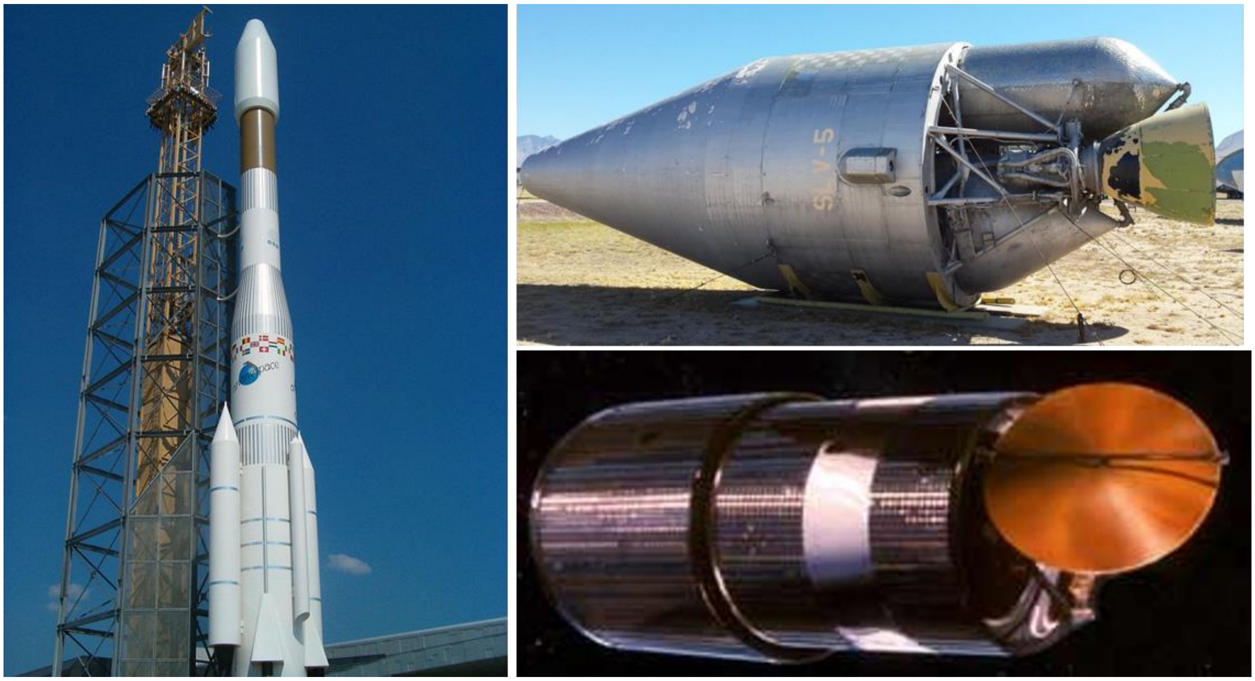

Fig. 7. UIST near-infrared spectra were obtained of Ariane 2 rocket body debris (Ariane rocket before launch, left [**Error! Reference source not found.**]), a Titan 3C transtage (note the fairing would not be part of the Titan Tran stage vehicle), top right [10]), and an HS-376 bus SBS-2. A representation of SBS-1 and 2 are shown, bottom right [11].

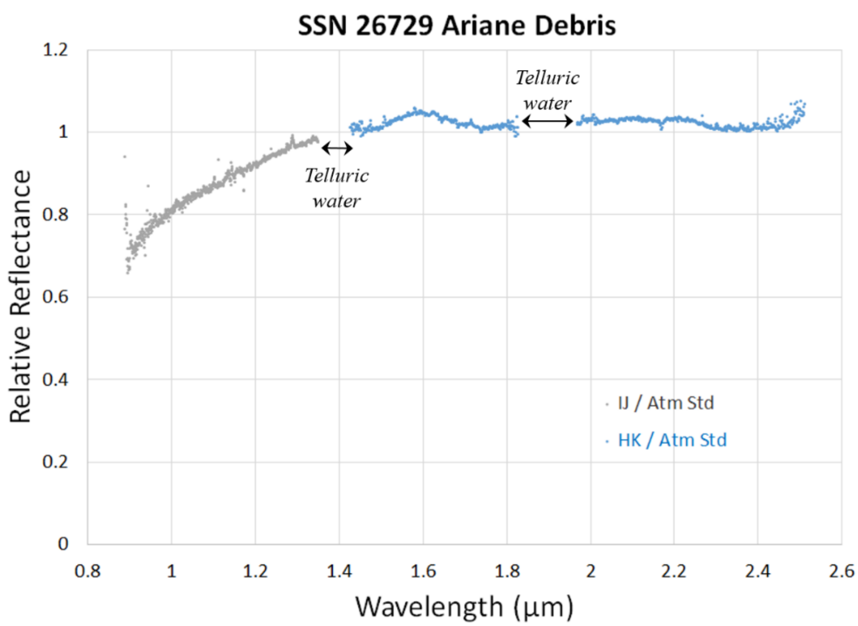

Fig. 8. UIST Spectrum of Ariane-2 rocket body debris (1989-006G). The broad feature seen between 1.6 and 1.8 μm may originate from aluminum 6061 [12]. While the Ariane rockets are typically painted white before launch, the integrity of the painted surface after decades in space is unknown.

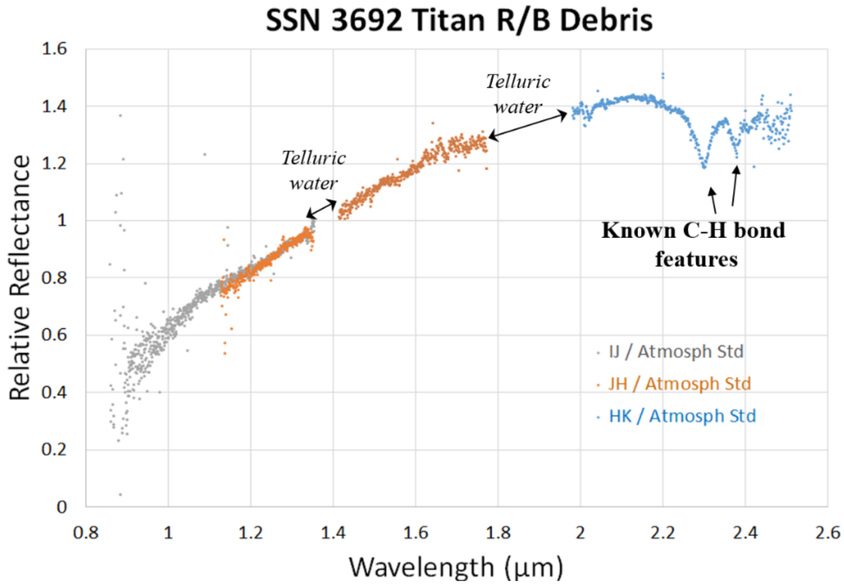

Fig. 9. UIST Spectrum of Titan rocket body debris. A C-H bond feature near 2.3 µm is typical of paint, while the absorption feature ~ 2.37 µm is attributed to organics. Notably, the C-H bond absorption features near 1.7 µm that are obvious in, e.g. SBS-2 (below), are not apparent here.

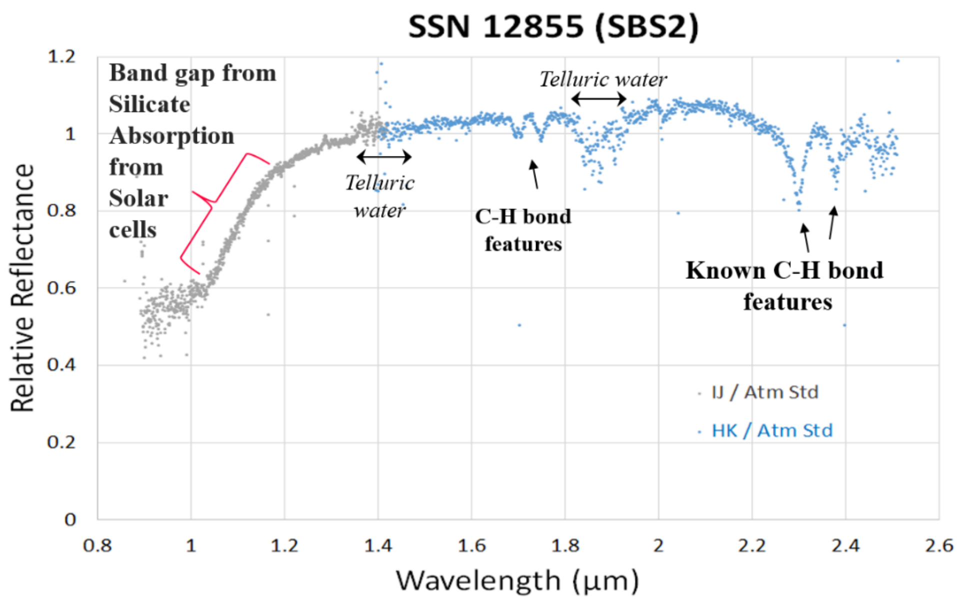

Fig. 10. UIST relative reflectance spectrum of an HS-376 bus, SBS-2. These cylindrical buses are covered in solar panels, so it is not surprising to see a steep rise, or 'band gap' from 1 – 1.2 µm, which is a typical signature arising from silicate absorption originating in solar panels. Four C-H bond features are also present in the spectrum at 1.7 and 1.75 µm, as well as near 2.3 and an absorption attributed to organics 2.38 µm; the latter two are similar to those observed in the Titan debris. Telluric water vapor bands at 1.4 and 1.9 µm bands are indicated.

In the near-Infrared, UIST is instrument of choice for reflection spectroscopy. Three grisms were selected for observations, including IJ [0.86 – 1.42 µm], JH [1.13 – 1.90 µm], and HK [1.40 – 2.51 µm]. Slit widths of 4 pixels (IJ and JH), giving a resolution of R=520, and 5 pixels (HK), yielding R=360, were selected to maximize signal and allow for a slight amount of motion of the debris within the slit. Standard stars and debris objects are centered in the slit by first imaging the object and finding its centroid, and then shifting the object to the slit to ensure it is located in the center of the slit.

UIST near-infrared reflectance spectra of a set of debris objects are shown, including Ariane-2 rocket body debris (Fig. 8), a Titan 3C transtage (Fig. 9), and an HS-376 (Hughes/Boeing) bus, SBS-2 (Fig. 10). Data were taken 12, 10, and 8 Oct 2015, respectively. Data were normalized first by an atmospheric standard within ~5 degrees of the observed object as well as solar analog stars. In all cases, G0 or G5 solar-type stars were chosen as atmospheric standards. Data were then normalized at 1.4 µm as this wavelength is the conjunction of the IJ, JH, and HK grism data. Water vapor in the Earth's atmosphere generates noise around 1.4 µm and between 1.8 – 2 µm. This telluric water was clipped from the data for the rocket bodies, as indicated by the gaps in the data, but is shown in the SBS-2 data as the water vapor content was lower on the night that these data were taken.

The Ariane 2 debris object observed was launched by France in January, 1989. This object is in a GEO-transfer orbit, presenting challenges for scheduling the observing as UKIRT can track the object at its apogee, but not at perigee. Ariane rocket bodies are typically painted white prior to launch, and are good subjects for investigating the effects of space weathering on paint, whether changing the color, or indicating that the paint itself has flaked off with time, exposing the bare metal surface beneath. The slope of the spectrum from visible to infrared and signatures of materials (including absorption features or general spectral shape) could be compared with other Ariane rocket bodies or debris, with respect to launch date to investigate these effects.

Two observed breakups of Titan transtages have occurred in GEO, one in GTO, and one in LEO. The cause of the GEO Titan break-ups is as yet unknown, but could be caused by a collision, or an explosion of unspent fuel. Comparison of debris fragments of in-tact transtage rocket bodies can help us gain insight into the nature of the break-up fragments. The Titan 3C transtage rocket body observed by UIST was launched in 1969. The ODPO acquired a Titan transtage, which was delivered to NASA JSC in August, 2016. Its spectral signatures are being analyzed by ODPO for comparison with data taken with telescopes, like the data shown here. C-H bond/organic features between 2.3 and 2.4 µm are evident in the spectra, as well as a significant slope with increasing wavelength from the visible to the near-IR. Laboratory spectra compared with telescopic data can be used to address causes of differences that might be evident between the telescopic and laboratory data. The differences (or similarities) might uncover possible space weathering effects on spacecraft materials, as well as provide insight into the types of materials comprising the fragments and thereby could hint at a possible cause(s) of the fragmentation event(s)..[13]

SBS-2, designed as a communications satellite, was launched Sep 24, 1981. A cylindrical bus covered in solar panels, the spectrum not surprisingly reveals a signature in the 1 – 1.2 µm spectral range that could be attributed to the band gap from silicate absorption in solar cells. C-H absorption features near both 1.7 µm and 2.3 µm are again present, and as is typically present in the spectra of paint used for spacecraft, while the 2.4 µm feature is, as noted above, attributed to an organic material. A more complete study of HS-376 buses observed with WFCam was reported in AMOS 2015 [14].

In all cases, the spectra observed with UIST can be spectrally 'unmixed' to determine the contributions from a range of materials, including paints, solar cells, aluminum, multi-layer insulation, and a variety of other spacecraft materials [12]. Slopes, general shapes, and absorption features can be used to fit a 'mix' of spectra of specific materials to determine what the target's spectrum is comprised of and thereby yield insight into their material properties [15].

Another UKIRT instrument, Michelle, is a mid-infrared imager/spectrometer designed to investigate thermal emission. It is comprised of an SBRC Si:AS 320x240 pixel array, operating in the 8-25 µm wavelength range. For the purposes of ODPO, Michelle has been employed in two observing modes: (1) Imaging (67.2 x 50.4 arcsec field of view at 0.21 arcsecs per pixel), and (2) Spectroscopy (~91-arcsec slit, 0.38 arcsec/pixel). More specifically, a suite of photometry was taken with the 8.8 µm, 11.6 µm, and 18.5 µm filters. For the spectroscopy mode, the lowN grating (10.5 µm) with spectral coverage from 6.02 – 13.98 µm and a resolving power of R=200 was chosen to investigate the thermal properties and sizes of objects. Data reduction of a set of debris targets is currently underway.

4. MAGELLAN TELESCOPE

The twin 6.5m Magellan Telescopes (Baade and Clay) have been tasked by ODPO with support from the University of Michigan to conduct deep imaging GEO surveys and collect spectra data on specific GEO debris of interest. The IMACS instrument on the Baade telescope has been used for several observing campaigns over the past several years to survey the optically faint population at GEO [16], and was employed to conduct a GEO break-up survey in orbit scan mode.

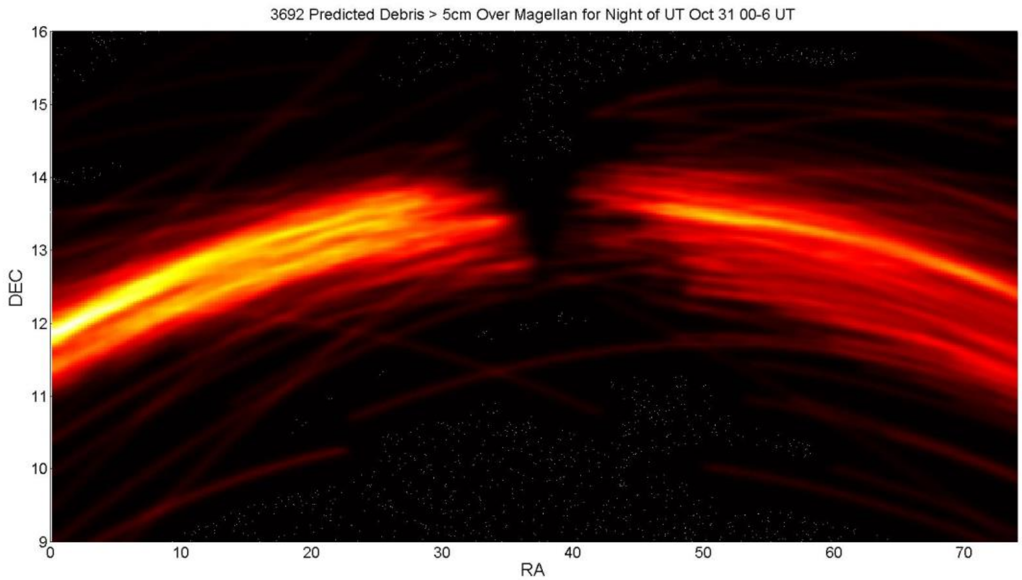

Fig. 11. Density of the expected orbits of the fragments from the breakup of SSN 3692 Titan 3C/Transtage on the night of UT 2015 Oct 31 over Las Campanas Observatory, Magellan telescope.

In October 2015, a campaign was completed to survey the break-up of a Titan 3C transtage using the ODPO break-up model to determine the best rate and position to track the fragment population. This is the same Titan transtage object observed with UKIRT/UIST on 10 Oct 2015 and shown above in Fig. 9. The breakup of parent body SSN 3692 occurred on 4 June 2014. The cause is unknown, but possibilities include an explosion from an unspent propellants, or a collision with another object. Locations of concentrations in the modeled debris field are indicated in Fig. 11. Models were also run to estimate the velocity in Right Ascension and Declination at which the fragments were most likely to be moving, and telescope rates of motion were chosen accordingly. Similar models were run to conduct a GEO survey in mid-January, 2016, using MCAT when a BRIZ-M rocket body break-up event occurred. Targeted surveys such as these are used by ODPO to search for fragments resulting from a known break-up, and help to characterize the newly generated cloud of debris, and monitor its evolution. Resulting data will then be used to test the fidelity of the NASA break-up model, and contributes to the overarching understanding of the growing population of orbital debris. Additional studies of the faint population of debris were also conducted using this 6.5m telescope with the IMACs instrument [16]

5. CONCLUSIONS

ODPO has utilized a suite of world-class telescopes, ranging from small to large classes, to investigate the population and physical characteristics of the orbital debris environment surrounding Earth. The 1.3m MCAT is in its commissioning phase, but has already demonstrated the ability to track objects from LEO out to GEO, employing a set of observing modes to conduct surveys, discover new uncorrelated targets, or characterize known targets with known TLEs. The complementary 0.4m JRBT is is scheduled to be installed by end of calendar year 2016 for initial testing, augmenting the science results of MCAT through its miniCAT configuration and allowing independent analyses of the atmospheric seeing as a DIMM.

The 3.8m UKIRT telescope is ideally designed to undertake in depth investigations of individual targets in GEO, MEO, or GEO transfer orbits. Near-infrared reflectance spectroscopy from 0.9 – 2.5 µm has been used to investigate the material properties of observed objects while Michelle thermal infrared photometry and spectroscopy from 6 – 14 µm is being employed to gain insight into the thermal properties and sizes of observed debris objects.

Finally, the 6.5m Magellan telescopes are well suited to scan regions of space where recent break-ups are likely to reveal new debris resulting from the breakup, including very faint debris due to the light collecting power of this large telescope. Models can be used first to intelligently design observing runs to search RA/Dec locations that may have a higher density population from the break-up events, and predict rates at which the objects associated with those break-ups are likely to be moving at. MCAT can also be tasked to search break-up orbits to complement the deeper magnitude Magellan targeted searches as ODPOs full access to MCAT results in much greater temporal and spatial coverage, though not reaching magnitudes as faint as Magellan.

Access to a suite of telescope with differing instruments and capabilities allows NASA's ODPO to better characterize the orbital debris environment from a broader perspective, which is a critical piece of the puzzle needed guide the community to make future decisions that further protect this very important environment.

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