NASA's GROUND-BASED OBSERVING CAMPAIGNS OF ROCKET BODIES WITH THE UKIRT AND NASA ES-MCAT TELESCOPES

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ABSTRACT

Rocket bodies comprise a class of human-made space debris that are at the same time essential for launching every spacecraft from the Earth, but are also a significant source of debris both as intact objects, as well as fragmented debris. Unspent fuel has been long theorized as a potential cause of catastrophic rocket body break-ups. Given typical orbital speeds range from ~2-3 km/s at Geosynchronous Orbit (GEO) and up to 15 km/s in low Earth orbit (LEO), collisions with uncatalogued and undetected debris can also cause catastrophic breakups.

Understanding break-ups is a necessary step in preventing them, and one key step in that process is to correlate and characterize daughter fragments with their parent bodies. Two very different methods include (1) conducting photometric surveys to correlate an object's motion and orbital elements to the parent body, and (2) characterizing what materials comprise the target to determine whether those materials are consistent with the parent body or like objects. With this in mind, photometric data were taken shortly after the breakup of one rocket body for short-term orbital studies, and a suite of spectral data were taken of rocket bodies that are fully intact to compare with debris, for characterization studies. Targets included Titan Transtage, Briz-M, and Ariane rocket bodies and debris. Spectra of each sub-class of rocket body were very similar within their rocket body type, but differed distinctly from one type to the next, supporting the effectiveness of this approach.

1 INTRODUCTION

In 2015, NASA's Orbital Debris Program Office (ODPO) completed the installation of the Meter Class Autonomous Telescope (MCAT) on Ascension Island [1,2,3]. In 2017, MCAT was dedicated to Eugene Stansbery, thus formally named the Eugene Stansbery MCAT, the ES-MCAT, or simply MCAT. This is a 1.3m optical telescope designed with a fast tracking capability for observing orbital debris at all orbital regimes (Low-Earth Orbit (LEO) to Geosyncronous (GEO) orbits) from a low latitude site. This new asset is dedicated year-round for debris observations, and its location fills a geographical gap in the Ground-based Electro Optical Space Surveillance (GEODSS) network. MCAT is well suited for targeted campaigns and surveys for statistically characterizing the debris environment in Earth orbit.

Since 2013, NASA's ODPO has also had extensive access to the 3.8m infrared UK Infrared Telescope (UKIRT) , located on Mauna Kea. At nearly 14,000-ft, this site affords excellent conditions for collecting both photometry and spectroscopy at reflected near-IR (0.9 – 2.5μm SWIR) and thermal-IR (8 – 25 μm; LWIR) regimes, ideal for investigating material properties as well as thermal characteristics and derived sizes of debris.

For the purposes of understanding orbital debris, taking data in both survey mode as well as targeting individual objects and break-up clouds for more in-depth characterizations are desired. With the recent break-ups of Briz-M rocket bodies and historical break-ups of Titan Transtage rocket bodies, we have collected a suite of data in the optical and near-infrared of intact rocket bodies and debris to better understand orbital debris.

A break-up at GEO of a Briz-M rocket occurred in January 2016, well timed for the first remote observing survey-campaign with MCAT. Access to the 3.8m UKIRT telescope also allowed for investigating this break-up in the near-infrared at wavelengths where certain materials may be significantly more reflective than the optical regime, allowing for the potential detection of a smaller population of debris. In addition, a suite of reflectance spectroscopy in the near-IR to Short Wave IR (NIR/SWIR) (0.8-2.5 μm) and thermal-IR, or Long Wave IR (LWIR from 8-15 μm) was taken of tank debris associated with Briz-M rocket bodies, as well as comparison Briz-M intact rocket bodies. The NIR/SWIR spectra are reported here.

Similar data sets of Titan intact and debris fragments, as well as of GEO-Transfer Orbit (GTO) objects Ariane 2 and 3 rocket bodies have also been collected. Analysis of the data are discussed herein.

2 ES-MCAT TELESCOPE

2.1 Eugene Stansbery-MCAT Telescope

The ES-MCAT, or MCAT telescope is a 1.3m f/4 visible

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telescope, sensitive from 0.3 to 1.06 µm. Equipped with a 4k x 4k Spectral Instrument imaging camera, it has a 41′ x 41′ field of view, Sloan Digital Sky Survey (SDSS) g′r′i′z′ filters, and Johnson/Bessell BVRI filters,. MCAT is capable of fast tracking for observing at any orbital regime. Located on Ascension Island in the middle of the Atlantic Ocean at nearly 8° S latitude, it is also well suited for orbital inclinations down to and including Low Inclination LEO (i.e. LILO).

With the prime purpose of MCAT to conduct surveys of the GEO population, it is capable of TDI (Time Delay Integration) and tracking at a user-defined non-sidereal rate. MCAT can also track TLEs (Two Line Elements) of specific objects in the SpaceTrack.org catalogue to characterize them through photometry, astrometry, and orbital elements. Currently, standard GEO survey modes assume circular orbits, but investigations of GEO populations with respect to eccentricity are anticipated for MCAT's future.

With installation completed mid-2015, MCAT is in its engineering phase of operations, undergoing extensive algorithm testing, thresholding, and verification of all systems [1]. However, with the GEO survey and Object Tracking modes working well, a suite of observations of the early 2016 Briz-M Breakup were collected. Testing and vetting of the data reduction algorithms necessary to complete the data analyses is currently underway.

2.2 UKIRT Telescope

The United Kingdom Infrared Telescope (UKIRT), is a 3.8m infrared telescope, with capabilities in reflected-infrared (IR), including near-IR (NIR, 0.86-1.4 µm), Short Wave IR (SWIR, 0.85 – 3 µm) and mid-wave IR (MWIR, 3 – 5 µm), as well as the long-wave IR (LWIR, 8 – 25 µm), 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 vapour 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 infrared observations, especially in the thermal bands, but also greatly improves observations at NIR/SWIR where telluric water vapour (from the atmosphere) contaminates specific bands near 1.4 and 1.8 – 2 µm. Seeing values, an indication of atmospheric turbulence, are < 0.55-0.6 arcsec in NIR/SWIR during ~70% of the year and can be as low as < 0.2 arcsec in any of these bands on an excellent night. Cooling of the primary mirror greatly enhances UKIRT's ability to rapidly achieve stable and excellent seeing.

A dichroic tertiary mirror allows visible light to be transmitted to UKIRT's autoguider. In all cases, UKIRT used an autoguider to lock onto an object directly to ensure it does not drift out of the slit or shift locations appreciably on the array during data collection. Ephemerides for telescope tracking 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.

In the reflected-IR (NIR/SWIR), the UKIRT Imager Spectrometer (UIST) is instrument of choice for spectroscopy. Three NIR/SWIR 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 ensure that a slight amount of motion of the debris within the slit would not significantly compromise the data quality. 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. The telescope 'nods' roughly 6-arcsec up and down the slit for removal of sky emission and thermal effects from the telescope.

The Signal to Noise (SNR) ratio for each object reported herein varies with total integrated exposure time and brightness of the object, but in general reached levels of at least ~100.

Unlike MCAT, which is designed as a fast-tracking telescope surrounded by a fast-tracking dome, UKIRT was originally designed for astronomical targets moving at sidereal rates, and was solely used as such from 1979 until 2013. In 2013, UKIRT's tracking modes were updated to allow for tracking TLEs downloaded through spacetrack.org [5]. However, given the hardware limitations, the capability of tracking objects in geocentric orbits is limited to slower moving objects in Medium Earth Orbit (MEO), GEO, and when nearing apogee, GTOs.

3 DATA REDUCTION

3.1 Visible Imaging from MCAT

All data collected with MCAT undergo standard image processing, including bias subtracting and flat fielding. Calibration standard star fields are observed through a range of airmasses with each filter used, and the appropriate catalogue of standards for the filterset used (e.g. Landolt standard for BVRI filters, and Pan-STARRS standards for the SDSS filters). However, as the data processing pipeline is being vetted now, these data give evidence solely of detection of objects for astrometric purposes, not photometric results. Future data collects will have full photometric calibration standards applied.

3.2 NIR/SWIR spectra from UKIRT

Spectral data taken with the UIST telescope were processed via the Starlink data processing software to apply the standard calibration frames to each observed object, including flats, arc lamps, and G0 or G5 atmospheric standard stars. Arc lamps allow for wavelength calibration. The object spectra in all cases were divided by a nearby G0 or G5 atmospheric standard (generally 5-10° from the object) to account for telluric water features caused by the Earth's atmosphere – thus the y-axis label of 'Relative Reflectance'.

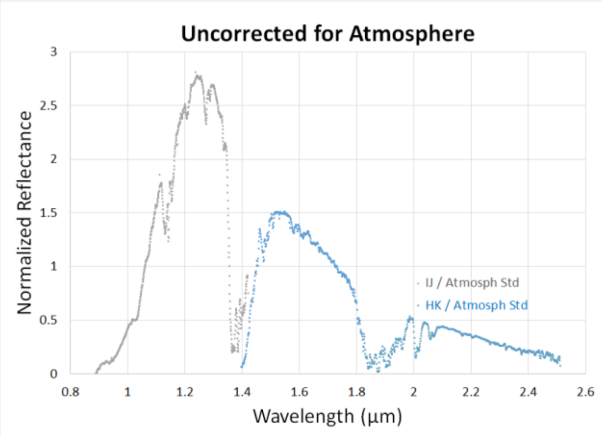

Figure 1: The spectrum above is bias and dark corrected as well as wavelength calibrated, but not yet ratioed to the nearby atmospheric standard star. The atmospheric standard is needed to correct for the strong telluric water vapour that absorbs at ~1.35–1.4 μm and ~1.8–2 μm windows. Because all target objects reflect solar light, the signature of solar spectrum must be ratioed out as well to allow the absorption features purely from the object to be disentangled from the raw spectra. Choosing a G0-G5 atmospheric standard accounts for both effects.

By choosing solar-like G0 or G5 stars, one removes the overall shape of the solar-like spectrum, as seen in Fig. 1, which is evident in all uncorrected spectra, by normalizing the object spectrum by the atmospheric standard. Specifically, this eliminates the variation in reflectance due to the solar spectrum not being a wavelength neutral illumination source. Ratioing thereby reveals the reflective response due simply to the materials comprising the object observed. This also removes much of the contamination from telluric water vapour (in the atmosphere). A suite of true solar analogue stars taken with the same set of grisms as the objects can be used to remove fine features not accounted for by a subset of the G0 or G5 atmospheric standards. An atmospheric standard was also taken within 5 degrees of each solar analogue star, and equivalent calibrations applied.

While this procedure is generally very effective at accounting for shape of the solar spectrum, the contamination from telluric (i.e. atmospheric) water

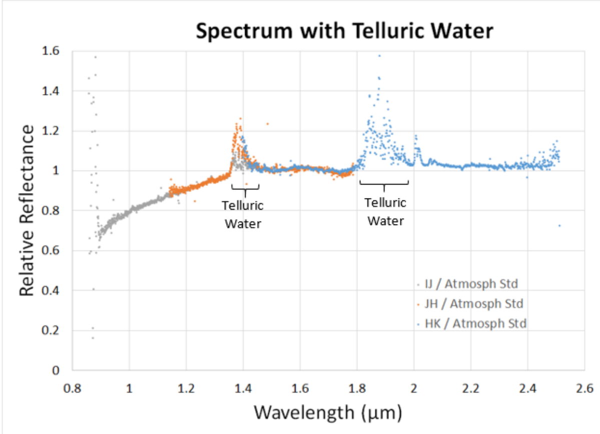

Figure 2: After ratioing with the atmospheric standard, the features of the solar spectrum and most, but not all of the effects from the atmosphere are addressed. However, often telluric water vapour in the Earth's atmosphere often remains. Data below clip these regions of noise.

vapour is not always fully removed – this effect is seen most strongly at ~1.35–1.4 μm and ~1.8–2 μm in the UIST spectra (Fig. 2). When the telluric features are not sufficiently removed by the data reduction procedures, those data points are deleted from the overall spectra and are seen as 'gaps' in the completed spectra shown below.

In all cases, the IJ (as grey dots in the plots) and HK (blue dots) grism spectra are shown. In only one case was a portion of the JH (red dots) included where the SNR of the JH spectrum in that case exceeded the HK SNR from 1.4 – 1.8 μm.

4 DATA ANALYSES AND RESULTS

UKIRT NIR/SWIR spectral data were collected with UIST in spectroscopy mode in April 2015, October 2015, and Sept 2016 on a suite of rocket bodies and debris, including Titan rocket rodies, Briz-M rocket bodies, and Ariane (2 and 3) rocket bodies (Table 1). To date, Briz-M and Titan rocket bodies have broken up in deep space orbits. GTO orbiting Ariane rocket bodies have produced debris in deep space orbits as well, causing (in some cases) debris fragments that are in the catalog and correlated with their parent bodies. Notably, based on NASA's Standard Satellite Breakup Model, the vast majority of debris fragments are too small to be catalogued and tracked by the Space Surveillance Network.

Spectra comparing known intact rocket bodies with debris or fragments of rocket bodies that have broken up catastrophically should give insight into the material surface properties of the fragments, and is hypothesized to support identification of the parent body. The data shown here support this hypothesis.

Table 1: UKIRT Observations with UIST Spectrometer

SSN	NAME	DATE of OBS
3692	Titan 3C Transtage R/B; Debris Parent Body	2015 Oct 10
8832	Titan 3C Debris	2015 Apr 20
5589	Titan 3C Transtage R/B	2015 Oct 12
39376	BrizM R/B (6)	2016 Sep 30
33598	BrizM R/B (8)	2016 Sep 30
36360	BrizM Debris tank	2016 Sep 7, 30
20127	Ariane 3 Debris	2015 Oct 12
26729	Ariane 2 Debris	2015 Oct 12

Figure 3: Titan Transtage rocket body test article, recently moved to NASA Johnson Space Center for studies by NASA's Orbital Debris Program Office. Note that the majority of the original surface is painted white with much of the yellow primer paint of the rocket's nozzle now weathered away, exposing the original green and blue glass frit surfaces beneath.

4.1 Titan Rocket Bodies – Intact and Debris Fragments

In 2016, NASA's Orbital Debris Program Office procured the Titan Transtage test article that was previously held at the 309th Aerospace Maintenance and Regeneration Group (colloquially known as The Boneyard) at Davis-Monthan Air Force Base in Tucson, Arizona, USA (Fig. 3). A suite of laboratory spectral measurements and analyses are being conducted by NASA's Orbital Debris Program Office (ODPO) that will allow a comparison of known materials properties with spectral and photometric data acquired with telescopes on Titan intact rocket bodies and associated debris that have been exposed to the harsh environment of space. Future work will investigate effects from space weathering on materials to better quantify the comparison between laboratory and telescopic data.

Titan rocket bodies, approximately 10-feet wide by 15 feet long, are comprised of a cylindrical monocoque aluminum structure, consisting of a control module (forward) and a propulsion module (aft). Space-rated white paint coated the structure (Figs. 4 and 5). The asymmetric fuel and oxidizer tanks were exposed to the engine plume and space environment and exhibit painted and foil insulation for the long-duration missions flown. Twin liquid rocket engine nozzles feature blue glass frit and green painted surfaces. The Transtage test article currently being examined by NASA's ODPO was overpainted with non-space rated aluminum paint (structure) and yellow primer (nozzles) (see Fig. 3). However, the ODPO has collected spectral data on the underlying, original paints and coatings sufficient for future analyses.

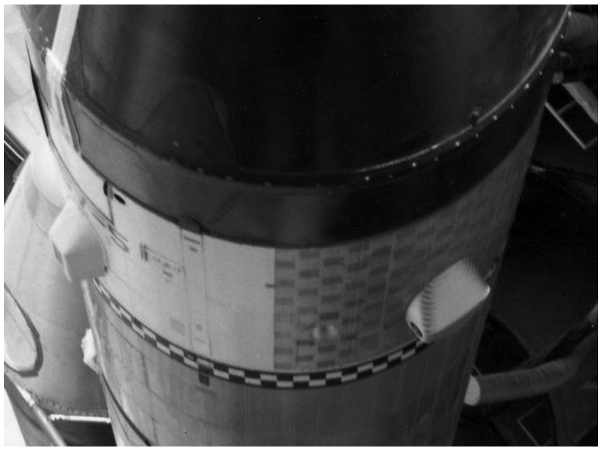

Figure 4: The Titan IIIC-7 Transtage R/B, clearly illustrating the white paint scheme and passive thermal control checkerboard.

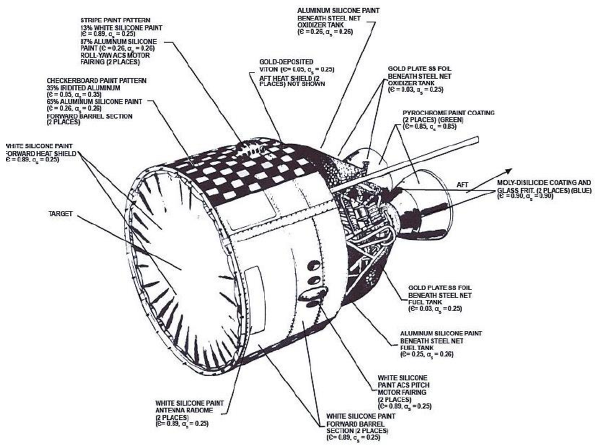

Figure 5: Nominal surface optical properties of an early model Titan Transtage upper stage using passive thermal control checkerboard. (Adapted from figure in [6]). Later Transtage models adopted an active thermal control system in lieu of the passive checkerboard, and the last Transtages eliminated thermal control altogether. These latter stages were painted white.

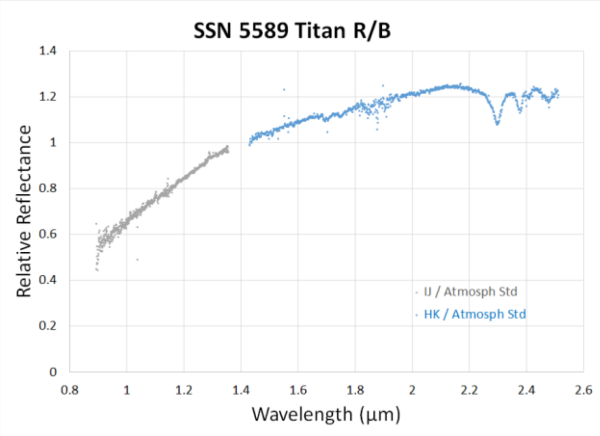

Figure 6: UIST spectrum of intact Titan rocket body SSN 5589. Like SSN 3692 and 8832 (Figs. 7 and 8), the overall shape is indicative of aluminum. Absorption features at ~2.3 and 2.4µm from a C-H signature are evident.

Two recorded breakups of Titan Transtage rocket bodies at GEO are known, as well as one in GTO (GEO Transfer Orbit) and one at LEO. Transtage 3C-5 (SSN 3432, 1968-081E) fragmented on 21 February 1992 after 23.4 years on-orbit. Transtage 3C-17 (SSN 3692, 1969-013B) fragmented on 4 June 2014 after 45.3 years on-orbit. The GTO and LEO events occurred on day of launch, likely due to propulsion events. Causes of on-orbit breakups are currently unknown, but suspected causes include explosions of unspent hypergolic propellants, or a collision with an unknown object.

Data were taken of an intact rocket body (SSN 5589, 1971-095C; Fig. 6) to compare with the parent rocket bodies of one of the known Titan IIIC Transtage GEO break-ups (SSN 3692, Fig. 7) as well as with mission related debris SSN 8832 (1976-023).

SSN 8832 is a Titan 3C Transtage debris object observed

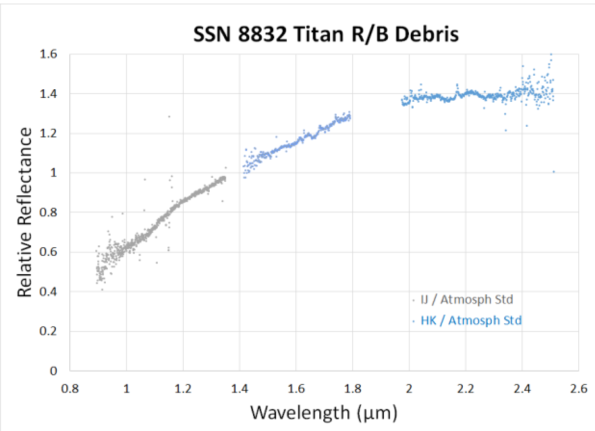

Figure 8: UIST Spectrum of the parent Titan rocket body SSN 8832. [3] When fit with a spectral unmixing model, the predominant material responsible for the shape of the spectrum is anodized aluminum.

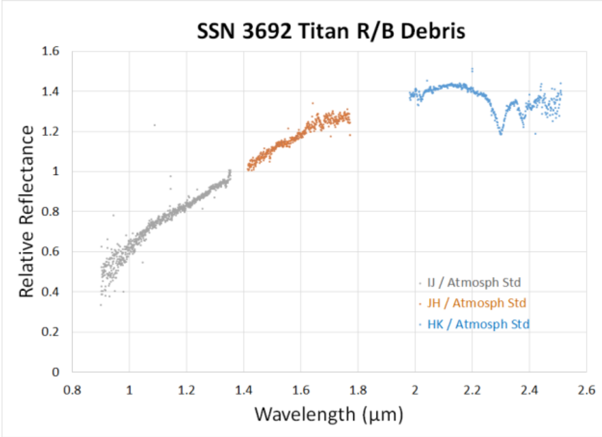

Figure 7: UIST Spectrum of the parent Titan rocket body SSN 3692 that fragmented in 2014. Again, the two most prominent absorption features at about 2.3 and 2.4 µm are attributed to C-H in organics.

in April 2015. This object is mission related debris (MRD), an apparently intact object (not fragmented debris) associated with the deployment of the mission's payload in GEO. Spectral unmixing of similar UIST spectra reveal that the predominant material comprising the spectrum is anodized aluminum.

In June 2014, the break-up of Titan 3C-17 (SSN 3692) was first discovered. Observation with the UKIRT telescope were collected the following year (October, 2015). Evident in the spectrum are two very prominent features near 2.3 and 2.4 µm believed to originate from C-H in organics, possibly from the painted surface [7].

The overall shape of the spectrum of SSN 5589, an intact Transtage rocket body, is quite similar to the Transtage parent fragment SSN 3692. They are clearly of the same class of materials, suggesting again a predominantly anodized aluminum signature, similar to SSN 8832.

The same absorption features from C-H in organics at 2.3 & 2.4 µm are evident in both SSN 5589, and to SSN 3692. Interestingly, MRD debris SSN 8832 does not have predominant organic absorption features at these wavelengths (Fig. 8), More analyses are needed to fully explain this difference.

4.2 BRIZ-M Rocket Bodies – Intact and Debris Fragments

Like the Titan rocket bodies, some Briz-M rocket bodies have also fragmented in GEO. In 2016, MCAT was able to track the parent body of a Briz-M object shortly after a known breakup occurred and collected photometry of expected orbits of the debris fragments. Reports of the break-up indicated at least 10 pieces orbiting close to the parent body. NASA Standard Satellite Break-up Model (SSBM) simulations of a generic object in LEO that experiences a collision or break-up event will evolve from a single source (the intact parent body) to a complete ring of debris encircling the Earth within a few hours to a few days. In GEO, however, the evolution takes longer, evolving to a complete ring within 1-2 weeks typically (Fig. 9). Titan and Briz-M break-ups shown herein have occurred in GEO. While it takes longer for a GEO breakup to disperse (compared with LEO), ideally, observations taken as quickly as possible after breakup are desired to correlate daughter fragments to their parent source.

For the break-up that was observed by MCAT in January 2016, observations commenced within 12 days of the public announcement of the break-up. Ten-second exposures in the Sloan r′ filter were taken (Fig. 10).

In addition, 15 nights of imaging data were taken with the UKIRT Wide Field Camera (WFCam) beginning early February, 2016. Analyses are now underway for both the MCAT and UKIRT data to determine whether any uncatalogued daugher fragments were observed and can be associated with the parent body. Further details of how the NASA SSBM was used to estimate where in the sky to conduct the surveys can be found in [8].

A pristine Briz-M rocket launched has several stages (Fig. 11). The stage observed may either be partially painted black and white, and partially exposed metal surface, or be fully white.

Because of the painted surfaces of the Briz-M, one might expect to detect evidence of the organic C-H signatures typically originating from organics and/or paint at the 2.3 and 2.4 µm bandpasses, as can be seen in the intact Titan rocket body (SSN 5589, Fig. 6) and the parent fragment of the Titan rocket body SSN 3692 (Fig. 7). However, the spectra of two different intact Briz-M rocket bodies (SSN 39376, 2013-062B and SSN 33598, 2009-007D) are relatively featureless (Fig. 12 and 13), as well as displaying a fairly flat slope from 1.4 – 2.5 µm, with just a slight rise from the very near infrared (0.86 µm) to about 1.2 µm.

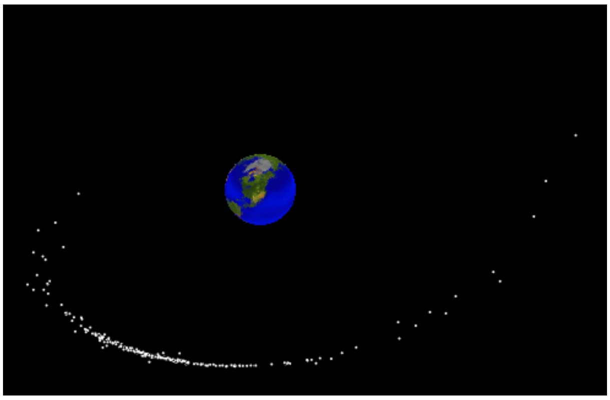

Figure 9: Evolution of a debris cloud in Geosynchronous orbit as modelled by the NASA SSBM. The location of the parent fragment is within the highest density arc. The evolution shown here would occur in ~a few days, and would evolve to a full ring within ~1-2 weeks.

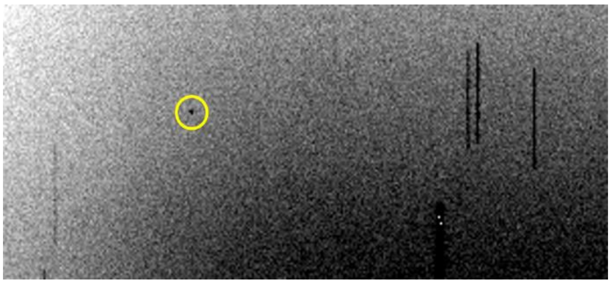

Figure10: Subframe image of the parent fragment of a Briz-M breakup observed by the NASA ES-MCAT telescope in January 2016 using the Sloan r′ filter.

Figure 11: The Briz-M Rocket body [9], believed to be painted mostly white with a black portion near the end of the rocket body, and a section of exposed aluminium. The material types illuminated during the observations are expected to affect the overall shape of the spectrum, which is dependent upon the stage of the rocket body that is observed (e.g. the central portion fully painted white vs. the lower stage with a potential aluminum or carbon or black-MLI or paint signature).

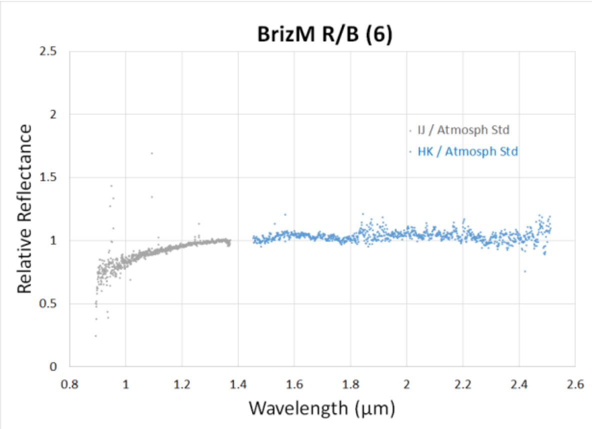

Figure 12: Spectrum of SSN 39376, a Briz-M rocket body, nearly flat and featureless, much as one would expect for a flat-white painted surface.

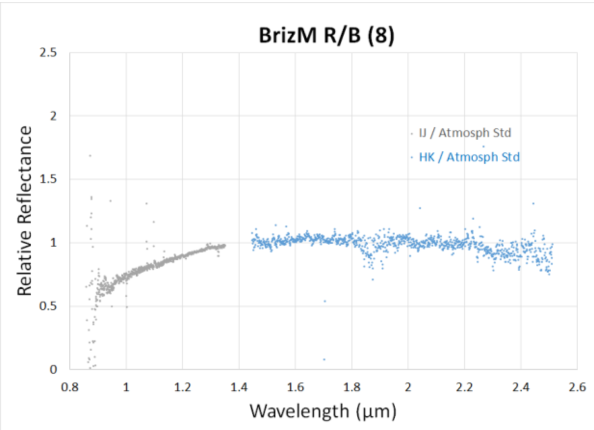

Figure 13: Spectra of SSN 33598 Briz-M rocket body is also flat and featureless, much like the debris spectrum below.

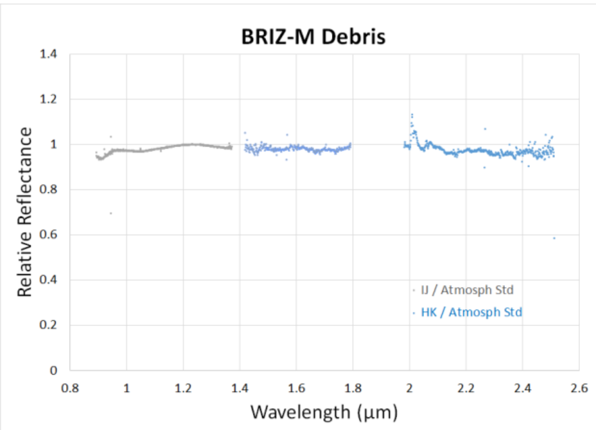

Figure 14: Spectrum of Briz-M debris (tank) is similar to the intact rocket bodies shown above with the exception that the gentle slope from 0.8 to 1µm is seen in the spectra of the intact bodies, but not in the tank's spectrum.

In comparison, a Briz-M debris object (tank) launched in 2010 shows a similarly flat and featureless spectrum, though without the slight downturn on the shortward side of the spectrum from 0.85 – 1.2 µm (Fig 14). The subtle differences are likely due to the differing illuminated materials of the rocket body versus the tank, which requires spectral unmixing to confirm. However, this infers again that the overall shape of the rocket bodies and debris tanks is quite similar and again supports the notion that spectra could be used as support for determining whether an observed object is likely to belong to a particular sub-class of objects, namely, Briz-M bodies as shown here.

4.3 Ariane Rocket Bodies – Intact

To further test whether the Ariane classes of rocket bodies (Fig. 15) have distinctly different spectral shapes and absorption features, a set of Ariane rocket body data were collected to compare with the Titan and Briz-M rocket bodies.

The objects observed include an Ariane 2 (SSN 26729, 1989-006G) and an Ariane 3 (SSN 20127, 1988-063E) rocket body, both intact objects in GTO (Fig. 16). As UKIRT was designed for observing at sidereal rates, an upgrade to the software was required to track Earth-orbiting objects. As the hardware is not suited for the speeds required at LEO, the Ariane targets were observed while they were near apogee when their motion through the sky was minimized.

Figure 15: Left: Ariane 44LP display article at Space Center Bremen. [10].

Right: Ariane third stage being prepared for transport to French Guiana for launch. [11] Note the lateral surface of the third stage is indicated by brown insulation; the insulation is coated with a 1-2 µm layer of white paint, but retains the appearance of the insulating foam.

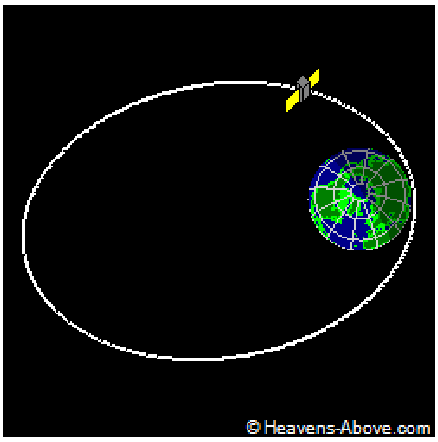

Figure 16: GTO orbit of Ariane R/B, SSN 26729. [12]

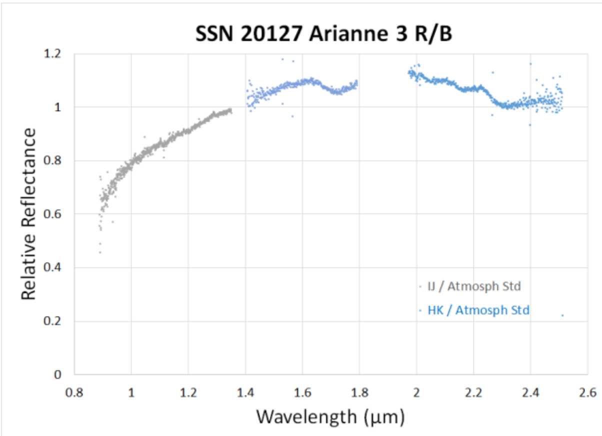

Figure 17: Spectrum of SSN 20127, Ariane-3 intact rocket body. The shape of the rise in reflectivity from 0.85 µm up to 1.5 µm, and then a dip centered at 1.7 µm matches the general spectral shape of aluminum well.

A third class of rocket bodies, the Ariane, demonstrates that again for the sample shown, the spectra are quite similar to each other, but dissimilar from the Transtage and Briz-M classes.

Shown here are an Ariane 3 (SSN 20127; Fig. 17), and an Ariane 2 (SSN 26729; Figs. 18 and 19). The latter two are the same Ariane 2 rocket body, and demonstrate the slight variability for a given object that may be due to variations with the rotational/tumble phase. In all three spectra, the general shape of the spectrum, especially from 0.85 to 1.8 µm, is the same general shape created by aluminum [13]. Further spectral studies and associations with their rotational state are required for confirmation of these effects.

The Ariane 2 (SSN 26729) was launched by France in January, 1989, while the Ariane 3 (SSN 20127) was

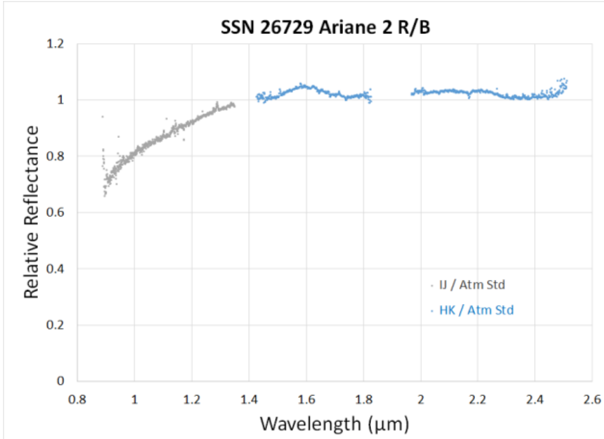

Figure 18: Spectrum of SSN 26729, Ariane-2 intact rocket body [3]. Like SSN20127, the shape of the spectrum short-ward of 1.8 µm looks very reminiscent of aluminum.

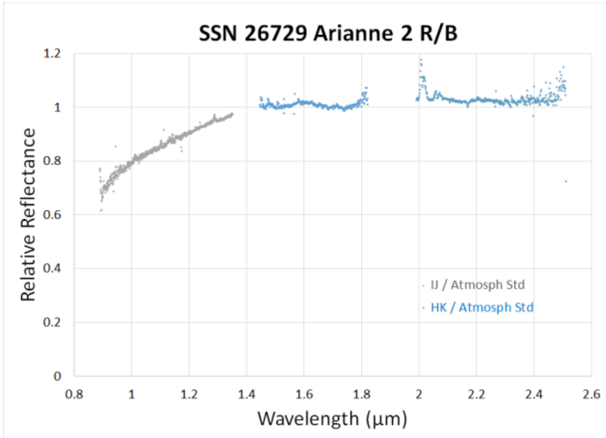

Figure 19: Same object as Fig. 18 above, but taken at a different time. The slight differences in the two spectra of this object demonstrate how a given object's signatures can vary with time and rotational/tumble phase.

launched in July, 1988. However, care must be taken in understanding the variations in the spectrum with rotational/tumble phase, as shown here, to ensure one does not take single snapshots of their spectra in time.

5 DISCUSSION

Debris modeling suggests that breakups in highly elliptical orbits such as Ariane orbits at GTO may be a reservoir of small particles passing through LEO. While orbital mechanics dictates that their passage time in any given orbit within LEO (here considered to be top of atmosphere to 2000 km altitude) is small, their orbital lifetimes are sufficiently long that they can form an important component to the total debris environment at GEO as well. Highly elliptical orbits pose difficulties to the US Space Surveillance Network (SSN) and fragmentations in elliptical orbits typically result in few objects entering the publicly available US Satellite Catalog. Analysis [14] of radar and optical data suggest that several objects in transfer orbits have fragmented but have not been generally recognized. Some, such as Titan Transtage 3C-8 (1965-108A, SSN 1863) have now been included in standard tables of breakups; however, these provisional fragmentations include Ariane 1-4 third stages associated with international designators 1983-105, 1984-023 and -081, 1988-098, and 1989-027. Additionally, ODPO analyses indicate that Arianes associated with international designators 1988-081 and 1992-072 may have fragmented, based on cataloged debris.

A means of assessing then nature of these provisional breakups is provided by spectral analysis. If debris objects associated with the parent bodies display metallic signatures, they may have broken up in a manner similar to the Transtage 3C-8. If, however, the cataloged debris are Ariane third stage cryogenic insulation, debris production mechanisms other than a fragmentation may be responsible. Spectroscopy may provide sufficient information to discriminate metallic from dielectric debris materials.

6 CONCLUSIONS

Spectra of three disctinctly different rocket body classes, including Titan, BRIZ-M, and Ariane rocket bodies support two important assumptions that can aid in characterizing and correlating human-made objects. First, that the general shape of the NIR/SWIR spectra of a given class of rocket bodies is similar from one object to the next, but dissimilar from one class of rocket bodies (e.g. Titan) to another (e.g. versus Briz-M or Ariane). This is based on the presumption that a given rocket body class will be be similarly painted, or have similarly exposed aluminum or other surfaces (e.g. nozzles or exposed tubing). Furthermore, the surface materials of the object in question can be analyzed by fitting the spectrum taken with a telescope of the object in space, with a spectral unmixing model using a suite of laboratory-based individual materials [7, 11].

Second, the signatures observed in the overall shape of the spectrum of an intact rocket body of a given class (e.g. Titan intact) can be used as a baseline to identify potential fragments associated or correlated with the fragments of a similar rocket bodies (e.g. Titan debris) that has broken up catastrophically. In the cases shown above, for Titan intact versus debris as well as for BRIZ-M rocket bodies versus tank debris, this assumption holds.

Analyses of NIR/SWIR spectra can give insights into and support the identification of the parentage of (fragmented) rocket body debris by investigating the surviving material‘s surface properties and comparing it with that of similar intact rocket bodies.

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8 REFERENCES

1. Lederer, S.M. et al. (2013) The NASA Meter Class Autonomous Telescope: Ascension Island. *AMOS Tech. Conf. Proceedings*.

2. Lederer, S.M. et al. (2015) Deploying the NASA Meter Class Autonomous Telescope on Ascension Island. *AMOS Tech. Conf. Proceedings*.

3. Lederer, S.M. et al. (2016) NASA's Orbital Debris Optical and IR Ground-based Observing Program Utilizing the MCAT, UKIRT and Magellan Telescopes. *AMOS Tech. Conf. Proceedings*.

4. http://www.ukirt.hawaii.edu/observing/taustats.html

5. Lederer, S.M. et al. (2014) NASA Newest Orbital Debris Ground-based Telescope Asset: UKIRT. *AMOS Tech. Conf. Proceedings*.

6. Sousek, D.D., "Orbital Simulation of the Titan III Transtage Spacecraft". Proc. IES **12** (1966): 561-76.

7. Abercromby, K., B. Buckalew, P. Abell & H. Cowardin (2015). Infrared Telescope Facility's Spectrograph Observations of Human-made Space Objects. *AMOS Tech. Conf. Proceedings.*

8. Frith, J.M. et al., Observing Strategies for Focused Orbital Debris Surveys using the Magellan Telescope. (2017) *Proc. Of the Seventh European Space Debris Conference, Darmstadt, Germany*.

9. **http://spaceflight101.com/re-entry/2015-075b-briz-m-break-up/**

10. http://space.skyrocket.de/doc_sdat/sbs-1.htm

11. C. Bonnal (CNES), personal correspondence (PA-M), 9 April 2017.

12. www.heavensabove.com

13. NASA JSC Spacecraft Materials Spectral Database, NASA JSC, 2001.

14. Stringer, M.E., B. Teets, and R. Thurston. "Identifying Satellite Launch Original Examples". Proc. 4th US/Russian Space Surveillance Workshop. University of Virginia Dept. of Astronomy (2000).