Characterization of spacecraft materials using reflectance spectroscopy

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ABSTRACT

Materials interact with light in a unique manner due to their individual elemental composition. Elements emit different light energies that fall within the electromagnetic spectrum, therefore corresponding to a specified wavelength per element. The reflectance spectrum produced from common spacecraft materials can be used to assist with remote orbital debris material identification techniques and can be further related to debris albedo and size. Materials used in aerospace design, such as aluminum alloys, stainless steels, ceramics, silicone paints, and solar cells, have been substantially characterized using reflectance spectroscopic techniques. An Analytical Spectral Device (ASD) was utilized to perform characterization on various spacecraft and rocket body structures by producing a spectrum relatively unique to a material from its properties in response to light. The materials used as specimen for this investigation specifically belong to a Titan IIIC Transtage test article rocket body, stainless steel radar calibration spheres, and solar cells used to construct a Hughes/Boeing HS-376 spacecraft. The spectrum results of said materials are presented in the subsequent work to enhance current spectroscopic data of interest within aerospace and orbital debris communities.

1. INTRODUCTION

The space industry has succeeded in launching various spacecraft into Earth orbit to explore the nature of our space environment. This originated with the launch of the first satellite, Sputnik, on October 4, 1957 [1]. Since then, multiple space missions have been executed, leaving our near-Earth space environment populated with spacecraft. However, such hardware is continuously faced with potential collision, explosion, or degradation events when in orbit for extended duration. These events cause the generation of orbital debris. Orbital debris is defined as all man-made objects remaining in Earth orbit that are not functional and no longer serve a useful purpose [2]. Orbital debris outweighs the population of all objects orbiting Earth. Of the 18,921 total objects in orbit as of 5 July 2018, fragmentation debris dominates that value with a total of 10,366 objects, compared to the number of spacecraft (4,618), mission related debris (1,987), and rocket bodies (1,950) in orbit [3]. Gathering knowledge of cataloged debris objects advances the aerospace community in characterizing materials of orbital debris particles [4]. Material characterization of orbital debris is necessary to advance the assessment of risk imposed on functional spacecraft and is beneficial in understanding fragmentation events if the inspected debris can be associated back to its parent object. Furthermore, material identification of a debris particulate can be used to interpret its albedo which would in turn assist in deducing the optical size of that object remotely [4, 5]. Data in this study holds significance to the orbital debris and aerospace communities with the presented reflectance spectroscopic measurement evaluations taken on a selection of materials used in space hardware that populate orbital debris fragmentations.

Reflectance spectroscopy is a powerful characterization tool that has aided in micrometeoroid and orbital debris (MMOD) material identification, particularly with asteroid examinations beginning in the 1970's [6]. The 1990's saw its application expanded into characterization of orbiting spacecraft materials [6]. Ground based spectral measurements are valuable references that benefit remote optical observations when analyzing debris material composition, object position, and movement in orbit. Reflectance spectroscopy has proven to be a viable tool in providing the aerospace industry with detailed characterization data from materials often used in space vehicle design such as iridited aluminum, stainless steels, glass, gold, various silicone paints, and a variety of solar cells [7]. Spectroscopic measurements acquired on associated spacecraft materials in the lab can then be compared to orbital debris spectroscopic or photometric data obtained remotely from telescopic instrumentation.

The following research primarily seeks to enhance current reflective response knowledge of spacecraft material surfaces through the collection of spectroscopic measurements. Different classifications of materials that are significant to the aerospace community have been analyzed and their reflectance spectroscopic signatures are presented in this work. The data collected in this study serves to augment information currently stored on the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Spacecraft Materials Spectral Database [8]. Additionally, the author is investigating material taxonomy with the volume of data currently stored in the database to help accelerate computer processing if data can be sampled from material families rather than analyzing data samples individually.

2. INSTRUMENTATION AND SET-UP

Data was attained using an ASD FieldSpec® Pro where light was collected through a fiber optic cable and delivered to the spectrometer detector which converted photons to electrons and furthermore to digital numbers to produce the acquired spectral data. The ASD utilized has capability of measuring reflected light within a full range between visible and near infrared regions (350-2500 nm) [9]. The instrument has a spectral resolution of a 3 nm bandwidth at a 700 nm wavelength within the visible and near infrared (VNIR) region (300-1000 nm) and a spectral resolution with a bandwidth of 10 nm at 2000 nm wavelengths within infrared regions of 1000-2500 nm [9]. The system comprises 512 channels within VNIR and over 2000 channels in infrared which are used to deliver the full range spectrum plot for a given material specimen [9]. Data was then transferred and stored on a computer system where in-house developed software was used to produce the absolute spectral reflectance material data plots.

Instrumentation set-up involved a quartz lamp illumination source opposite to the ASD's fiber optic cable secured within a pistol grip that were both perpendicularly oriented at approximately 45° with respect to the material target surface and 90° with respect to each other (see Fig. 1). All data readings were taken in a dark lab to minimize light scattering. To receive a calibrated reflectance response, a white Spectralon panel was utilized to provide absolute reflectance measurements. For each spectral reading, the fiber optic detector direction and angle of incidence were modified when testing the material specimen to gain a maximum signal without saturating the system.

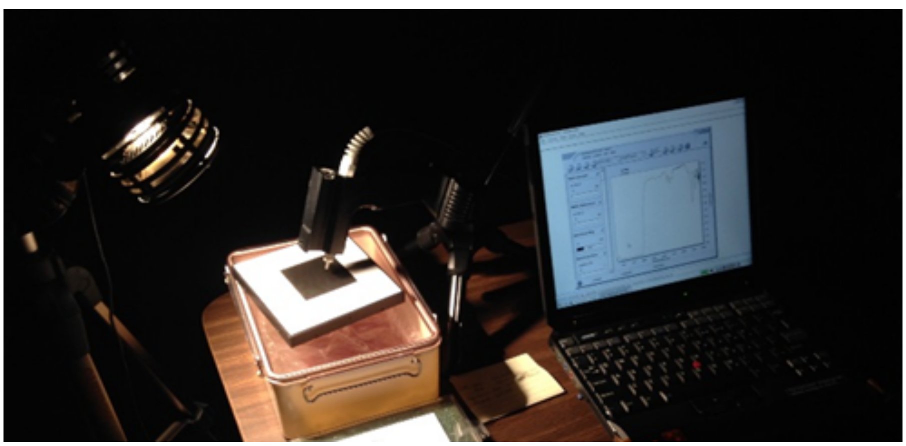

Fig. 1. Lab set-up with light source (left), fiber optic (center), and computer (right).

3. AEROSPACE RELATED MATERIALS

The materials of interest in this study belong to the Titan IIIC Transtage test article, Falcon Orbital Debris Experiment deployable calibration spheres, and HS-376 spacecraft solar cells. Analysis of materials related to the flown Titan Transtage is significant to orbital debris examination due to its discovered fragmentations after undergoing breakup events in low Earth orbit (LEO), geosynchronous Earth orbit (GEO), and GEO transfer orbit (GTO) throughout its time in flight [10]. Due to the large quantities of HS-376 spacecraft models in orbit, acquired spectra on its solar cells provide significant data for the orbital debris and aerospace communities when examining solar cell fragmentation and debris. It was also imperative that the stainless steel calibration spheres undergo initial spectroscopic inspection to produce pre-flight material characterization in addition to a recommendation on which spheres produced least variability in reflectance signatures over their entire surface. Many of the materials investigated in this work are often used in aerospace design and their obtained spectral signatures will refine previously acquired spectral data while also serving as a future reference tool.

3.1. Titan IIIC Transtage

The Titan IIIC Transtage is an upper stage rocket body belonging to the Titan IIIC launch vehicle [10]. It was developed in the 1960's to lift large or multiple small payloads to specific locations in LEO and GEO [10]. The vehicle was the world's first "space tug" capable of multiple engine restarts and could deliver multiple spacecraft to precise orbits in a single mission [10]. A total of four catalogued fragmentation events have been associated with the Titan Transtage. Transtage 3C-5 (International Designator 1968-081E, U.S. Strategic Command [USSTRATCOM] Space Surveillance Network [SSN] catalog number 3432) fragmented on 21 February 1992 after 23.4 years on-orbit [10]. Transtage 3C-17 (1969-013B, SSN #3692) fragmented on 28 February 2018 after 49.085 years on-orbit [3]. As of 4 July 2017, the 1968-081E breakup had 28 debris pieces associated with this fragmentation [10]. Moreover, the 1969-013B breakup had 18 cataloged debris pieces as of 5 July 2018 that are associated with its fragmentation event [3]. The GTO (1965-108A) and LEO (1965-082DM) events occurred on day of launch, likely due to propulsion-related events [10]. The GTO and LEO events yielded 107 and 472 cataloged debris pieces, respectively, but may have produced significantly more debris than are currently cataloged [3].

A schematic of the Titan IIIC Transtage structure, along with the Transtage thermal control surfaces and coatings of the early flight test vehicle series (vehicles 1-16) are demonstrated in Fig. 2 [11]. A test article of the Titan Transtage, which was discovered in the custody of the 309th Aerospace Maintenance and Regeneration Group (AMARG) in Tucson, Arizona, was deemed comparable to the flown Transtage and worthy of inspection, having 12 different external material surfaces analyzed using reflectance spectroscopy (Table 1). Selected measurement results are presented in section 4.

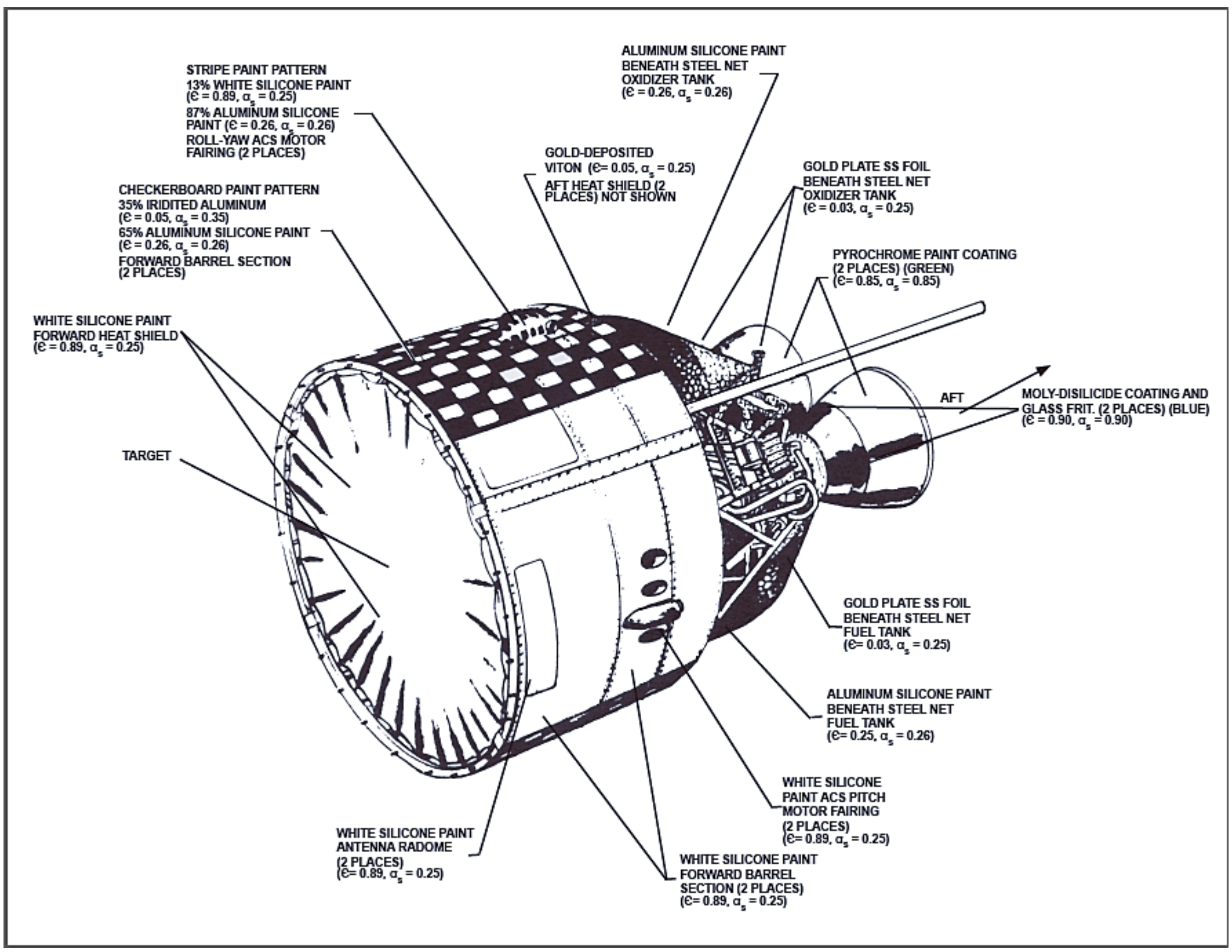

Fig. 2. Schematic of Titan Transtage thermal control structure [11].

Table 1. List of materials taken from the multiple data collects of the Transtage test article. Note twelve materials were analyzed, but only two (denoted with *) are presented in this paper.

001	Blue Glass Frit
002	Dark Checkerboard Locations
003	White Checkerboard Locations
004	Columbium Metal
005	Engine Shroud
006	Exposed Engine Bell
007	Exposed Metal Top
008*	Gold Foil
009	Green Paint
010	Red Paint
011	Strut
012*	White Paint

Analysis of three different data collects was conducted to compare the spectral measurements acquired from the test article [10]. The first data collect was based on 12 of 28 samples removed from the article in Arizona. The second data collect was conducted at NASA JSC after the test article was considered safe for continued analysis [10]. The last data set was a repeat of the same materials analyzed during the second data collect, but each material was cleaned with water or isopropyl alcohol to remove dust/debris/oxidation and to compare how the spectral measurement reflectance properties changed [10]. Data was collected on fragments removed from the test article while in its original location (Fig. 3a), as well as on the structure itself after it had been transported to its location for lab testing in the environmentally controlled NASA Johnson Space Center high-bay (Fig. 3b). The Transtage test article in its condition prior to and post transportation is depicted in Fig. 3a and Fig. 3b respectively.

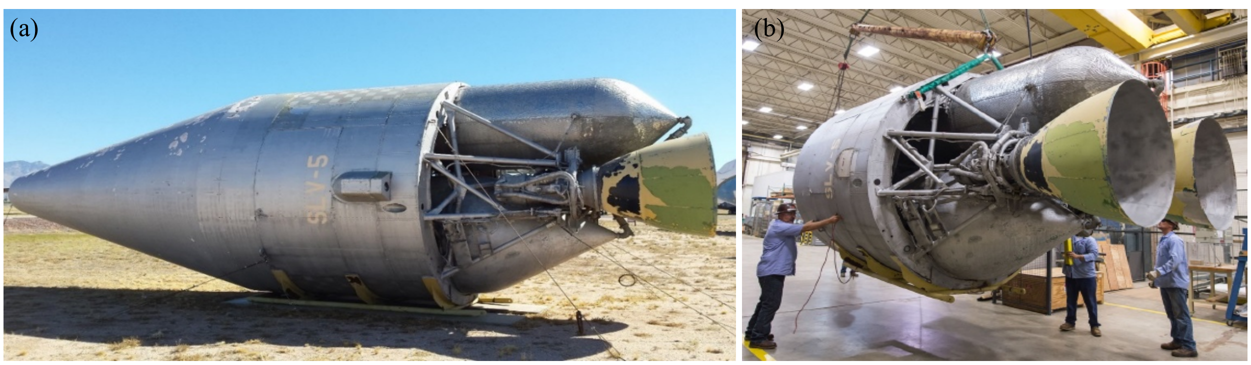

Fig. 3. Transtage test article (a) at its original location and (b) as received for further lab testing [10].

3.2. Radar Calibration Spheres

As part of a collaboration with the U.S. Air Force Falcon Orbital Debris Experiment, NASA's Orbital Debris Program Office provided a pre-flight characterization of ten stainless steel spheres to be used for optical calibration of ground based radar systems. The reflectance spectroscopic data collected on the spheres at every cardinal direction in north and south hemispheres allow for substantial characterization of the flight hardware since material albedo variations may impact brightness and size calculations. Obtaining initial material spectroscopic signature of the metal prior to its launch is relevant since flight duration will alter the slope of the material spectra, particularly within the visible region (350-1000 nm wavelengths) of the spectrum [12]. Previous spectral measurements performed on spacecraft materials pre-flight and post-flight commonly exhibit spectral variations; anodized aluminum absorption features alter, gold materials are apt to redden in color, and white materials tend to appear more yellow or brown likely due to the atomic oxygen and UV exposure throughout their life in orbit [12, 13].

The ten stainless steel spheres were analyzed to provide recommendations on which spheres were best suited to be launched in orbit for calibration of ground-based radar systems. Of the ten spheres, five were 2 cm in diameter (Fig. 4a), and five were 4 cm in diameter coated with an electrodeposited zinc plating (5.08E-4 cm thick) with yellow chromate (Fig. 4b). All test measurements were obtained using reflectance spectroscopy to determine which spheres of the 2 cm and 4 cm groupings produced the most consistent spectral response signatures and would be identified as flight-ready deployable spheres. All spheres were mounted using the same Styrofoam cup seen in Fig. 4a and Fig. 4b.

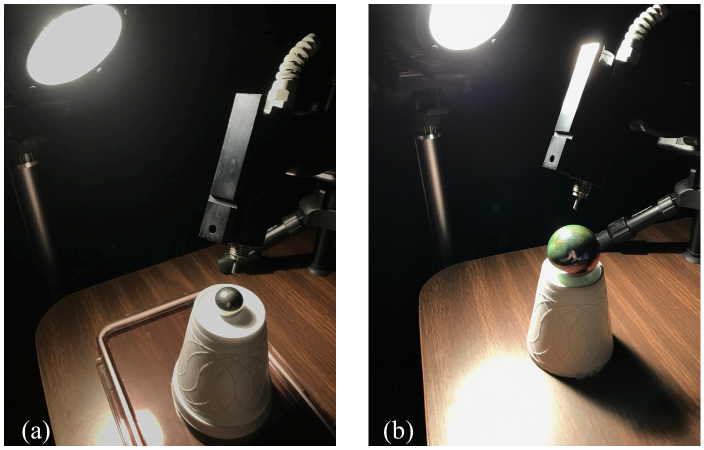

Fig. 4. (a) 2 cm diameter and (b) coated 4 cm diameter stainless steel spheres mounted for spectroscopic testing.

3.3. <u>Hughes/Boeing HS-376 Solar Cells</u>

The Hughes/Boeing HS-376 spacecraft is a 2 m diameter cylinder with simple geometry externally constructed of multiple solar cell arrays which encompass a variety of internal parts to complete the spacecraft system (Fig. 5c). The materials and design used to produce the HS-376 were selected for their near-identical physical characteristics which help constrain albedo and size ambiguity [14]. Characterization of the HS-376 is of particular interest since over fifty of these models have been launched into geosynchronous Earth orbit (GEO) between the years 1980-2003 [14].

The solar cell arrays used on the exterior surface include those of GaAs/Ge (Fig. 5a), $GaInP_2$/GaAs/Ge (Fig. 5b), Silicon K4 3/4 (Fig. 5d), and Silicon K7 (Fig. 5e) cells. GaAs/Ge cells are fabricated as a GaAs device grown on Ge substrate. $GaInP_2$/GaAs/Ge solar cell arrays involve a dual junction n/p device that is grown on an inactive Ge substrate [14]. K7 and K4 3/4 cells are shallow junction n/p silicon cells having a back surface reflector [14]. In addition, K7 solar cells have a back surface field and textured front surface [14].

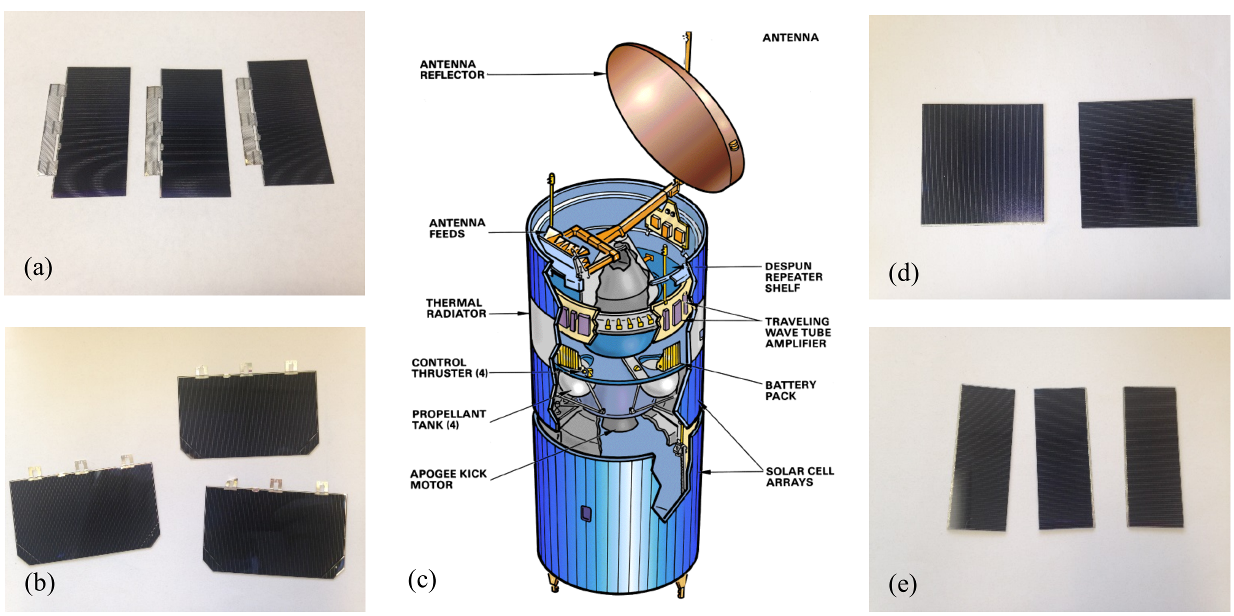

Fig. 5. (a) GaAs/Ge cells (b) $GaInP_2$/GaAs/Ge cells (c) Configuration of Boeing HS-376 spacecraft [15] (d) Silicon K4 3/4 cells and (e) Silicon K7 cells [14].

4. MEASUREMENTS AND ANALYSIS

The following spectral analysis performed used absolute reflectance as a function of wavelength in nanometers (nm). The data presented in the plots below will use a ".mn" extension shown within the legend to represent mean measurements for material samples that were tested over several trials. A minimum of three trials were performed for each target on a specimen and the trials were conducted immediately following one another. Nomenclature for the curves on each plot are designated with a title specific to the material specimen tested shown on each legend. The preceding titles for the Titan IIIC Transtage material sample curves are specified with either "Sample_", "9S_", or "9SClean_" to differentiate between the data collects on samples retrieved from AMARG in Arizona, the test article surface as received at NASA JSC in B9S, and the cleaned test article surface at NASA JSC B9S, respectively. The spectral data collected was output to a laptop computer and was post-processed using in-house developed software to provide the absolute spectral reflectance. All processed data has currently been uploaded to the JSC Spacecraft Materials Spectral Database.

4.1. Titan IIIC Transtage

All 12 materials of the Titan IIIC Transtage test article listed in Table 1 were thoroughly investigated using reflectance spectroscopy, however, data for gold foil and white paint material samples are most worthy of discussion. The spectra plot (Fig. 6) obtained from the gold foil specimen depicts an evident gold/yellow color band gap between 350-600 nm with minor absorption dips present showing slight organic traits at 1150 nm and 1950 nm wavelengths. Often, foil is composed of aluminum coated in oxides to enhance corrosion resistance [16]. It can be deduced that these oxides are potentially responsible for the organic spectral results if the gold foil on the Transtage had these typical properties. The spectrum pertaining to the gold foil reaches above 100% reflectance, suggesting that the material was emitting increased specular reflections and possibly causing laboratory instrument saturation.

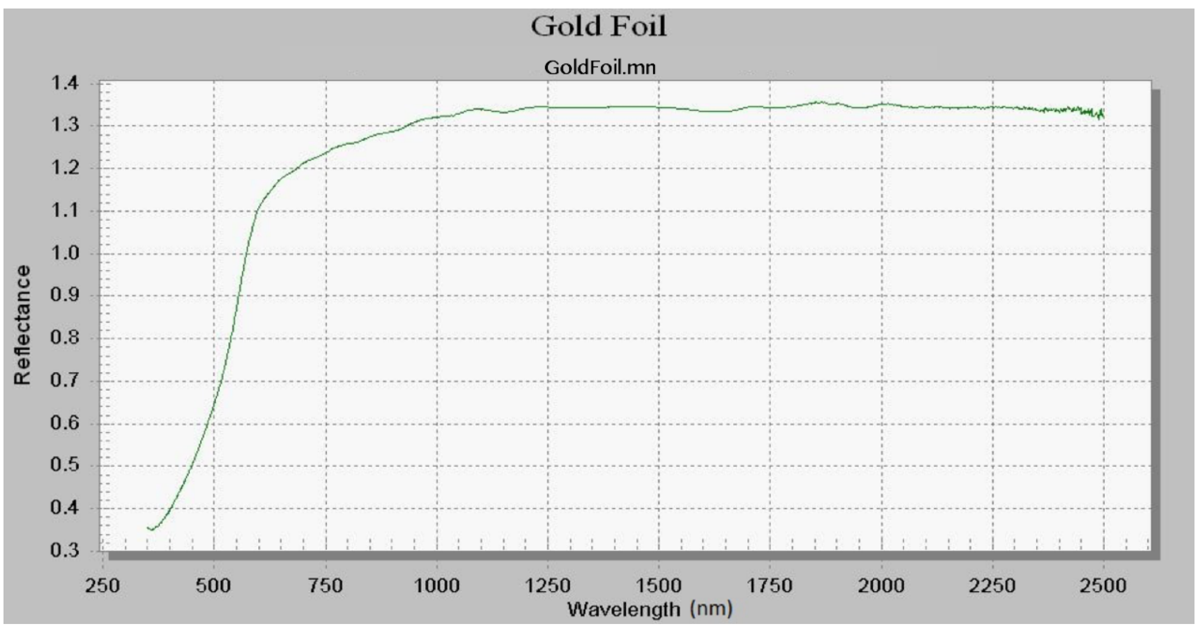

Fig. 6. Reflectance spectrum for gold foil samples taken from Titan IIIC Transtage test article.

Fig. 7 shows spectral data for white paint found on the exterior of the test article. The consistency of features between the multiple white paint spectral readings is sufficient, presenting apparent white band gaps at approximately 400 nm followed by organic features beyond 1100 nm, most likely due to the properties found within the paint on the test article. The white paint sample, "Sample_OrigWhtPaint.mn", showed equal reflectivity measurements as that of the "9S_WhitePaintPort.mn" data curve. The cleaning process significantly increased the reflectance properties for the "9SClean_PortWhitePaint.mn" sample, although minimal effects were seen with the white paint samples taken from the starboard side. Paints often utilize H_2O as a solvent, and O-H\C-H bonds are found in paint binders, which are used to secure pigment and therefore take on polymeric properties [17, 18]. These molecular bonds, or any additional organics discovered within their respective paint compositions, presumably could be responsible for the absorption features beyond 1000 nm. As discussed previously, these samples were examined for further material characterization of the test article.

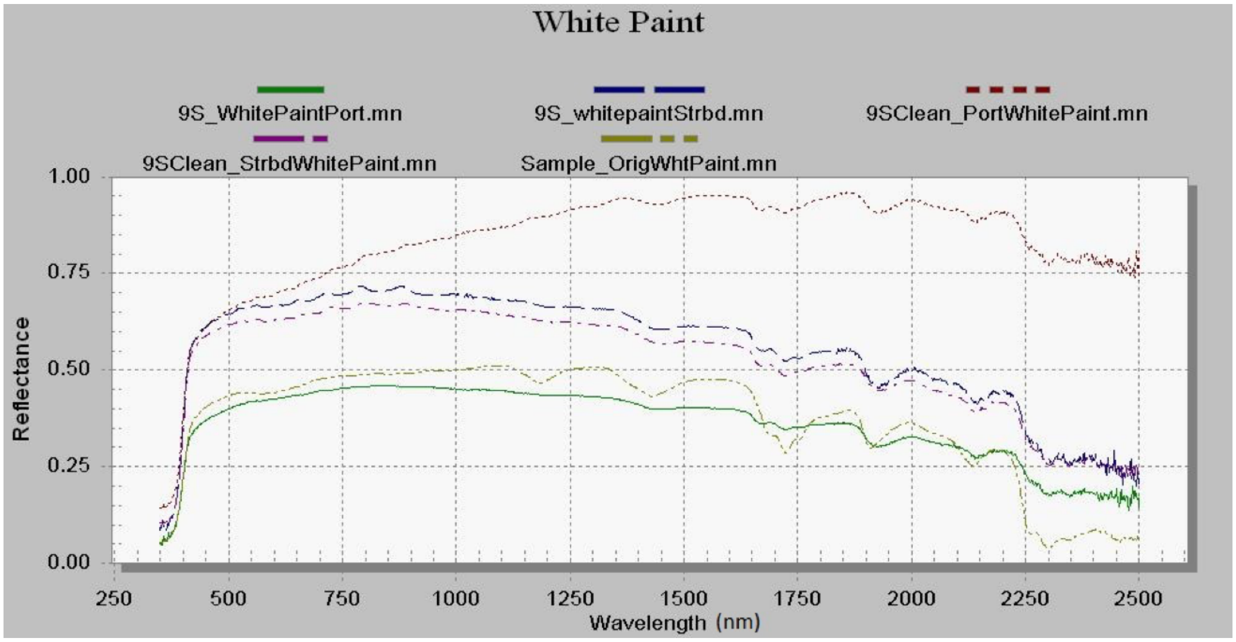

Fig. 7. Reflectance spectrum for white paint taken from Titan IIIC Transtage test article.

4.2. Radar Calibration Spheres

In an effort to determine optimum properties of the stainless steel calibration spheres, sphere #2 produced the most consistent spectra of the 2 cm diameter uncoated stainless steel spheres (Fig. 8) over all readings (north and south hemispheres at each cardinal direction). The spectral plot for sphere #2 conveys evident absorption with a depression

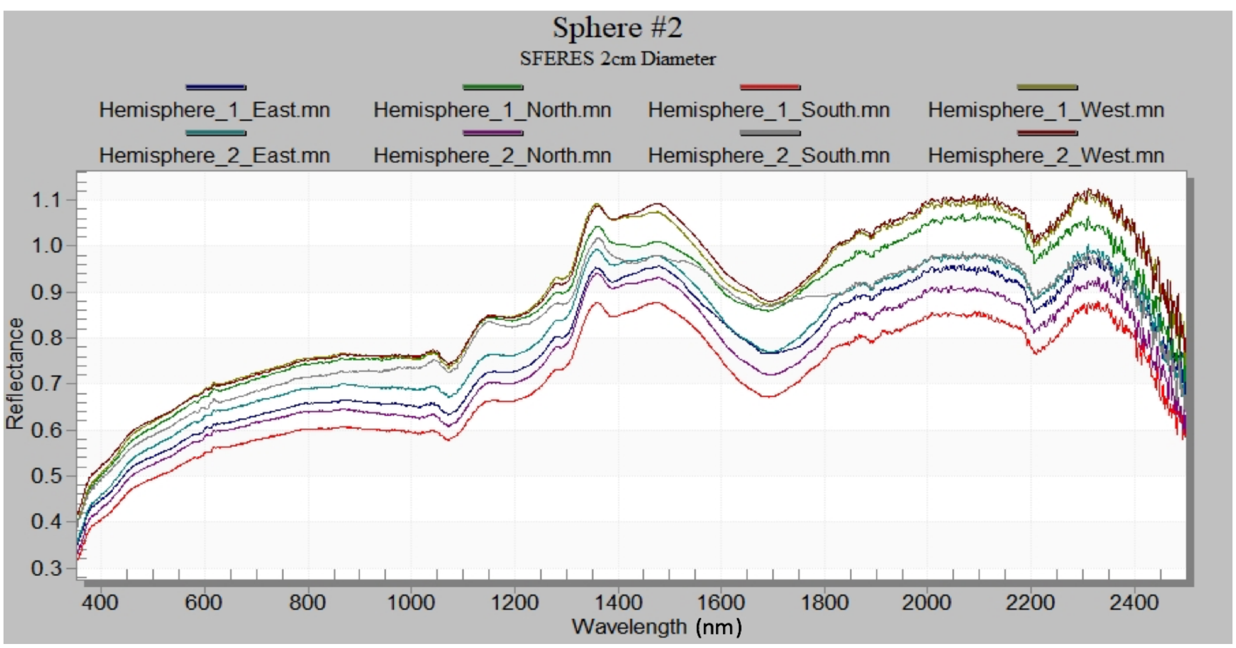

Fig. 8. Reflectance spectra plot for uncoated Sphere #2.

in the curve at 1700 nm, suggesting C-H bonding [12]. The presence of the 1700 nm feature in the spectrum, however, could be due to the potential interference from the polymeric Styrofoam cup. Regarding the other spectrum features, the small peak present at 600 nm is a common feature seen in steels [12]. The steady parabolic increase in slope in the visible region can be associated with iron or vanadium alloyed content within the steel [19]. The small dips present at 1400 nm and 1650 nm are due to O-H and C-H molecular bonding, respectively. The more apparent depression in the infrared region at 2200 nm is indicative of a metal-OH bond [12]. It can be noted that there is an absence of the aluminum feature at ~800 nm, which could suggest further information regarding the steel's alloyed content.

Of the five coated 4 cm diameter stainless steel spheres, sphere #5 presented the lowest standard deviation results (Fig. 9). Upon visual inspection, each sphere did qualitatively appear to have different hues of green, yellow, blue, and pink. Green typically has absorption features near 450-550 nm, yellow near 500-600 nm, and red closer to 600-650 nm. The absorption feature first present at 500 nm in the visible region is likely due to yellow chromate. The depression at 1000 nm within this bandgap has been seen in zinc-aluminum alloys, which further vindicates the material composition since zinc is a common element present in commercial aluminum alloys [20]. The absorption dip at 1400 nm is most likely due to O-H bonding, or could likely be H_2O when paired with the absorption feature also present at ~1850 nm. Like 2 cm diameter sphere #2, the small depression located at 2200 nm is due to a metal-OH bond. In this case the metal is suggested to be alloying with the element aluminum. Due to the highly specular and spherical nature of the targets, it is likely the spectral data was biased with scattering from the Styrofoam mount that led to the organic features noted above.

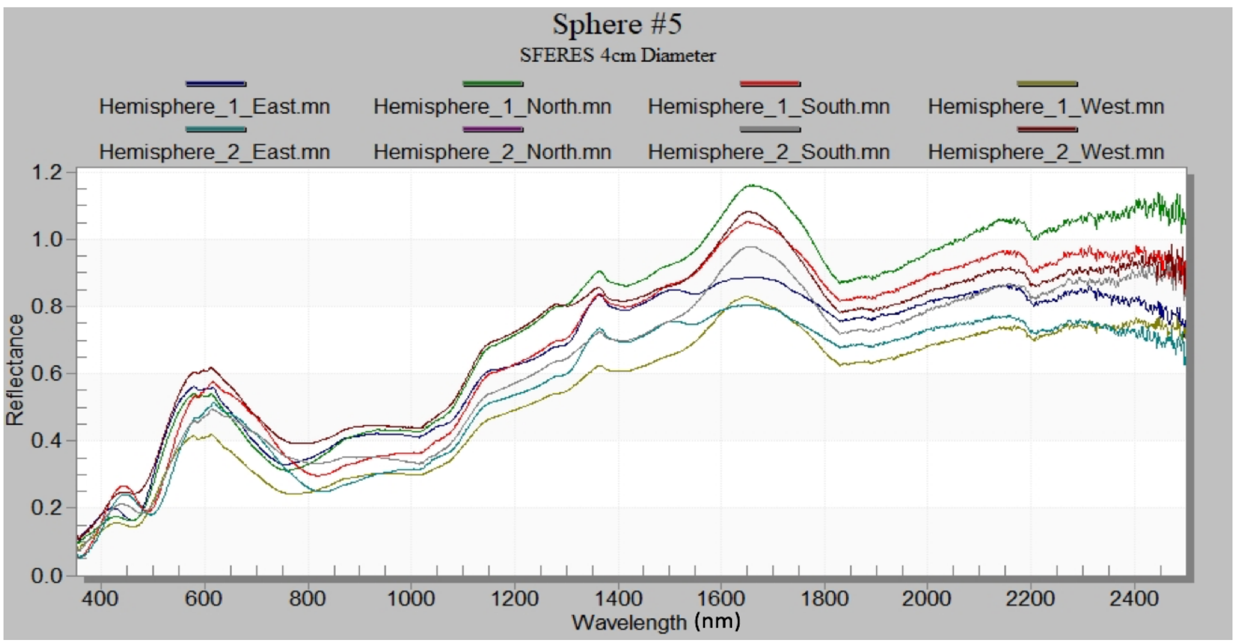

Fig. 9. Reflectance spectra plot for coated Sphere #5.

4.3. <u>HS-376 Spacecraft Solar Cell</u>

Spectra for the GaAs/Ge solar cells displayed in Fig. 10 conveyed an evident peak at 850 nm which correlates with a Ge quantum efficiency (QE) [21]. Although not documented here, the $GaInP_2$/GaAs/Ge cells had similar spectrum results to that of the GaAs/Ge solar cells with an additional peak at 700 nm to correlate with the QE of $GaInP_2$ [21]. Fig. 11 displays the spectra for Silicon K4 3/4 cells having a bandpass in the visible region of the spectrum (400 nm – 1000 nm) and a doublet present at 1700 nm indicative of C-H bond presence [12]. Although not palpably documented here, Silicon K7 cells had nearly identical results to that of Silicon K4 3/4 cells with no additional features to note.

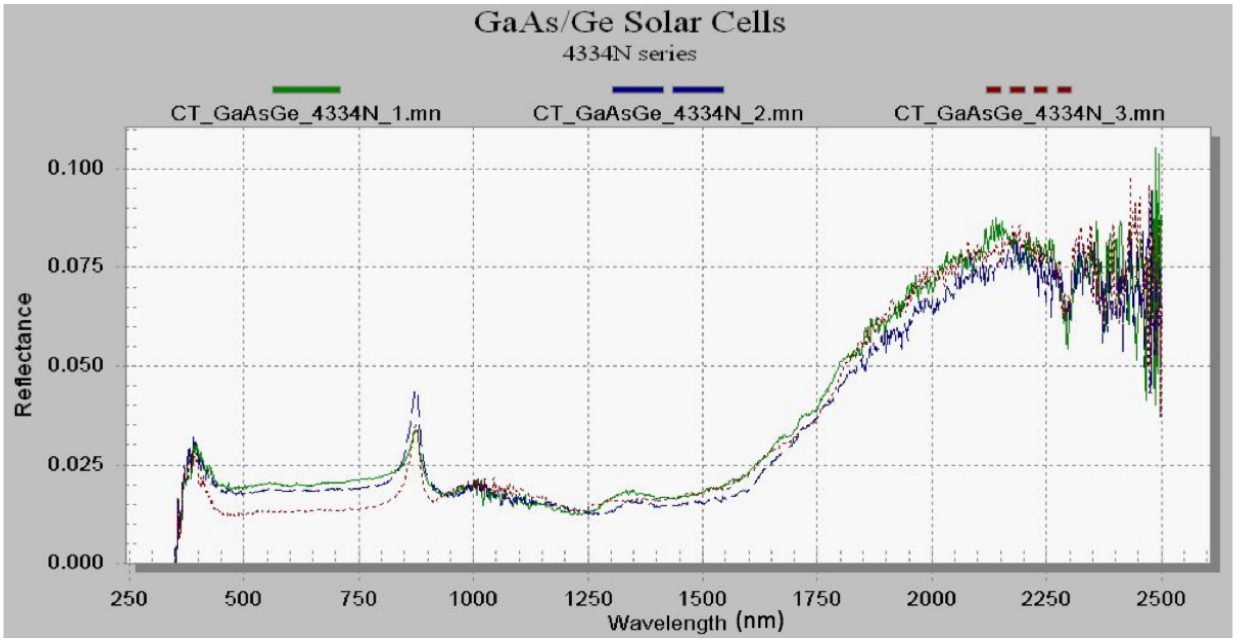

Fig. 10. Reflectance spectra of GaAs/Ge solar cells.

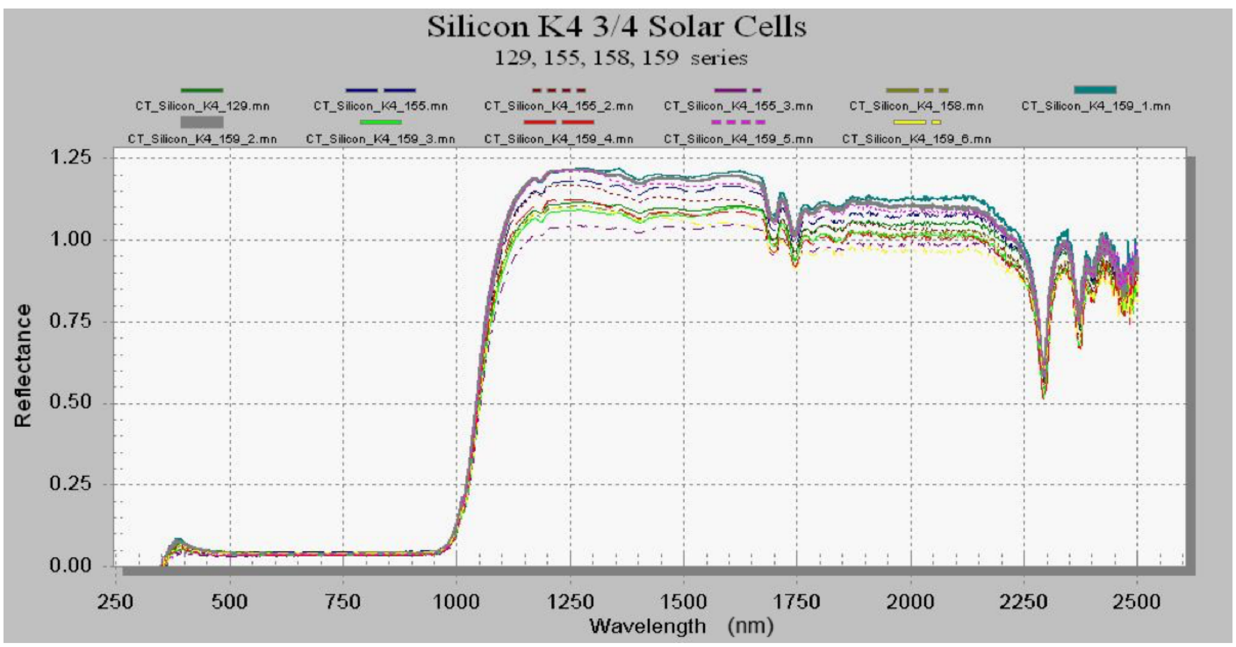

Fig. 11. Reflectance spectra of Silicon K4 3/4 solar cells.

5. CONCLUSION

The chemical nature for a variety of aerospace related materials have been analyzed using reflectance spectroscopy. The spectra of these materials can be examined to assist with sufficient orbital debris characterization and knowledge of material type can benefit the understanding of that material's albedo during launch and throughout its time in flight [22]. In the future, the incorporation of a goniometer system with the spectrometer set-up is to be explored. This will allow the bidirectional reflectance distribution function (BRDF) of material surfaces to be measured at multiple angles, which will enhance and augment collected data particularly with determination of orbital debris position. All acquired spectral data of these materials have currently been stored in the NASA JSC Spacecraft Materials Spectral Database. To date, the data can be and has been used for comparison with multiple telescopic data and optical assets [13]. The author plans to perform future spectral analysis on numerous additional space hardware materials in their pristine, space weathered, and laboratory space weathered conditions. Ongoing efforts on spectral unmixing in collaboration with NASA and the University of Texas at El Paso (UTEP) will utilize the data presented here in addition to the total data accessible in the NASA JSC Spacecraft Materials Spectral Database. A thorough material taxonomy assessment using the data stored in the database is to be presented in the future with the goal of sampling spectral data from material families contrary to individual samples.

6. ACKNOWLEDGEMENTS

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