Linear Spectral Mixing for Spacecraft Characterization

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ABSTRACT

We present a summary of our spectral mixing pipeline to aid in spacecraft characterization. After analyzing several spacecraft, we have been able to demonstrate preliminary capabilities to use spectroscopy and linear spectral mixing in identification of spacecraft. In this research we have found five materials within our database that are likely to be materials used on the surface of six Hughes bus type satellites that we have observed.

We have developed capabilities to classify spacecraft using visible wavelength spectroscopy (450-900 nm) and spectral modeling, demonstrated on the Hughes type satellites. We plan to continue developing the spectral mixing pipeline for further analysis of spacecraft and expanding our material database, as well as investigate phase angle spectral effects on telescopic satellite observations.

1. INTRODUCTION

Ground based observations are affected by earth's atmosphere resulting in the blurring of light from the sources. Because of this, even the largest telescopes cannot resolve objects in geostationary orbits without the use of adaptive optics. Traditionally there is no way to determine what ratio of the reflected sunlight from a spacecraft is from specific components or materials (e.g., solar panels, metals, or mylar). The spacecraft appears as a point source, and we have no information about the shape of the object, the size, or materials. The size of an object is not a one-to-one correlation to the brightness of the object, as phase angle can change the observed brightness drastically. Using spectroscopy, we can gain more information about the object and can identify possible ratios of the materials composing the spacecraft.

To get information about possible materials used on the spacecraft, we can use linear spectral mixing to identify the endmembers and their abundances [1]. Linear spectral mixing is the process of linearly combining endmember laboratory spectra in different ratios to identify the mixture that best correlates to an observed telescopic spectrum. Through this, we may determine the likely abundances of the endmembers within the telescope spectrum that would allow us to uniquely identify the spacecraft [2].

The spectroscopy technique we employ utilizes diffraction gratings to split the reflected light the telescope observes into the corresponding wavelengths. This allows us to analyze the spectra and use our spectral mixing pipeline to determine likely combinations of spacecraft materials. One complication is the observed phase angle which is the angle between the sun, the target satellite, and the observer. Phase angle changes over the course of the night and affects the spectrum of a satellite. It is necessary for us to get observations over a range of phase angles so that we can confirm understand this non-compositional effect and constrain the likely combinations of materials on these satellites. In this study we present spectra of five geostationary satellites and the preliminary analysis of their composition constrained through a linear spectral mixing algorithm.

2. HARDWARE

To obtain the spacecraft spectra, we use the Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy (RAPTORS I) located at the University of Arizona. The telescope is a 24-inch Newtonian telescope with a 16x16 arcminute field of view and a 0.9 arcsecond per pixel plate scale used as a slitless visible spectrometer (0.4-0.95 microns). The spectrometer is comprised of a 1056x1027 pixel CCD and a filter wheel with a 30 line per millimeter grating resulting in resolution of 14.6 nm per pixel (R~30 at 450 nm).

3. OBSERVATIONS

As noted earlier, phase angle variations affect the spectrum of spacecraft, which can vary from -180° to 180° with 0° being a fully illuminated object (typically local midnight for objects on/near local meridian). For each of our five objects we observed each of them for the full night to get large phase angle range. The spin-stabilized Hughes bus types of HS-376, HS-376HP, HS-376L, and HS-376W were observed because they are all cylindrical satellites whose surface areas are dominated by solar cell material. An example artist rendition of a HS-376 satellite is shown in Fig. 1. We therefore expect the solar cell material to be the most prominent material returned in the spectral linear mixing results. This will show if the mixture remains true to what we expect.

Fig. 1. HS-376 artist rendition taken from Gunter's Space Page

We observed five satellites of the Hughes bus types to test the limiting case of the solar material dominated surface in our linear spectral mixing code. These targets are on inclined orbits with respect to the celestial equator and were only observable for a limited time before their orbits took them below the pointing limit for the telescope in Tucson. Due to the targets' inclinations, they often set below the roof limit during the night of observations, limiting the observable phase angle range. The observational circumstances, including the observed phase angle range are presented in Table 1.

Table 1. Observational circumstances for spectral observations

Satellite Name	NORAD ID	Date Observed (UTC)	Phase Angle Range
Astra-3A	27400	2022-06-15	0° to 75°
Eutelsat-33A	27948	2023-06-07	-40° to 60°

Bonum-1	25546	2023-06-12	-10° to 70°
Brasilsat-B4	26469	2023-06-14	-30° to 80°
Thaicom-2	23314	2023-06-15	-40° to 10°

4. METHODOLOGY

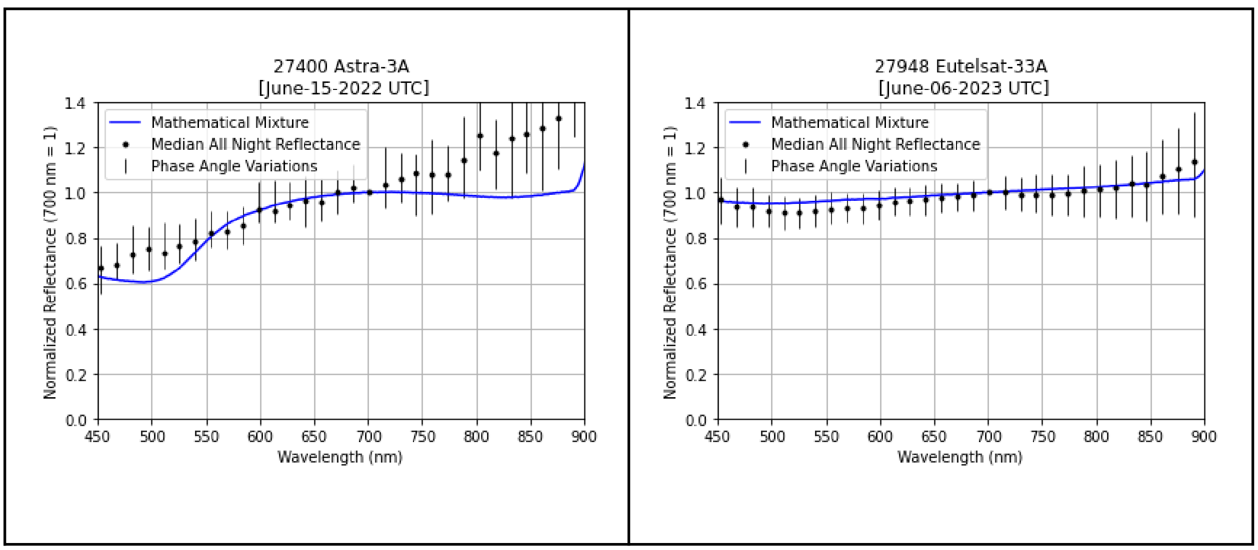
We processed the telescope spectral data with a processing script established in [3] prior to linear mixing. Light is extracted from the images in columns along the spectrum and background subtracted using a nearby background estimate. Every column represents a specific wavelength and each column's brightness is normalized to a user-defined wavelength's brightness. This process is done for each individual target spectrum and divided by a median solar analog spectrum to produce reflectance.

A Python pipeline that we developed to perform the spectral mixing analysis with our chosen endmembers is used. Each endmember is a lab-measured spectrum of a single material commonly used on spacecraft including paints, mylars, assorted metals, and solar panel materials. This pipeline takes in a list of possible endmembers as well as the observed telescope spectrum, and returns the ratio of possible materials, and the Mean Squared Error (MSE) of that mixture to best match the telescope spectrum. The goal of this project is to create a pipeline that can match observed visible spectra (0.4-0.95 microns) of spacecraft with their associated materials and percent composition.

To do the spectral mixing we create lists of the endmembers we want to consider in the mixture. We do an exhaustive search of every combination of all endmembers to be considered up to the desired precision in the contribution of those endmembers. For each combination, a test spectrum is created by multiplying the fraction of each endmember in the combination with that endmember's spectrum and adding the resulting fractional spectra together. Once the test spectrum is produced the MSE is calculated and the combination with the lowest MSE is given to be the most likely combination of the endmembers considered.

5. RESULTS

We have done modeling on five Hughes spacecraft with solar panel dominated surfaces to see how phase angle affects the spectral mixing. We have been able to identify composition ratios for each satellite observed to test our spectral mixing pipeline on this limiting case of Hughes spacecraft. In Fig. 2, the five Hughes satellites reflectance spectra and their best associated spectral mixtures are shown.



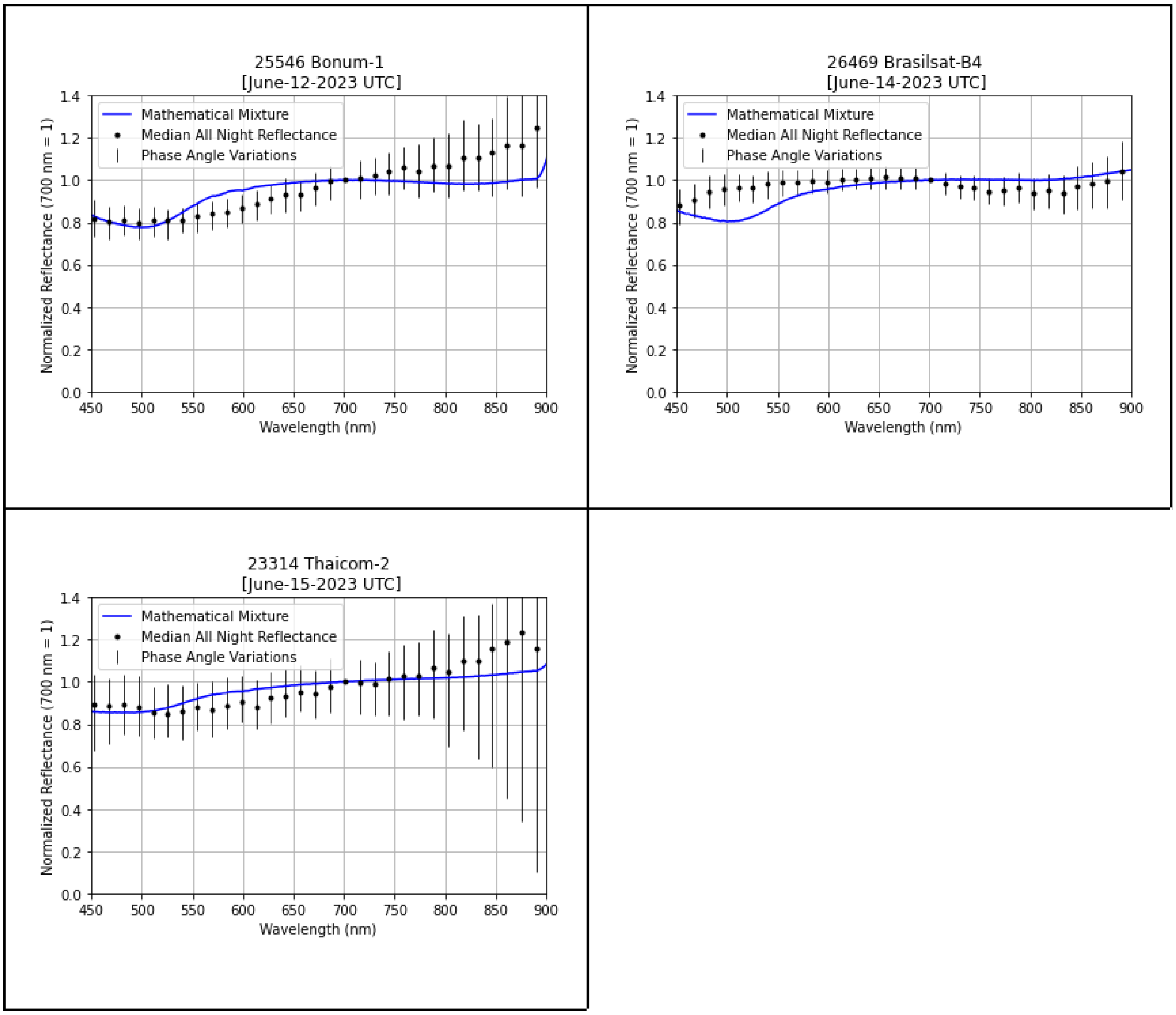


Fig. 2. The reflectance spectra of each Hughes satellite and the best-found mixture to such satellite. The reflectance is normalized to 700 nm and wavelength ranges 450 nm to 900 nm. The blue line is the calculated mixture, the dots are the median all-night reflectance of the spacecraft, and the vertical bars are the phase angle variations of the satellite.

Table 2 shows the results of the mathematical mixtures shown above in Fig. 2 in 0.1% incrementation. For each mixture three endmembers were used to calculate the best mixture combining solar cell material, gold mylar, and various metals. They were chosen intuitively from our archive of # endmembers based on materials visible in Fig. 1.

Table 2. Shows the endmembers and their ratios calculated in each of the satellites observed.

	Gallium Arsenide Solar cell	Silicon Solar cell	Gold Mylar	Titanium	Stainless Steel	MSE
Astra-3A	27.4%	0%	41.5%	30.9%	0%	0.52
Eutelsat-33A	22.2%	0%	2%	0%	75.7%	0.026

Bonum-1	50%	0%	27.8%	0%	22.1%	0.26
Thaicom-2	14.7%	0%	11.7%	0%	73.5%	0.15
Brasilsat-B4	0%	75%	25%	0%	0%	0.43

6. DISCUSSION

We see that all the satellites have solar cell materials in their best mixtures, which is what we would expect given that the satellites are primarily solar panels on the visible sides. Gallium arsenide solar cells have an identifying feature near 850 nm [4] which is visible in the spectra of Astra-3A, Eutelsat-33A, and Bonum-1. Despite having 60 materials in our catalog, we found that there were five likely materials for these five satellites. Our findings support the results in [5] because the five targets of similar bus types each have similar material composition found from our linear mixing modeling.

Given that the five targets we selected are covered with solar panels, we would expect that our modeling results would be nearly all solar cell material. However, that is not what we see happen. This could be due to effects of phase angle we need to investigate further. Additionally, the slopes of the mixture do not fully match the observed spectra. This is likely due to space aging effects, as materials slopes change when exposed to the space environment [4],[6].

Previous studies suggest that most spacecraft are composed of aluminum [6]. Our results do not suggest the presence of aluminum because of a lack of a complete database and the current inability to match space aging effects in our spectral database. We recommend the community invest in creating a complete database of spacecraft materials at various phase angles, including space aged materials.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Jorgensen, K., "Using Reflectance Spectroscopy to Determine Material Type of Orbital Debris," Ph.D. Thesis, Colorado Center for Astrodynamics Research, Univ. of Colorado, Boulder, CO, 2000.

[2] Jorgensen, K., Africano, J., Hamada, K., Sydney, P., Stansbery, E., Kervin, P., Nishimoto, D., Okada, J.,Thumm, T., and Jarvis, K., "Using AMOS Telescope for Low Resolution Spectroscopy to Determine the Material Type of LEO and GEO Objects," AMOS Technologies Conference, Maui Economic Development Board, Kihei, Maui, HI, Sept. 2001, pp. 127–134.

[3] Battle, Adam, et al. "Physical Characterization of Near-Earth Asteroid (52768) 1998 OR2: Evidence of Shock Darkening/Impact Melt." *The Planetary Science Journal*, vol. 3, no. 9, 2022, p. 226.

[4] Reyes, Jacqueline A., and Darren Cone. "Characterization of spacecraft materials using reflectance spectroscopy." The Advanced Maui Optical and Space Surveillance Technologies Conference. 2018.

[5] Abercromby, K., Paul Abell, and Ed Barker. "Reflectance spectra comparison of orbital debris, intact spacecraft, and intact rocket bodies in the GEO regime." 5th European Conference on Space Debris, March. 2009.

[6] Jorgensen, Kira, et al. "Determining the material type of man-made orbiting objects using low-resolution reflectance spectroscopy." Multifrequency Electronic/Photonic Devices and Systems for Dual-Use Applications. Vol. 4490. SPIE, 2001.