

Updates on the Visible Spectral Atlas of Geostationary Satellites

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ABSTRACT

We present a summary of the completed RAPTORS I visible spectroscopic atlas of over 60 geostationary satellites visible from Tucson, AZ. The Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy (RAPTORS) is an automated 0.61-meter, f/4.6 telescope constructed by five engineering students at the University of Arizona.

Observations were conducted with a cadence of at least one spectrum per minute, producing an average of ~800 spectra per satellite each night. Data reduction frames include flats once per lunation along with dark- and bias-frames each night. Nightly spectra of a solar analog star for solar reflectance calibrations were collected each night and an additional airmass correction star was also observed most nights to better account for atmospheric extinction effects if needed.

Initial results presented at the AMOS 2021 conference show that visible spectroscopy is a powerful tool for satellite characterization and differentiation. Examples of the 3-dimensional Spectral Phase Map (SPM) showing longitudinal phase angle (LPA) vs. wavelength vs. normalized reflectance (out-of-plane) have the possibility to uniquely fingerprint a target. These SPMs show feature consistency with more traditional, photometric lightcurve methods of GEO characterization while also showing new, “flux-neutral” color features in the SPM. These “flux-neutral” features show no obvious feature in the lightcurve, either by maintaining a constant brightness or having a steady-slope change in brightness. In addition to the SPMs, photometry from the zeroth order point source can be extracted from the data to produce panchromatic, uncalibrated lightcurves of the objects.

Initial machine learning applications to the data set show that the SPMs and their corresponding full night median spectra are excellent tools for target characterization and differentiation. Initial analyses show a strong correlation between a target’s SPM and its bus type exists for certain bus types. Additionally, machine learning techniques are able to extract potential eigenfeatures from the full set of data that are representative of GEO satellite features. Progress has been made on linking these eigenfeatures to physical features of the satellite to improve the usefulness of the spectral data. Initial results show that the GEO spectral survey meets its goals of providing methods to discriminate targets via lightcurve data and Spectral Phase Maps as well as for fingerprinting individual satellites. It is possible that these spectral data represent the foundations for a GEO satellite taxonomy, which exceeds the expectations of this survey.

In addition to the atlas of all GEO targets visible from Tucson, AZ, a set of targets representative of their bus type were chosen for a more in-depth analysis. This set of data contains regular spectra of three targets in each of four bus types. These twelve targets were observed over the course of a year to measure effects of seasonal variations that alter the lightcurves and SPMs for a given target. This experiment will highlight the importance of full characterization of targets in order to better differentiate objects in the future and extract the meanings of spectral features. This data set will also expand on our capabilities for bus type identification, spectral modeling for material composition, and improve our understanding of the physical interpretation of eigenfeatures extracted from the data.

Because this visible spectroscopy atlas of the geostationary belt observed from Tucson promises to be such a powerful resource for the Space Domain Awareness community, this paper will focus on detailing the final state of the atlas and making the atlas available to the public. We include details on the methodologies, objects observed, preliminary results, and challenges faced during the project. Future work will focus on results found from machine learning analyses of the data.

1. INTRODUCTION

The characterization of resident space objects (RSOs) is crucial to object differentiation and change detection (e.g., power loss, tumbling, etc.). Traditional characterization techniques typically rely on photometric lightcurves, however [1-5] demonstrate that low-resolution reflectance spectroscopy can successfully identify select RSO materials. In [6], a proof of concept study was performed for the Rapid Automated Pointing Telescope for Optical Reflectance Spectroscopy (RAPTORS I) hyperspectral survey of the geostationary Earth orbit (GEO) belt. The success of this proof of concept lead us to start the GEO spectral atlas of all geostationary objects visible from Tucson, AZ, the initial results of which were presented in [7]. The observations have been completed and updates on the status of the GEO atlas are presented here.

2. OBSERVATIONS

The RAPTORS I telescope is a 0.61-meter, f/4.64 equatorially mounted Newtonian reflector located on the campus of the University of Arizona. The telescope is equipped with a Finger Lakes Instrumentation Proline CCD and a filter wheel with a transmission grating, resulting in a slitless spectrometer system in the wavelength range of 450 – 950 nm (R~30).

Observations were obtained by tracking at the GEO's rate and acquiring images at a cadence of roughly one per minute. Trusted G2V or equivalent solar analog stars were observed once per night to calibrate the GEO spectra into reflectance measurements. Altogether, the GEO spectral atlas spans 192 nights of observations with a total of ~140,000 spectra and includes data on 102 unique GEOS. A breakdown of the number of each bus type observed is shown in Table 1. The asterisk in the bus name indicates that multiple variations exist, such as the SSL-1300 and SSL-1300HL variation.

Table 1. Breakdown of the number of observations of each bus type included in the GEO spectral atlas. Asterisks act as a reminder that most bus types have multiple variations from the base model, but here they have been combined in one row for simplicity.

Target Bus type	Quantity
SSL-1300* Bus	80
BSS-702* Bus	62
Eurostar* Bus	41
Star-2* Bus	43
A2100* Bus	29
Spacebus*	5
DFH-4 Bus	3
BSS-601*	5
GEOStar*	8
Arsat*	2
A-500	1
Other	3
Total	282

3. UPDATED RESULTS

Three main data products can be produced for each object observed for the GEO spectral atlas: lightcurves, full-night median spectra, and spectral phase maps (SPM) [7]. All three data products show how light reflecting off of the GEO changes with longitudinal phase angle (LPA). LPA is the East-West component of the sun-target-observer angle and is used to quantify illumination conditions on GEOS. The lightcurves use brightness measurements extracted from the zero-order point source using traditional aperture photometry techniques to show how the brightness changes with LPA. The full-night median spectra and SPMs both use the spectral data produced by the

diffraction grating, where each pixel along the spectrum gives a brightness at a specific wavelength value. The full-night median data uses vertical bars to illustrate the amount of spectral variation occurred due to changes in LPA. These bars use the inner quartile range (IQR) as a nonparametric way to illustrate the phase variation. The data extraction process is explained in more detail in [7]. Fig. 1 shows an example combined plot of the lightcurve and full-night median for Wildblue-1 (29643) on 2022 Feb. 03. This style of two-panel combined plot will be used to produce the atlas of observations with one panel produced for each object observed.

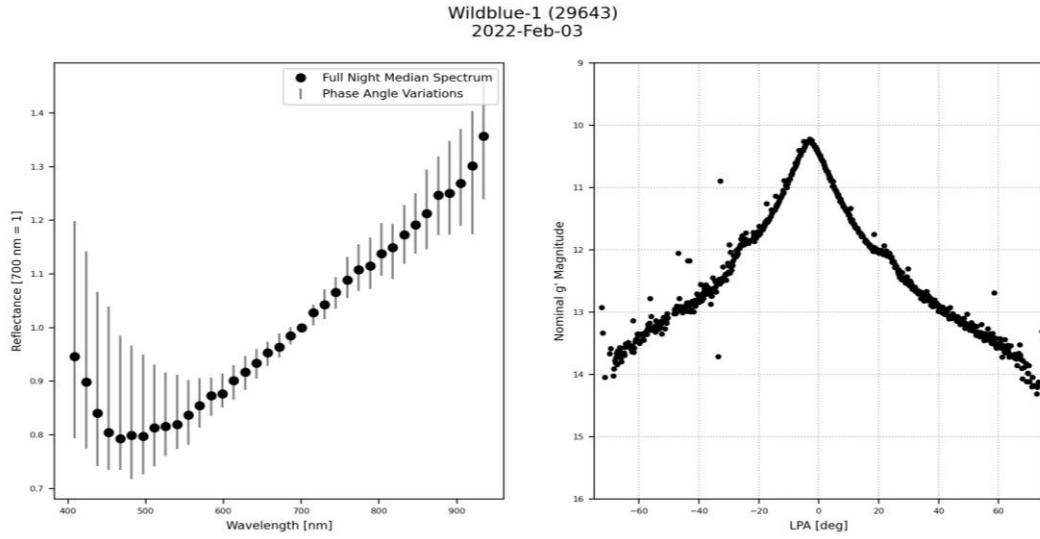


Fig. 1. Two-panel combined data visualization that will be used for generating the GEO spectral atlas. (Left) the full-night median of the target's spectrum with vertical bars showing the inner quartile range (IQR) of phase variations for that night. (Right) the lightcurve for the target showing nominal magnitude versus LPA.

Comparing full-night median spectra between objects is a potential way to differentiate objects. Fig. 2 shows full-night median spectra for three objects that are angularly near each other on the sky in a satellite cluster. By being angularly near each other in the sky, the objects will experience the same airmass and LPA range during the observations. Due to RAPTORS I's small field of view, two nights of observations were required to get all three objects of the cluster. The observations were performed within one day of each other to ensure no seasonal variations for comparisons. Fig. 2 shows good separation between the three objects, which are also three separate bus types, and three uniquely shaped spectra.

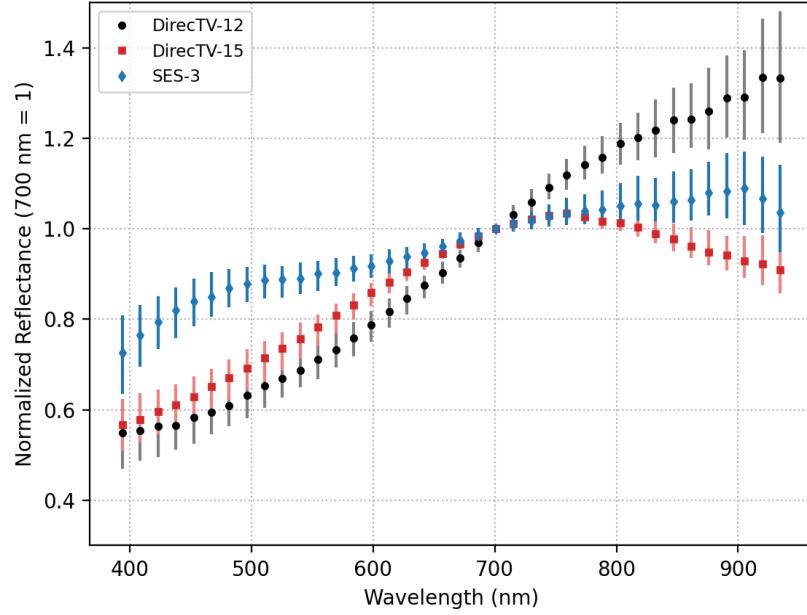


Fig. 2. Full-night median spectra for DirecTV-12 (36131), DirecTV-15 (40663), and SES-3 (37748) showing the feasibility of object differentiation. The two DirecTV satellites were observed on 2020 May 18 and SES-3 was observed on 2020 May 19.

Now that the study has been completed and most of the data is processed, we have seen more trends begin to appear. One trend mentioned in the initial results of [7] was that objects of the same bus type have similar full-night median spectra. Although this seemingly continues to be true, it has become much more complex due to LPA coverage differences and seasonal variations. LPA coverage that is not roughly equivalent across the objects being compared means that objects are not getting the same amount of information in the full-night median spectrum. For example, one object may be on the meridian and receive an even LPA coverage (e.g., -60 to 60°), but another object is near the horizon and has a very skewed LPA range (e.g., -100 to 20°) making the comparison less meaningful. Ideally, our analyses in the machine learning portion of the project will focus on using observations with comparable LPA coverage.

The other complication to the bus type comparisons is seasonal variations. Throughout the year, the sun's declination changes resulting in latitudinal phase angle effects, where latitudinal phase angle is the North-South component of the phase angle. These effects occur slowly throughout the year and are thus called seasonal variations. This can make comparisons of even the same object difficult. Fig. 3 illustrates the degree to which seasonal variations can affect an object's full-night median spectrum. Full-night median spectra of Wildblue-1 (29643) are shown for four different months, resulting in up to ~30% reflectance variations in the blue-extreme wavelengths from one month to the next.

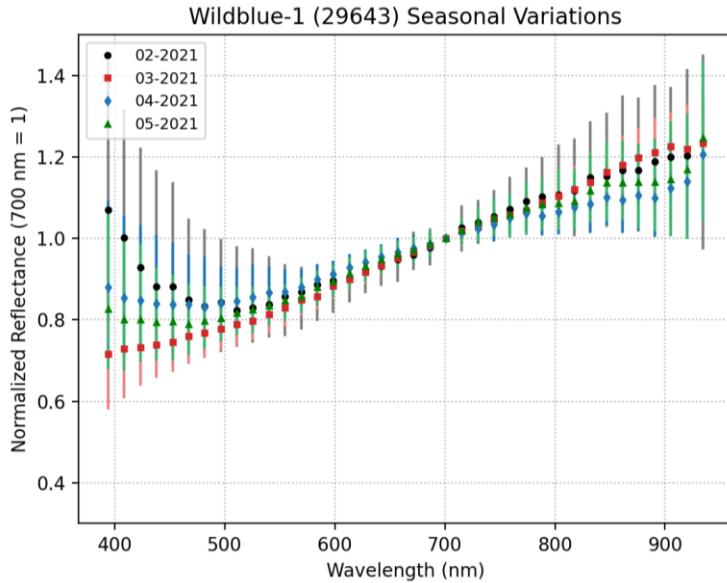


Fig. 3. Full-night median spectra for Wildblue-1 across four different months. This shows seasonal variations for the same object can be significant when attempting to differentiate or identify objects.

The best way to visually represent how the satellite's spectra change throughout the night is with the spectral phase maps which plot LPA versus wavelength with the normalized reflectance on the out-of-plane axis. This style of plot, shown in Fig. 4, shows all of the data collected during the observing run and explicitly shows the magnitude and position of spectral features. In this plot, each horizontal slice is an individual spectrum at a specific phase angle. The SPMs are a visualization of the information that will be used in the machine learning phase of this project.

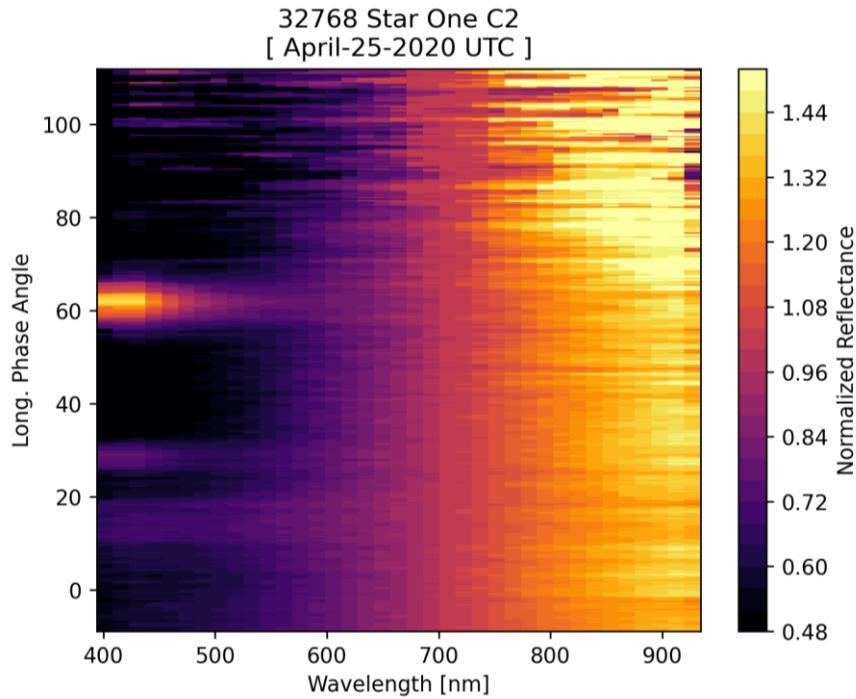


Fig. 4. Spectral Phase Map of GEO Star One C2 (32768) observed on 2020 April 25 UTC showing LPA (degrees) versus wavelength (nm) with the out-of-plane axis being the normalized reflectance ($700 \text{ nm} = 1$). Each horizontal slice across the SPM is an individual spectrum from the night of observations. The spectra are smoothed with a median kernel to bin small sets of spectra and make the image more readable.

Now that the data has been collected, the GEO spectral atlas will be used to train deep learning machine algorithms for more complex analysis of the data and the development of models for predicting characteristics of GEOS based on a limited number of spectra. The next steps for this project will be to publish the GEO spectral atlas and the methodology in a peer-reviewed journal. Then we will continue with the deep learning methods on the large data set, resulting in a second, machine learning based manuscript.

4. ACKNOWLEDGEMENTS

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