RAPTORS: Hyperspectral Survey of the GEO Belt

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ABSTRACT

Robotic Automated Pointing Telescopes for Optical Reflectance Spectroscopy (RAPTORS) is an automated 0.6-meter F/4 telescope with transmission grating to conduct a slitless spectroscopic survey of the GEO belt in visible wavelengths. Five engineering undergraduate students constructed the telescope as part of their senior design project at the University of Arizona. The telescope instrument combination enables us to collect visible wavelength spectra (0.4-0.8 microns) at a spectral resolution of ~30. Our goal is to conduct a systematic survey of the GEO belt to create a taxonomic classification of resident space objects (RSOs). We will present preliminary results from the survey where we attempt to identify multiple RSOs in a single field of view using their spectral signatures.

1. INTRODUCTION

Currently there are >17,000 objects in the US space surveillance network catalog that are in Earth orbit with thousands more that are tracked but not in the catalog (Orbital Debris Quarterly News). With <5% of these objects being active satellites, the threat of a runaway collisional cascade is real. Exploiting this dire situation are nation states that have adversarial motives, and could resort to a range of tactics including masking an active satellite as debris with malicious intentions. Space materials typically have diagnostic absorption features in the visible wavelength range and other non-diagnostic parameters such as spectral slope could be used to uniquely identify objects in conjunction with other information such as astrometric position and photometric light curves.

Pioneering work in the application of spectroscopy as a remote sensing tool to characterize resident space objects (RSOs) has been carried out by [1-5] where it has been demonstrated that low-resolution reflectance spectroscopy can be successfully used to identify material composition. These activities can be categorized into two areas: laboratory spectral measurement of analog material in a controlled environment and Earth-based telescopic measurements of reflectance spectra of RSOs in orbit. While most past spectral studies have focused on characterizing a small subset of materials or RSOs, systematic surveys of a specific debris population have been mostly lacking [6]. The goal of RAPTORS GEO Belt Hyperspectral survey is to systematically collect visible wavelength spectra (0.4-0.8 μm) of all objects in the geostationary orbital regime and exploit key advances in spectral fingerprinting to uniquely identify an RSO.

2. HARDWARE

A major challenge to a systematic spectral survey of RSOs has been the lack of dedicated access to ground-based telescopes. Most telescopes available to academia do not cater to the SSA community. This affects us in two ways: 1) It is challenging to get time on telescopes when the time allocation committee is predominantly astronomers; 2) Hardware and software limitations including: the inability to rate track RSOs, and spectrometers not being optimized for doing low-resolution spectroscopy. Hence having a dedicated telescope for the task allows us to overcome the primary burden that has hindered progress in the RSO characterization field over the last few decades. However, a dedicated telescope would also come at a premium where resources need to be in place to design, build and commission the hardware before observations could be made.

Our primary constraints for building a dedicated spectroscopy survey telescope was the diameter and focal length of the primary mirrors. Since our resources were limited, we used a surplus 0.6-meter F/4 mirror to build the telescope for the survey. Five engineering undergraduate students constructed the telescope as part of their senior design project at the University of Arizona [7]. The optical tube assembly has a Newtonian focal plane with a focal length of 2831 mm and an FLI ProLine 16803 4kx4k CCD camera. This gives us a field of view of 44x44 arc minutes with a pixel scale of 0.64 arcsec/pixel unbinned.

Spectroscopic measurements are made by dispersing the light through an optical element (prism or grating) to separate white light into different wavelengths. Ideally this is done with a spectrometer where an entrance slit would serve several useful purposes including controlling the sky background so only signal from the RSO reaches the detector, and spectral resolution. However, a slit spectrometer also creates additional challenges that prevent automated survey mode data collection because the object has to be precisely placed in the entrance slit and cannot be rate tracked without a human in the loop. This operation has to be carried out multiple times over the course of each night with minimal chances of failure. The slit orientation is also another factor we considered. Spectral slope of a reflectance spectrum is affected by differential refraction where the blue end of the spectrum is selectively removed if the slit is not oriented with the parallactic angle (perpendicular to the horizon). This would require the entire instrument to rotate. Given that most RSOs in the geostationary belt are relatively bright (visual magnitude ≤15) and the challenges associated with automatically placing objects in the slit consistently, we decided to explore slitless spectroscopy where a transmission grating would be used in the focal plane to disperse the light rather than a slit spectrometer.

We explored three custom transmission gratings (30 lines/inch, 35 lines/inch, 75 lines/inch) from Richardson Grating for our survey each with increasing resolution (lines/inch). The blaze wavelength for 30 lines/inch grating is 405 nm, 35 lines/inch is 640 nm and 75 lines/inch is 730 nm. The 75-line grating gave us enough resolution (R~60) to calibrate the spectrum in wavelength space without any challenges. However, this grating was most affected by order overlap where the second order overlapped with the 1st order at about 400/800 nm wavelength. The 30-line grating was least affected by order overlap and gave us a resolution R~25 (20 nm/pixel) when we used a 2x bin (18 micron pixels) on the FLI ProLine 16803 camera. We chose the 30-line grating because of these characteristics and it also provided us maximum signal-to-noise ratio, enabling us to collect spectra of RSOs brighter than visual magnitude 15 with a 0.6-meter telescope. The 30-line granting also provides a much higher spectral resolution (20 nm/pixel) than traditional broadband filters (UBVRI) that have band passes ranging from 70-150 nm. The 30-line transmission grating is 50x50 mm square and is placed in the filter wheel between the CCD camera and the focal plane of the telescope.

3. SURVEY PLAN

The primary goal of our survey is to collect visible wavelength spectra of all RSOs in geostationary orbit. As the first step we have established the first node at the University of Arizona to collect spectral data of all objects visible from Tucson, Arizona, using the RAPTORS telescope. Visibility of an object is defined based on standard astronomical protocols where the object is at least 30 degrees (2 airmass) above the horizon during the entire observing period. This restricts the number of objects we can observe from Tucson to about 100 on any given night. Observing cadence is predicated by the fact that non-compositional effects such as phase angle (viewing geometry) affect spectral slope and absorption band depth. In order to overcome these non-compositional effects, a single target will be observed the entire night rather than switching between multiple targets. With 300 clear nights a year, our site offers at least three opportunities to observe each of the 100 targets visible from Tucson per year.

4. DATA REDUCTION

Wavelength calibration and data extraction were conducted using custom software designed specifically to work with data taken with a transmission grating. The Python NumPy library was used to perform the data analysis to convert the fits data into a 2D array to allow exact pixel DN values to be extracted (Python, 2015). The custom software uses the pyDS9 library to provide an interface between SAO DS9 and Python and loads each image so the users can identify the 0th order, rotation angle of the spectra, vertical width of the spectra, and where to measure the background values.

Moving objects like asteroids and satellites require a flexible program for spectra extraction to avoid contamination from stars drifting by in rate tracked images. Standard photometry uses an inner circle to measure the source and an annulus to measure the background. The average background value is calculated and multiplied by the number of pixels inside the inner circle and subtracted from the source count. The same principle applies for spectra, however instead of an inner circle, a series of vertical rectangles one pixel wide are used. The satellite data was taken at a non-sidereal rate, therefore star trails are a source of error. We allow for the background rectangle to be moved anywhere in the image so the background measurement can be taken while trying to keep the measurements as close to the satellite spectra as possible while still avoiding star trails. An average background value can then be calculated and subtracted from each pixel value.

We conduct two-point wavelength calibration using an A-type star. The 0^{th} order is the primary position used in all data analyses, however, this also represents the 0 nm position. Therefore, the number of pixels between the 0^{th} order and the hydrogen 486.1nm line needs to be determined in order to get the wavelength calibration and spectral resolution at 550nm. Once the wavelength calibration is determined, the data set is analyzed one image at a time in order to determine the 0^{th} order and extract the background. Image extraction uses the 2D array to sum each vertical row of pixels then subtract the background and apply the wavelength calibration. The result is a raw extracted spectrum that is wavelength calibrated and individual spectra of the RSOs are then combined into a single average. This process is repeated for a G-type solar analog star to develop a solar analog average. The final step is to divide the raw averaged RSO spectra by the average solar analog, which can be turned into a reflectance versus wavelength plot.

5. PRELIMINARY RESULTS

As a proof of concept we tested the feasibility of using a transmission grating as a spectroscopy tool in a small aperture refractor while we were completing the construction of the 0.6-meter F/4 RAPTORS telescope. This telescope has a primary objective that is a 70 mm F/6 (420 mm focal length) apochromatic triplet. The 100 lines/inch transmission grating is located in a filter wheel between the telescope and a Starlight Xpress Trius-SX814 CMOS camera. We used an A-type star HD119537 for wavelength calibration and to determine the spectral resolution. The number of pixels between the 0^{th} order and the hydrogen alpha line at 486.1nm line has been determined to be 202 pixels. Thus, the wavelength calibration gives a 2.4nm/pixel resolution, a resolution of R=229 at 550nm. While this is higher resolution than necessary, it was perfectly acceptable for testing our reduction pipeline.

Fig 1 shows the spectrum of Anik F1-R from our prototype system. The spectrum is an average of 110 individual spectra each with an exposure time of 10 seconds. The scatter in the spectrum is due to the small aperture of the telescope but shows a broad rise in reflectance with an increase in wavelength. Due to higher dispersion, the spectrum has better spectral resolution (more data points) than our RAPTORS system.

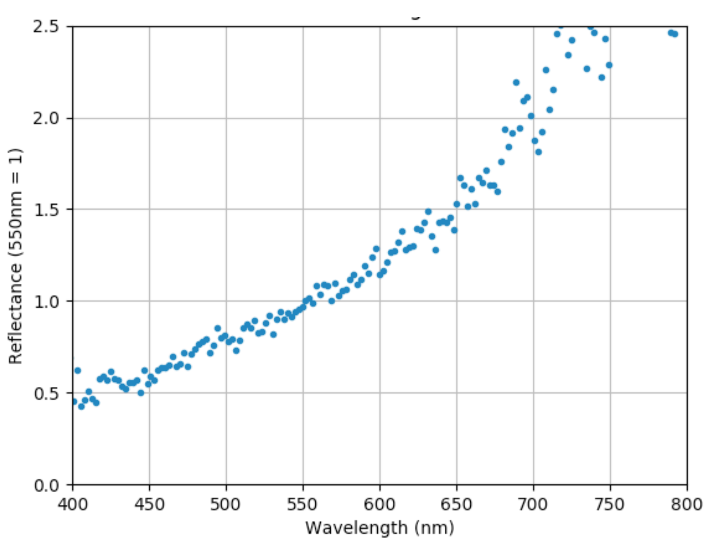

Figure 1. Visible wavelength spectrum of Anik F1-R from our prototype 70 mm F/4.2 refractor system. The spectrum is an average of 110 spectra each 10s long.

Encouraged by these early results, we collected spectra of the Anik F1-R cluster with our RAPTORS telescope. The image from the telescope is shown in Figure 2 with the four objects in the field marked for reference.

Since the image was captured while rate tracking GEO objects, the 0^{th} order image of the four RSOs appears as a point source where as the stars in the background are trailed along with their spectra. The spectra of Anik G1 and Anik F1-R overlap and hence their data could not be extracted for this paper.

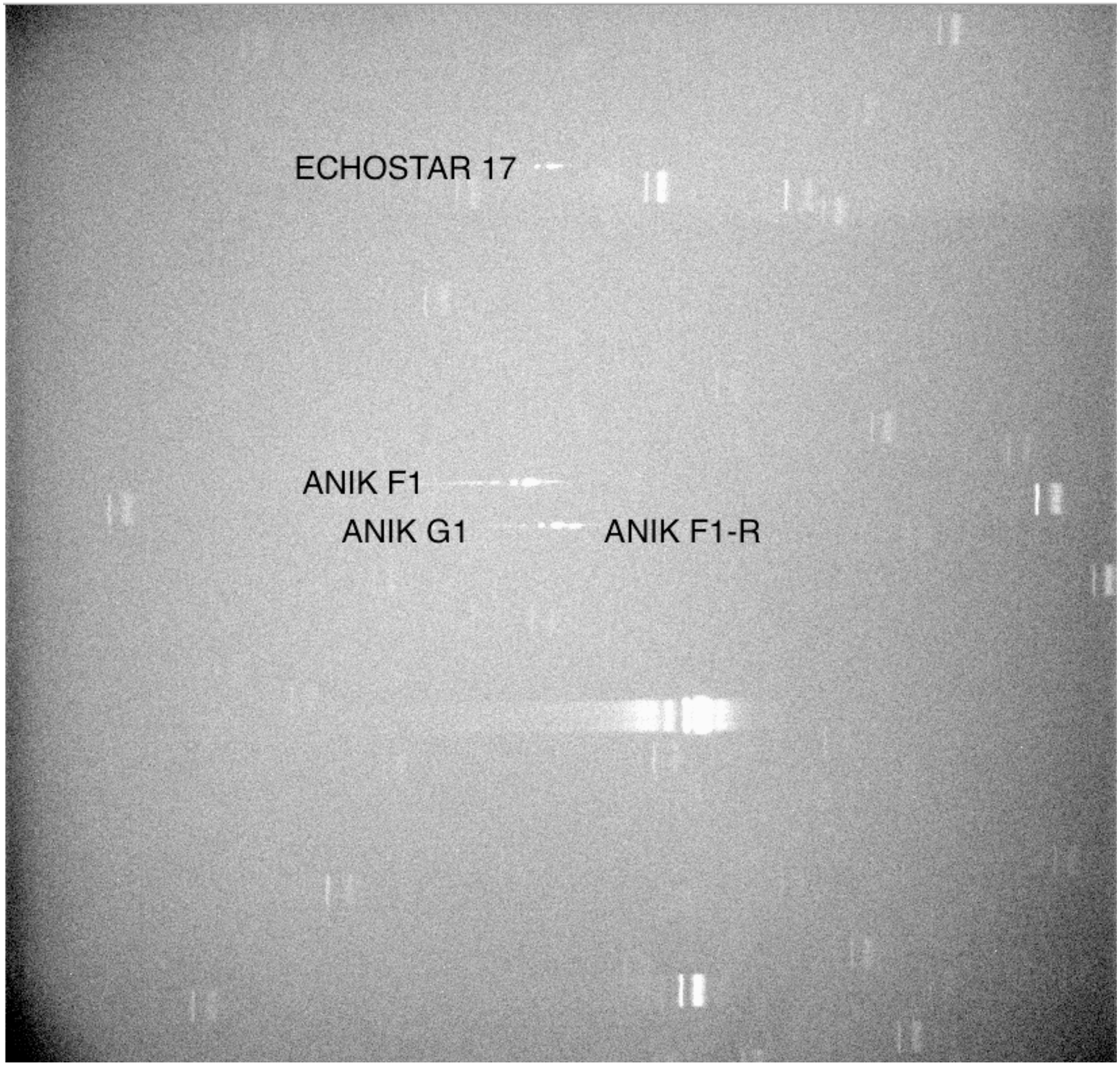

Figure 2. Rate tracked image from RAPTORS telescope located at the University of Arizona showing the Anik cluster. The field of view is 44x44 arc minutes with a pixel scale of 1.28 arcsec/pixel (2x bin). The image was taken with a 30 lines/inch transmission grating yielding in a resolution R~25 (20 nm/pixel). Each RSO has several components in the image. For example, Anik F1 has a 0^{th} order point source image followed by the 1^{st} order spectrum to the right and a fainter 2^{nd} order to its right. On the left side of the 0^{th} order are fainter -1 and -2 order spectra. The 1^{st} order spectrum contains the most amount of signal and is used for analysis. Note that the spectrum spans only 25 pixels due to the low dispersion.

Using the same python code we used for the proof of concept, we extracted the spectra from Anik F1 and ECHOSTAR 17, which are shown in Figure 3. Compared to our proof of concept spectra from the 70 mm refractor, the RAPTORS spectrum spans only 21 data points between 400 and 800 nm due to lower dispersion. Normalizing the spectra of the two objects (Figure 4) at 550 nm (V filter) shows the spectrum of Anik F1 is bluer (lower reflectance) shortward of 550 nm than ECHOSTAR 17. Both objects show a drop in reflectance ~750 nm which could be due to telluric oxygen (A band). While slope differences are not diagnostic of a particular material on the RSO, the technique shows promise to identify objects in a field with multiple objects if non-compositional effects such as phase angle could be accounted for.

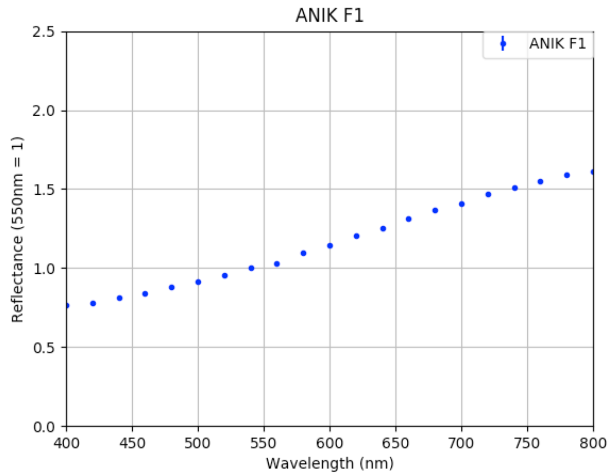

Figure 3. Visible wavelength reflectance spectra of Anik F1 (left) and ECHOSTAR 17 (right) obtained using RAPTORS 0.6-meter F/4 with a 30 lines/inch grating. The spectral resolution is R~25 (20 nm/pixel).

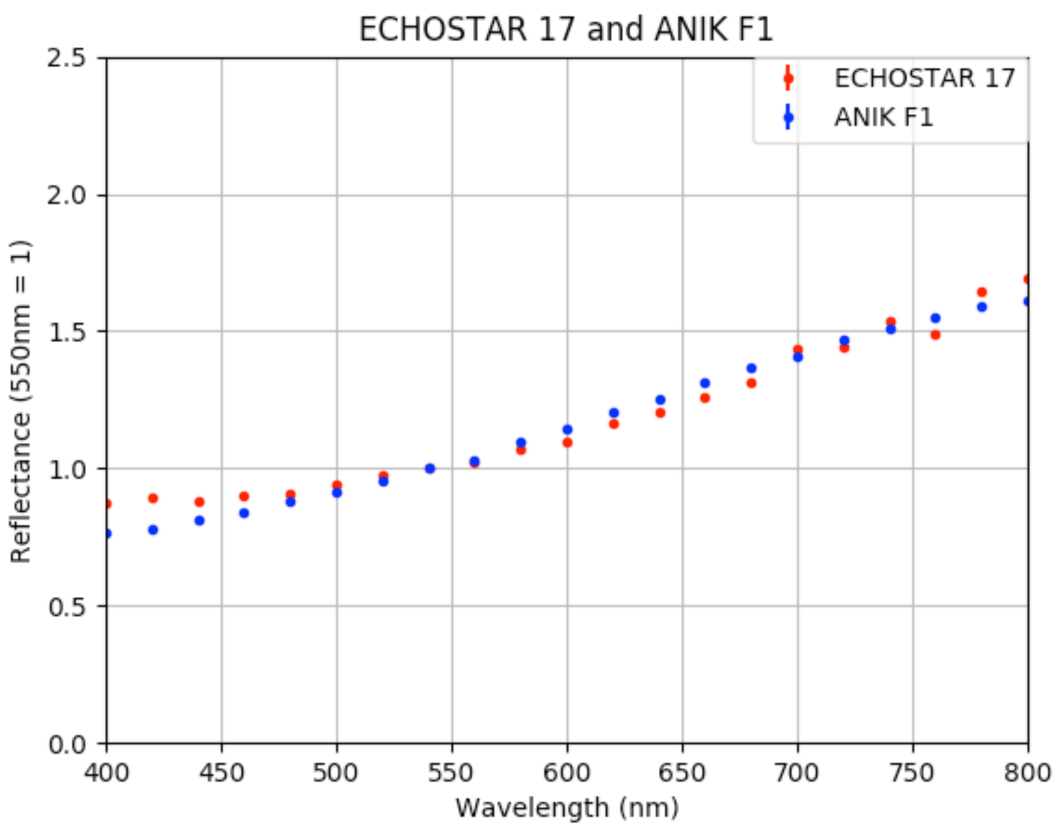

Figure 4. Normalized spectra of Anik F1 and ECHOSTAR 17 showing a difference in spectral slope shortward of 550 nm. This slope difference could be due to a range of compositional/non-compositional effects including phase angle.

6. FUTURE WORK

With a working pipeline, we are planning to start our regular survey operations starting mid-September 2018 with nightly data collection. Our sensor tasking software is capable of autonomous data collection (without any person in the loop) for 30 nights at a time. Data will be streamed in real time to CyVerse, an NSF funded cyber infrastructure for data management and analysis. We completed the tools necessary to upload the data automatically from the sensor to CyVerse and are currently in the process of automating the data reduction pipeline. RSOs spectral data can be potentially employed to devise a data-driven approach to classification of space objects. Recently, our team worked on employing deep learning methods to design, test and train a set of Convolutional Neural Networks (CNNs) capable of discriminating between different classes of RSO based on light curve information [8]. CNNs have been trained both on simulated and observed light curves and show promising results especially when compared with standard machine learning techniques [9]. The same methodology can be potentially applied to devise a set of CNNs that discriminate the object based on the observed spectral curves. It is expected that the CNN automatically learns a set of hierarchical features that reflect the most important spectral properties. One we collect a sufficient number of labeled spectral data we intend to train deep networks to uniquely identify the RSOs.

7. ACKNOWLEDGMENT

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