Characterization of NaK Coolant Droplets from Soviet RORSAT Reactors

Adam Battle
Lunar and Planetary Lab, University of Arizona

Tanner Campbell
Lunar and Planetary Lab, University of Arizona
Department of Aerospace and Mechanical Engineering, University of Arizona

Roberto Furfaro
Department of Systems and Industrial Engineering, University of Arizona

Vishnu Reddy
Lunar and Planetary Lab, University of Arizona

ABSTRACT

As technologies evolve and adversaries in the space domain implement new tools, the observing community must continue to push the limits of telescopes to counter those measures. Although much of the current focus is on catalog maintenance, characterization of active satellites and debris especially in low Earth orbit (LEO) is critical for a comprehensive Space Domain Awareness (SDA) mission.

The Radar Ocean Reconnaissance Satellites (RORSATs) were Soviet LEO radar reconnaissance satellites used to monitor ocean traffic. Thirty-three of these satellites were launched between 1967 and 1988 at a relatively low altitude of 200 – 250 km and used nuclear reactors for power. When these satellites were successfully retired, the reactors were ejected into a higher altitude graveyard orbit where they leaked droplets of the liquid metal sodium potassium (NaK) coolant used in the reactor.

Although most of the orbits of the millimeter to 1-cm-sized droplets have decayed, droplets larger than 1 cm will remain on orbit for several decades. Despite their small size, the velocity at which the debris travels means that they carry enough energy to cause serious damage to on-orbit assets. Their small size is part of what makes them dangerous. Objects between 1-10 cm are successfully detected by static SSA radar sensors. Current optical tracking systems typically cannot track particles of this size in LEO due to their faintness and fast rate of motion.

To exercise the tracking and characterization capabilities of the Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy II (RAPTORS II) on centimeter-size objects, we performed a test set of observations on NaK coolant from the Soviet Radar Ocean Reconnaissance (RORSAT) satellites' nuclear reactors.

We performed observations of five of these coolant droplets on 14 Oct. 2022 to test the capabilities of our systems on these small, fast-moving LEO debris. Based on documented radar cross sections, these objects have diameters on the order of 10 cm and the observed visual magnitude ranged from ~13 - 16. We present the results of our photometry and spectroscopy of these objects, demonstrating our ability to track and characterize small, high-albedo targets with a small aperture telescope.

1. INTRODUCTION

Orbital debris can have many origins including spacecraft collisions, flecks of paint, launch vehicle upper stages, and other causes, both intentional and accidental. More than 25,000 pieces of debris larger than 10 cm are known and another 500,000 debris objects in the 1 – 10 cm range are on orbit. While the larger objects (> 10 cm) are routinely tracked with optical systems in the U.S. Space Surveillance Network, objects in the 1 – 10 cm size range are not routinely tracked and can only be detected. The population estimate for this size range comes from static radar systems that are capable of detecting, but not tracking, objects as small as 3 mm [1]. Thus, the tracking and characterization of objects in the 1 – 10 cm size range is a current gap in routine space situational awareness (SSA) capabilities. In this study, we focus on drops of liquid metal coolant released from the Soviet Radar Ocean Reconnaissance Satellites (RORSATs) upon their decommissioning [2]–[4].

RORSATs were Soviet satellites used for monitoring ocean traffic and 33 were launched between 1967 and 1988 [5]. To maximize signal return to the radar, the satellites were stationed in low-Earth orbits (~200 – 250 km). Due to the low orbital altitude, however, the use of solar panels was unfeasible as they would have produced too much drag on the satellites; RORSATs were instead powered by nuclear reactors. Upon their decommissioning, the nuclear reactor was jettisoned to a disposal orbit (900 – 950 km), but residual pressure in the coolant lines expelled droplets of the liquid-metal sodium potassium (NaK) onto orbit [2], [6], [7].

References [6], [7] report that there were originally approximately a million droplets, but most of the smaller droplets decayed into Earth's atmosphere by the 1990s. Drops larger than ~1 cm will remain on orbit for several decades and there are an estimated ~50,000 of this sized droplet on orbit currently [6]. Despite their relatively small size, these particles still have enough energy to cause catastrophic damage to other spacecraft on orbit [1]. The goal of this study is to successfully track and characterize several of these NaK droplets with a small, optical telescope. We present preliminary brightness measurements and a visible reflectance spectrum from two nights of observations. These observations will help bridge the gap between radar detections and optical tracking and characterization of these small objects to better understand of the physical characteristics of the debris population on orbit and expand the capabilities of small telescopes for this application.

2. OBSERVATIONS

The Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy II (RAPTORS) telescope is a 0.61-meter, f/4.64 altitude-azimuth mounted Newtonian reflector located at the Biosphere 2 Space Situational Awareness Observatory outside of Tucson, AZ. The telescope is equipped with a ZWO ASI 6200 CMOS detector and a filter wheel with a transmission grating, resulting in a slitless spectrometer system in the wavelength range of 400 – 800 nm (R~300 at 450 nm).

Observations were obtained by tracking at the debris' orbital rates and acquiring images for the duration of the satellite pass. Stable G2V spectral type or equivalent solar analog stars were observed once per night to calibrate the satellite spectra into reflectance measurements. Table 1 shows the nights of data collection and the targets observed on those nights.

Table 1. List of objects observed for this study and their size estimate, derived from radar cross sectional area retrieved from N2YO.com

Object Name	Norad ID	Date Observed (UTC)	Filter	Size Estimate (cm)
Cosmos 860 Coolant	29195	2022 Oct. 14	Open	10.8
Cosmos 860 Coolant	29196	2022 Oct. 14	Open	11.1
Cosmos 1579 Coolant	26521	2022 Oct. 14	Open	7.3
Cosmos 1579 Coolant	27573	2022 Oct. 14	Open	6.6
Cosmos 1579 Coolant	27638	2022 Oct. 14	Open	6.7
Cosmos 1579 Coolant	26514	2022 Oct. 21	Diffraction Grating	7.5

3. METHODOLOGY

This study continues to build upon our network on small-aperture telescopes performing visible spectroscopy. The extraction of spectra is performed using a custom Python pipeline established in [8]. Wavelength is calculated based on the number of pixels from the zeroth order point source's centroid and then multiplied by the known resolution of the system. Flux is summed in each column along the spectrum in the image and each resulting spectrum is self-normalized at the user-defined wavelength. Spectra of the target are divided by a solar analog star's spectrum to produce a reflectance spectrum.

Target centroiding is performed by Source Extractor [9]with a detection threshold of 1.5-sigma above the background. Using this as a metric for detection, we can estimate the detection limit for the coolant droplets during our observations. A smaller aperture is used for detection than for photometry correlating to a single full width at half maximum (FWHM) of the point spread function (PSF). The median FWHM for the satellites observed was 6.8 pixel, corresponding to 3.6” which is on the order of the seeing at the site during observations. Filling an aperture of this size with the 1.5-sigma counts above the background and using the night’s zero-point magnitude to estimate this brightness gives us our hypothetical detection threshold. For the night of observations, the median detection threshold across all five photometric targets was ~16.6 Gaia G mag.

The spectral resolution was initially calculated using the grating equation for this system and was adjusted and verified by comparing our spectra with archival spectra of an asteroid. We observed asteroid (6) Hebe on 2023 May 03 and compare our results with both archival NASA visible spectra from the Small Main-belt Asteroid Spectroscopic Survey (SMASS) [10] spectra of the asteroid and our own RAPTORS I data. All spectra were taken at similar phase angles. The process was repeated for asteroid (13) Egeria on 2021 April 25 and data was compared to archival SMASS data in order to best estimate the resolution. Fig. 1 shows the resulting comparisons.

4. PRELIMINARY RESULTS

Validation of our resolution and observing capabilities is performed on bright asteroids (6) Hebe and (13) Egeria which have well-known reflectance spectra in the visible (0.4 – 0.9 μm) and near-infrared (0.7 – 2.5 μm). Fig. 1 shows the resulting reflectance spectra compared with archival spectra from SMASS and our RAPTORS I telescope which has been previously validated [8]. The resolution was altered in 0.01 nm steps to find the best resolution that matched both asteroid observations resulting in a 1.45 nm px^{-1} resolution.

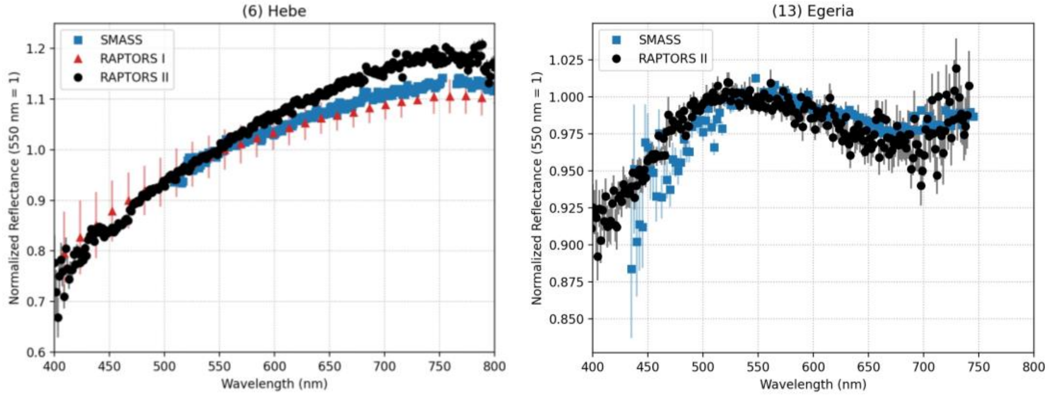

Fig. 1. Comparison of asteroid data to validate the RAPTORS II spectral resolution. (Left) Asteroid (6) Hebe is an S-type asteroid with prominent absorption features near 0.9 μm which cannot be observed by RAPTORS II. (Right) Asteroid (13) Egeria is a Ch-type asteroid with a subtle 0.7 μm feature that is well approximated by RAPTORS II. Archival data is from SMASS [10].

With the spectral resolution well-defined, we can generate spectra of objects we wish to characterize. The reflectance of one of the coolant droplets is shown in Fig. 2. The spectrum is largely flat from 400 – 650 nm, with no discernable features or slope outside of the noise. In wavelengths redder than 650 nm, the reflectance begins to increase. There is a potential absorption feature near 710 nm, but it is hard to say with confidence due to the uncertainty from observing such a faint target. This wavelength is near a 715 – 730 nm atmospheric water absorption band. Further analysis and more data is needed to better identify if this is an absorption due to the atmosphere or from the NaK droplet itself. Although the experimental setup is very different from on-orbit conditions, reference [11] notes a major absorption band in both Na and K at this wavelength, but not in the eutectic phase NaK that was used in the RORSAT nuclear reactors.

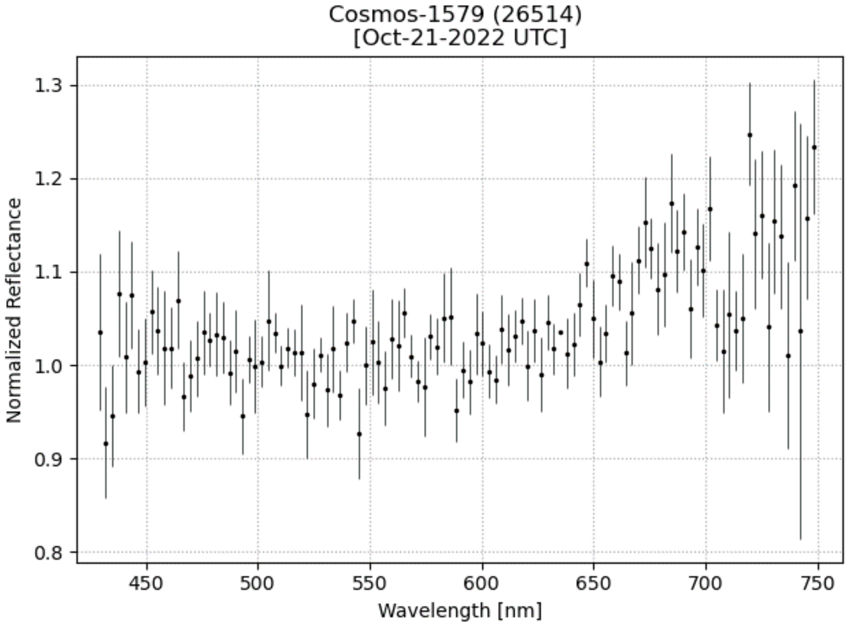

Fig. 2 Reflectance spectrum of Cosmos 1579 Coolant droplet (26514) which is estimated to be 7.5 cm in diameter. The spectrum is normalized to 550 nm.

We use three luminosity type G stars to estimate the brightness of five coolant droplets observed on 2022 Oct. 14 UTC. These measurements of the coolant droplets can help establish a brightness range for future studies that may search for new droplets. In Table 2, we show the observed brightnesses of each target. Together, the targets observed have an average brightness of 14.4 G magnitude, with a standard deviation of each target's average brightness of 1.3 G magnitude.

Table 2. Photometric estimates for coolant droplets observed. The variance in each object's brightness is assumed to be dominated by changes in phase angle as the object crosses the sky.

Object Name	Norad ID	Gaia G Mag ± 1σ
Cosmos 860 Coolant	29195	15.6 ± 0.3
Cosmos 860 Coolant	29196	15.8 ± 0.2
Cosmos 1579 Coolant	26521	13.1 ± 0.2
Cosmos 1579 Coolant	27573	14.4 ± 0.4
Cosmos 1579 Coolant	27638	13.0 ± 0.2

5. DISCUSSION

We present observations of asteroids (6) Hebe and (13) Egeria for validation of our telescope spectroscopy setup. Brightness estimates of five coolant droplets and the visible reflectance spectrum of one droplet from the Soviet RORSAT program are also presented to help understand the characteristics of the debris environment in low-Earth orbit. The brightness of the objects ranges from 13.0 – 15.8 Gaia G magnitude with an average of 14.4 G mag. Brightness differences among droplets could be due to size, range to the target, and the observed phase angle.

Although a few laboratory studies have investigated the reflectance spectrum of NaK, the composition and experimental conditions do not always match what is expected in the space environment (i.e., temperature and vacuum). Some of these experiments have also produced spectra of the metal while it is reacting with the atmosphere, which would not be representative of the droplets on orbit [11], [12]. This work provides an opportunity to understand the physical characteristics of these droplets since laboratory studies of sodium-potassium are difficult due to the volatile nature of the material. Our reflectance spectra show a mostly featureless spectrum for most wavelengths which we might expect from the highly reflective, liquid metal droplets. A subtle absorption band near 710 nm may be indicative of the physical state of the droplet, but more lab studies or modeling of NaK's properties would need to be conducted to give context to those observations. More spectral observations are also needed to confirm any proposed absorption bands and identify other potential features of the droplets.

Future work will expand greatly on these observations and will sample a larger subset of the coolant droplet population. In addition to the observations of the coolant droplets, we will include observations of stars with known, absolute flux spectra from the Hubble CalSpec library [13], [14]. These targets will be used to estimate the albedo of the droplets which has been suggested to be lower than laboratory measurements [3], [15]. Spectra of the droplets on orbit may also suggest a cause for this difference.

This proof-of-concept study has shown that small aperture telescopes are capable of tracking and characterizing small debris in low-Earth orbit. We present data that is useful for characterizing the population of debris in the gap between current radar detection methods and routine optical tracking efforts. This cm-sized debris is still potentially hazardous to spacecraft on orbit and, for the unique cause of the NaK droplets, telescope characterization may be the best method for understanding the physical properties of the population due to the difficulty of laboratory measurements of the highly reactive substance.

6. ACKNOWLEDGEMENTS

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