

Time-resolved CubeSat photometry with a low cost electro-optics system

Forrest Gasdia, Aroh Barjatya, Sergei Bilardi

Department of Physical Sciences, Embry-Riddle Aeronautical University

ABSTRACT

Once the orbits of small debris or CubeSats are determined, optical rate-track follow-up observations can provide information for characterization or identification of these objects. Using the Celestron 11" RASA telescope and an inexpensive CMOS machine vision camera, we have obtained time-series photometry from dozens of passes of small satellites and CubeSats over sites in Florida and Massachusetts. The fast readout time of the CMOS detector allows temporally resolved sampling of glints from small wire antennae and structural facets of rapidly tumbling objects. Because the shape of most CubeSats is known, these light curves can be used in a mission support function for small satellite operators to diagnose or verify the proper functioning of an attitude control system or deployed antenna or instrument. We call this telescope system and the accompanying analysis tools OSCOM for Optical tracking and Spectral characterization of CubeSats for Operational Missions. We introduce the capability of OSCOM for space object characterization, and present photometric observations demonstrating the potential of high frame rate small satellite photometry.

1. INTRODUCTION AND BACKGROUND

Between 2000 and 2015, more than 1 in 3 typical CubeSats to reach orbit suffered mission failure [1]. Additionally, the low cost of entry, rapid development cycle, and increasing capability of microelectronics has led to an exponential growth in the number of CubeSats launched each year. In order to provide feedback to satellite operators and scientists on the performance of their satellite, enhanced failure analysis to spacecraft engineers, and identification and characterization of CubeSats as they end their operational phase and become debris for other satellites, Embry-Riddle Aeronautical University developed the OSCOM system in 2014. OSCOM, which stands for Optical tracking and Spectral characterization of CubeSats for Operational Missions, is a system of hardware and software for observation and analysis of small satellite optical signatures. The primary function of OSCOM is targeted characterization and physical state estimation of small satellites and debris with known low earth orbits rather than detection of these objects. OSCOM therefore utilizes rate-track observations instead of staring optics and streak detection.

To produce photometry at several samples per second for CubeSat-class satellites or debris, OSCOM takes advantage of recent developments in commercial-off-the-shelf (COTS) hardware. The result is an inexpensive and portable, yet sensitive telescope system which can be deployed alone or in multiples for simultaneous multi-color or multi-site observations. The image data is then reduced, processed, and analyzed by a custom OSCOM Python package in order to promptly provide results from each observation.

In section 2, we describe the OSCOM system and how it can be deployed for observations. In section 3, we provide several sample light curves that demonstrate the ability of the system to observe CubeSats and nanosats. Finally, in section 4 we discuss ongoing work to utilize OSCOM for small satellite operational mission support by integrating optical markers onto the spacecraft bus.

2. SYSTEM DESCRIPTION

Following the Raven system paradigm, OSCOM chose to utilize entirely COTS hardware in order to minimize the cost and development time of the system [2]. The goal was to produce an electro-optical system capable of imaging CubeSats at up to 10 Hz and larger objects at rates exceeding 100 Hz. Additionally, a wide field of view was important in order to accommodate CubeSats with old or inaccurate orbital elements, and it was necessary to balance the pixel sampling to maximize satellite signal against the background sky.

The introduction of the Rowe-Ackermann Schmidt Astrograph by Celestron provided high throughput optics at $f/2.2$ for low cost. OSCOM has utilized the 11" optical tube, which is available for only \$3,500 [3]. This same telescope series has been reviewed in greater detail by reference [4]. We pair the RASA with the Manta G-235 machine vision camera made by Allied Vision. The Manta is a CMOS camera with a global shutter Sony Pregius IMX174 monochrome sensor, and is available for only \$1300 [5]. The camera has a peak QE of about 70% and produces 12 bit imagery at about 25 frames per second. A cropped region of the sensor can be read out for higher frame rates. When paired with the 11" RASA, the field of view is $1^\circ \times 0.7^\circ$. Sloan Digital Sky Survey (SDSS) u'g'r'i'z' filters can be inserted into the light path to provide color information; otherwise, no filters are used for maximum radiometric sensitivity.



Fig. 1. The 11" Celestron RASA and Manta G-235 on a Losmandy G11 mount in Needham, MA before a night of observations.

The RASA/Manta system has been mounted on several COTS tracking mounts: a Losmandy G11, Software Bisque Paramount MX, and Paramount ME. Each of these mounts are controlled by custom OSCOM software which uses Two Line Element sets (TLEs) published by Space-Track.org to provide initial pointing and rate-track information to the mounts. If the target satellite is captured near the edge of the field due to errors in pointing or the published TLE, a human operator or machine vision algorithm can provide inputs to the mount to center the satellite while tracking.

Most OSCOM observations have been made from permanently mounted piers on the veranda of the College of Arts and Sciences building on Embry-Riddle's Daytona Beach campus. The veranda is specially designed to not retain heat from solar heating during the day and the piers are mounted independently from the roof deck in order to isolate vibrations from the footsteps of telescope operators. On several occasions the system has been deployed in the field operating entirely on battery power. These observations have been made with a tripod-mounted Paramount ME from the Palm Beach area in Florida and from a tripod-mounted G11 in the suburbs of Boston, Massachusetts. The portability of the system has allowed us to be flexible when choosing sites for simultaneous observations of particular satellites.

After data is collected, it is processed using an OSCOM Python software package called the Optical Satellite Analysis Toolkit. This tool provides image processing, reduction, photometry, and analysis algorithms in a single multi-threaded environment in order to efficiently process large sets of image data. Typically, a single short script can be developed for a particular observing campaign and be run for tens or hundreds of thousands of images over as many nights of observation as necessary.

3. SAMPLE LIGHT CURVES

In its most basic form, OSCOM can be operated with as little as \$10,000 of hardware. Despite the low cost, it is capable of capturing photometric measurements of nanosats and CubeSats at up to about 10 Hz. This relatively high temporal resolution reveals the presence of smaller facets or sharper glints that would otherwise be averaged out if longer integration times are used. In this section, we present several representative light curves of small satellites taken by OSCOM. The light curves were created by performing standard bias and flat image reduction followed by circular aperture photometry with OSCOM's Optical Satellite Analysis Toolkit. The background value is determined across the immediate area around the satellite and subtracted from the image before summing the flux in the satellite aperture and converting to astronomical magnitudes. The error bars shown are the single frame photometric error. Each light curve is corrected for first order atmospheric extinction, normalized for satellite range, and shifted in magnitude to approximately match the true apparent magnitude of the brightest glint. No corrections are made for changing solar phase angle throughout the pass.

The Orbiting Picosatellite Automatic Launcher (OPAL) was the second Satellite Quick Research Testbed (SQUIRT) satellite developed by the Space Systems Development Laboratory (SSDL) at Stanford University and the largest satellite with a light curve presented here. The OPAL spacecraft is shaped like a hexagonal prism and has a total of four UHF monopole antennas mounted on the top and bottom panels. OPAL deployed six picosats on orbit and continued to provide long-term characterization of the bus and magnetometer. OPAL does not have a complete attitude control system, but it does have a passive damper to ensure the satellite will spin around only one axis [6]. OPAL's light curve (Fig. 2) shows smooth and steady variation.

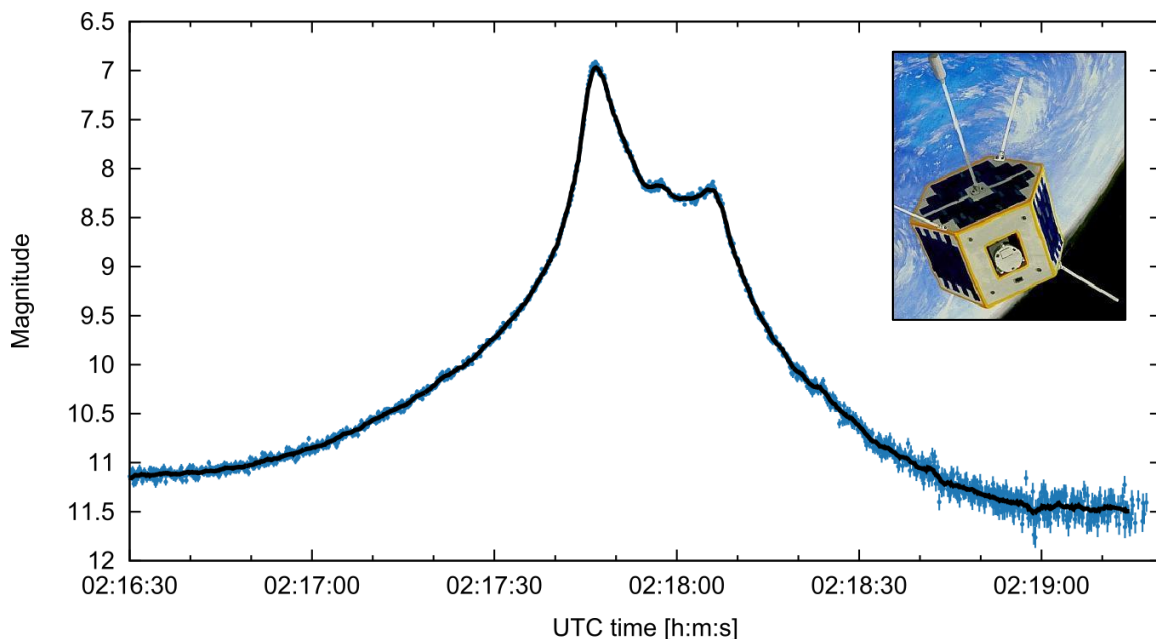


Fig. 2. An OPAL pass observed from Needham, MA on August 1, 2015 with 80 ms integration time. In the inset, an artist's rendition of the OPAL satellite in orbit [7].

The second largest satellite presented in this paper is DANDE, the Drag and Atmospheric Neutral Density Explorer. DANDE is a half-meter diameter sphere covered with small flat solar cells and was developed by University of Colorado at Boulder as part of the University Nanosat Program. DANDE's primary mission is to provide a better understanding of the satellite drag environment in the lower-thermosphere. DANDE was designed to be spin stabilized around the orbit normal vector perpendicular to the equator of the sphere at a nominal rate of 10 rpm, although contact was lost with the satellite in early 2014. DANDE is in an elliptical orbit of 320×1375 km and was at a slant range between 1000 and 2000 km during the light curve shown in Fig. 3.

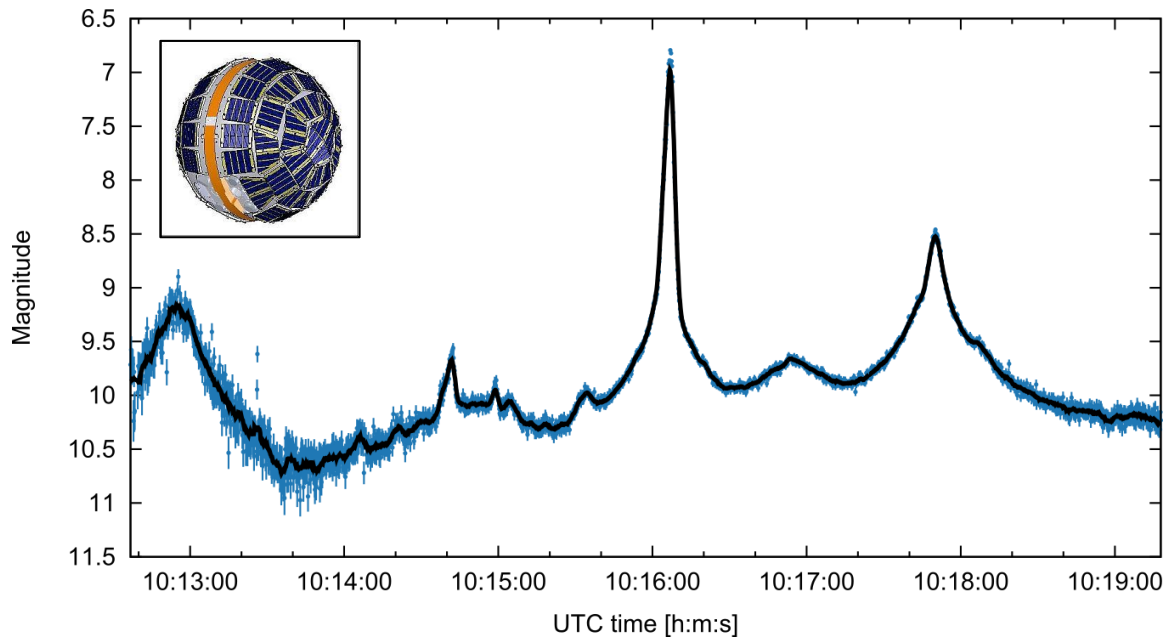


Fig. 3. DANDE observed for over 6 minutes from Daytona Beach, FL on January 18, 2016 with 100 ms integration time. In the inset, an illustration of the DANDE satellite [8].

CanX-6, also known as the Nanosat Tracking Ships (NTS), is a 20 cm cube using the Generic Nanosatellite Bus (GNB) developed by the Space Flight Laboratory (SFL) in conjunction with the University of Toronto Institute for Aerospace Studies (UTIAS). The primary mission of NTS is to demonstrate key components of a space-based Automatic Identification System (AIS) for detecting ships. CanX-6 is in a 600 km orbit and has 4 wire UHF antennas and a black VHF payload antenna. Using the Generic Nanosatellite Bus it has full 3-axis attitude determination and control for inertial or orbit-frame alignment. Several GNB satellites, including CanX-3, 4, and AISSat, have been observed on multiple occasions by OSCOM, including the observation of CanX-6 that produced the light curve in Fig. 4, below. OSCOM's sample rate is usually limited by the integration time necessary for providing a reasonable signal-to-noise ratio for small satellites, so with 150 ms integration, the light curve is captured at about 6.6 Hz.

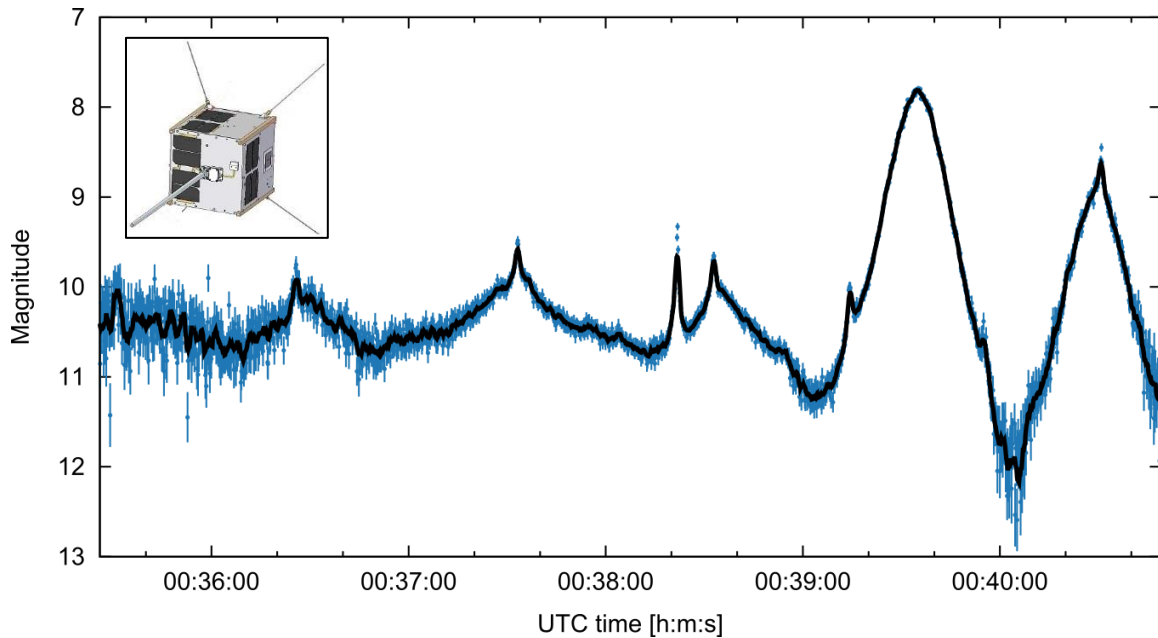


Fig. 4. CanX-6 observed for over 5 minutes from Daytona Beach, FL with integration time 150 ms on April 9, 2016. In the inset, a diagram of the CanX-6 nanosat with VHF antenna.

CINEMA, the CubeSat for Ion, Neutral, Electron, Magnetic fields, is an international nanosatellite mission with collaborating institutions in the United States, United Kingdom, and Korea. CINEMA's main objective is to provide critical space weather measurements including mapping of energetic neutral atoms from low Earth orbit. The spacecraft is a 3U CubeSat with a magnetometer on the end of a 1 meter long boom. During operation, it was spin stabilized nominally at 4 rpm with the spin axis oriented normal to the ecliptic plane [9]. In Fig. 5 is one of a series of 40 second glints from CINEMA-2 (KHUSAT-1) observed on the night of April 9, 2016 from Daytona Beach, FL. This satellite was confirmed operating in 2014, but its mission had ended at the time of observation.

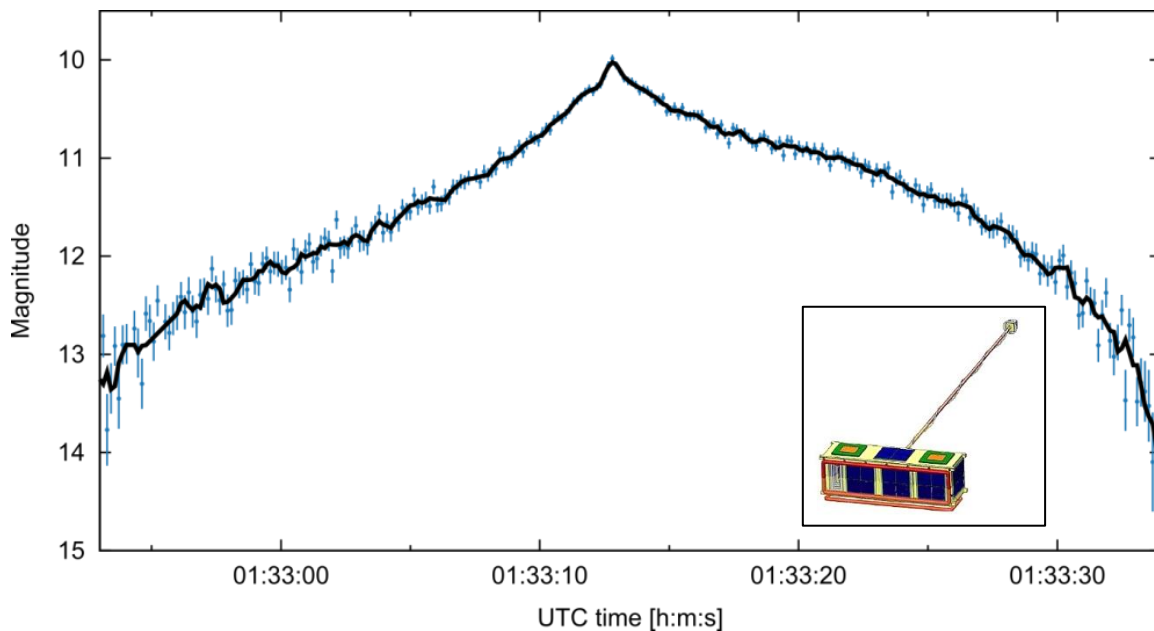


Fig. 5. One glint off the CINEMA-2 (KHUSAT-1) CubeSat observed April 9, 2016 from Daytona Beach, FL with 150 ms exposures. In the inset, a diagram of the CINEMA CubeSat with 1 m magnetometer boom deployed [10].

The Dynamic Ionosphere CubeSat Experiment (DICE) is a pair of 1.5U CubeSats and is the smallest satellite bus shown here. DICE's primary mission was to map geomagnetic storm enhanced density plasma bulge and plume formations in Earth's ionosphere. DICE has several expandable booms and antennae and is supposed to be spin stabilized about the body length axis and aligned parallel to Earth's rotation axis. Once a stable spin of approximately 2 Hz is achieved, the four 5 m electric field probe (EFP) booms are designed to begin slowly despooling. When fully deployed, the spin rate should be about 0.1 to 0.2 Hz [11]. Unfortunately, on neither DICE spacecraft could the EFP wire booms deploy. DICE-2 was able to achieve a stable spin about its z-axis, but had issues making consistent contact with the operations center and had electronics resets likely due to the space environment. DICE was not operational during our observations and thus it is unlikely DICE-2 was spinning at the nominal rate. The primary flash period of DICE-2 is 1.17 Hz, as shown in Fig. 6.

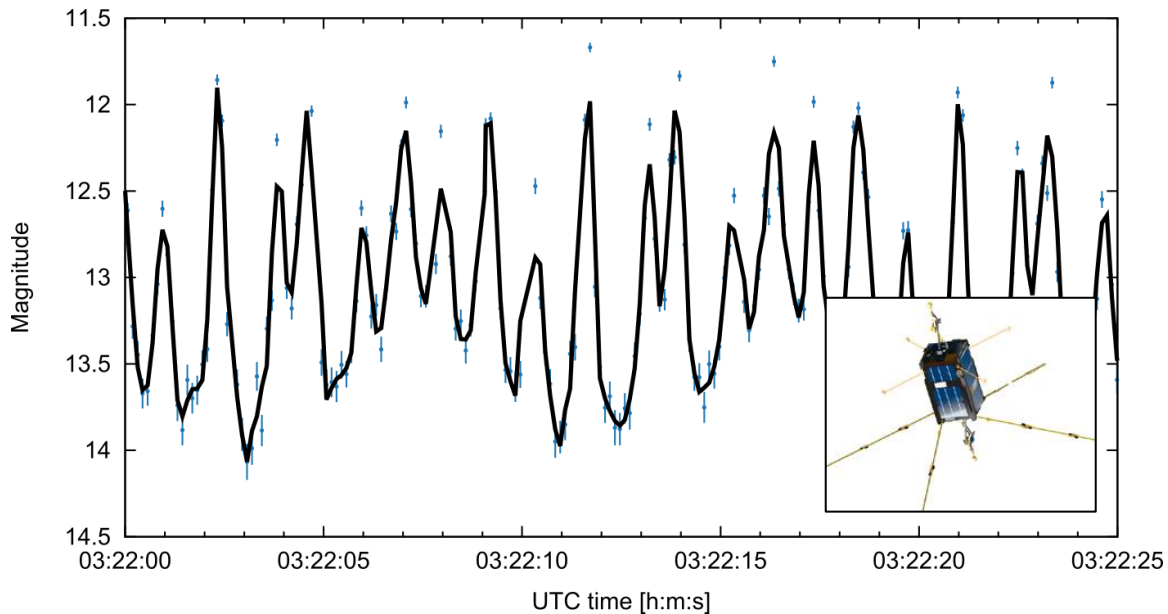


Fig. 6. DICE-2 observed from Needham, MA on August 1, 2015 using 125 ms integration time. Only 26 seconds are shown so the 1 second glints are clearly visible. In the inset, a diagram of DICE with electric field probe booms shown [12].

4. ONGOING WORK

A major goal of OSCOM is to use observed light curves for small satellite and CubeSat mission support. CubeSat failures may be due to several reasons: uncontrolled spin, failed antenna deployment, or unfavorable pointing leading to power loss. In such cases, optical observations are potentially the only resource for troubleshooting and failure analysis because they are completely independent of the satellite's telemetry data and condition. Optical observations can provide information on the state of spacecraft physical features and parameters. For example, telemetry might suggest that a solar panel has been deployed, but if the spacecraft registers low power in house-keeping data, then an optical observation can provide further evidence as to whether or not the solar panels were completely deployed. Optical telescope measurements can also assess spin-rates and possibly give some indication of spacecraft attitude.

Many CubeSats already have some identifying optical characteristics, such as number and size of antennae or other deployed instruments. We are reaching out to the university CubeSat community to assist in the next phase of OSCOM. By actively making small changes to a CubeSat bus, one can provide a more unique or useful reflected optical signature for simpler and more confident attitude or physical state estimation. One basic technique stems from the concept of albedo-area product. A satellite can be broken up into many individual facets each with an albedo-area product—the multiplication of the facet projected area and albedo of the surface material. This product directly drives the reflected brightness of the facet. Each illuminated facet that is visible to the observer contributes

to the total observed brightness of an unresolved satellite. Payne, et al. have shown the relationship between projected albedo-area product and aggregate photometric measurement and the product has been used by several others for objects in geosynchronous orbit (GEO) [13] [14].

For CubeSats, the albedo-area product offers two opportunities. For diffusely reflecting flat plates, there is a strong dependence on the plate area, especially when the area is very small, i.e. less than 0.1 m^2 [15]. This means that if a CubeSat is able to change its area slightly, there is a meaningful change in its magnitude. For CubeSats which have fixed size, the albedo of CubeSat rails can be changed by differential polishing: each consecutive rail is polished more than the one before it. This stepped change in albedo should provide a signature to help orient an observed light curve with respect to the real orientation of the satellite. Continuing work on multi-band color or spectral characteristics, as well as polarization, may also prove to be useful indicators on CubeSat buses.

5. CONCLUSION

Embry-Riddle's OSCOM system for optical tracking and spectral characterization produces CubeSat-class satellite photometry at up to about 10 Hz from an inexpensive and portable platform. This electro-optical system takes advantage of COTS hardware including the Celestron RASA and machine vision CMOS sensors. We have presented several examples of OSCOM nanosatellite photometry and have shared general plans to actively modify the optical signature of CubeSats in order to more easily estimate their attitude and mission status.

6. REFERENCES

- [1] Michael Swartwout, "CubeSats and Mission Success: A Look at the Numbers," , 2016.
- [2] Paul F. Sydney et al., "Raven automated small telescope systems," in *Imaging Technology and Telescopes*, oct 2000. [Online]. <http://dx.doi.org/10.1117/12.405780>
- [3] Celestron, LLC. (2014) Rowe-Ackermann Schmidt Astrograph. [Online]. <http://www.celestron.com/browse-shop/astronomy/optical-tubes/rowe-ackermann-schmidt-astrograph>
- [4] Mark Ackermann, Peter Zimmer, John McGraw, and Eric Kopit, "COTS Options for Low-Cost SSA," in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, 2015.
- [5] Allied Vision Technologies GmbH. Manta G-235. [Online]. <https://www.alliedvision.com/en/products/cameras/detail/Manta/G-235.html>
- [6] Brian Engberg, Jeff Ota, and Jason Suchman, "The OPAL Satellite Project: Continuing The Next Generation of Small Satellite Development," in *Ninth Annual AIAA/Utah State University Conference on Small Satellites*, 1995.
- [7] Space and Systems Development Library. (2016) OPAL (Orbiting Picosatellite Automatic Launcher). [Online]. <https://directory.eoportal.org/web/eoportal/satellite-missions/o/opal>
- [8] Lee Jasper and Kyle Kemble, "Drag and Atmospheric Neutral Density Explorer (DANDE) Spherical Spacecraft Design Challenges," University of Colorado at Boulder, 2009.
- [9] European Space Agency. (2016) eoPortal. [Online]. <https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cinema>
- [10] Gunter Dirk Krebs. (2016, Jan.) Gunter's Space Page. [Online]. http://space.skyrocket.de/doc_sdat/cinema.htm

- [11] Tim Neilsen, Cameron Weston, Chad Fish, and Bryan Bingham, "DICE: Challenges of Spinning CubeSats," in *37th Annual AAS Guidance & Control Conference*, 2014.
- [12] Space Dynamics Laboratory, "DICE Dynamic Ionosphere CubeSat Experiment," Utah State University Research Foundation, Logan, UT, 2013.
- [13] Tamara E. Payne et al., "A Derivation of the Analytical Relationship between the Projected Albedo-Area Product of a Space Object and its Aggregate Photometric Measurements," in *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, 2013, p. E33.
- [14] Brandoch Calef, John Africano, Brian Birge, Doyle Hall, and Paul Kervin, "Photometric signature inversion," in *Unconventional Imaging II*, aug 2006. [Online]. <http://dx.doi.org/10.1117/12.683015>
- [15] G. A. McCue, J. G. Williams, and J. M. Morford, "Optical characteristics of artificial satellites," *Planetary and Space Science*, 1971. [Online]. <http://www.sciencedirect.com/science/article/pii/0032063371901371>