Larger Optics and Improved Calibration Techniques for Small Satellite Observations with the ERAU OSCOM System

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ABSTRACT

OSCOM, Optical tracking and Spectral characterization of CubeSats for Operational Missions, is a system capable of providing time-resolved satellite photometry using commercial-off-the-shelf (COTS) hardware and custom tracking and analysis software. This system has acquired photometry of objects as small as CubeSats using a Celestron 11" RASA and an inexpensive CMOS machine vision camera. For satellites with known shapes, these light curves can be used to verify a satellite's attitude and the state of its deployed solar panels or antennae. While the OSCOM system can successfully track satellites and produce light curves, there is ongoing improvement towards increasing its automation while supporting additional mounts and telescopes. A newly acquired Celestron 14" Edge HD can be used with a Starizona Hyperstar to increase the SNR for small objects as well as extend beyond the limiting magnitude of the 11" RASA. OSCOM currently corrects instrumental brightness measurements for satellite range and observatory site average atmospheric extinction, but calibrated absolute brightness is required to determine information about satellites other than their spin rate, such as surface albedo. A calibration method that automatically detects and identifies background stars can use their catalog magnitudes to calibrate the brightness of the satellite in the image. We present a photometric light curve from both the 14" Edge HD and 11" RASA optical systems as well as plans for a calibration method that will perform background star photometry to efficiently determine calibrated satellite brightness in each frame.

1. INTRODUCTION AND BACKGROUND

OSCOM, which stands for Optical tracking and Spectral characterization of CubeSats for Operational Missions, is a hardware and software system developed at Embry-Riddle Aeronautical University in 2014 for observation and analysis of small satellite optical signatures. The team was driven by the high failure rate of CubeSats to find a way of independently providing feedback to satellite operators on the status of their satellites, enhance failure analysis, and characterize SmallSats as they end their operational phase and become debris for other satellites. OSCOM focuses on the targeted characterization and state estimation of satellites and debris with known orbits rather than detection and orbit determination of uncatalogued resident space objects (RSOs).

OSCOM typically uses a rate-track mode to observe satellites in low Earth orbit (LEO). This observation mode, coupled with sensitive commercial-off-the-shelf (COTS) CMOS machine vision cameras and optically fast telescope systems, allows photometric observations to occur at several samples per second, even for 1U (10 cm x 10 cm) CubeSats. The systems are relatively inexpensive and portable, which has allowed the OSCOM team to make simultaneous multi-color and multi-site observations including unique high frame rate observations in support of large satellite missions [1].

This paper provides an update on OSCOM's progress towards regular small satellite mission support using optical observations. Section 2 discusses new hardware and software development that has occurred over the last year and section 3 introduces our plan to provide consistent and calibrated photometric observations from OSCOM small telescope systems.

2. CURRENT DEVELOPMENT

OSCOM acquired additional equipment: a Celestron 14" Edge HD (C14) telescope with a Starizona Hyperstar, shown in Fig. 1. The C14 with Hyperstar has greater optical throughput than the Celestron 11" RASA that OSCOM primarily uses. This new system allows OSCOM to observe small satellites whose brightness is beyond the limiting magnitude of the 11” RASA. The C14 has dual functionality. Besides being used for photometric observations, it can be used without the Hyperstar to resolve large satellites such as the International Space Station or the Hubble Space Telescope. We have performed simultaneous observations of satellites using both the C14 with Hyperstar and RASA telescope systems with identical machine vision cameras. Fig. 2 shows the resulting light curves from each system.

Fig. 1. Picture of the Celestron 14” Edge HD with Hyperstar on top of a Losmandy Titan mount.

There are several OSCOM software programs currently under development. Earlier in the year, progress was made towards a more automated and user-friendly satellite tracking and mount control program. To advance our analysis of small satellite light curves, a new modeling program is being developed. This program simulates light curves that would be observed on the ground based off a satellite’s geometric model, attitude, and orbital parameters through two-line elements (TLEs). Finally, we are also developing an automated image calibration and photometry software to calibrate satellite instrumental magnitudes using the background stars in each frame. This is described in detail below.

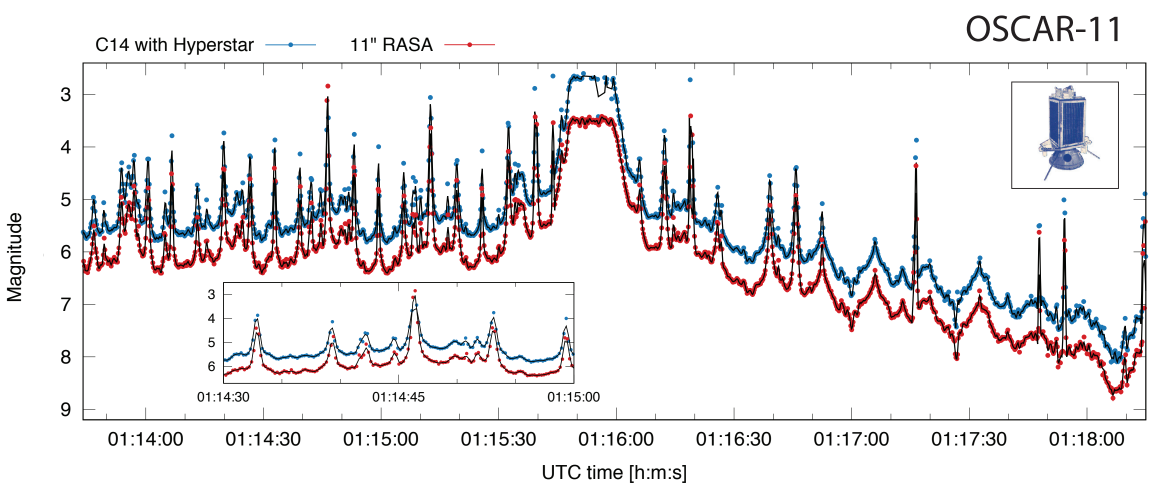

Fig. 2. The light curves of the satellite OSCAR-11 observed by the Celestron 14” Edge HD with Hyperstar and 11” RASA. Observation occurred from Daytona Beach, FL on May 25, 2017 and was acquired with 200ms integration time for both telescope systems. The inset is an artist’s rendition of the satellite [2].

3. AUTOMATING CALIBRATED PHOTOMETRY

Photometric observations by any ground-based telescope are biased and made noisy by instrument and environmental effects. Examples of these disturbances include noise in the readout of detector electronics, non-uniform spectral response in the electro-optics and through the atmosphere, and atmospheric scintillation above the observatory. If these system biases could be accounted for, the photometric observation approaches a radiometric measurement. Knowledge of the actual photon flux reflected by an RSO, as opposed to relative intensity measurements during a pass, allows estimation of surface properties and improved estimates of size and shape as the photometry becomes more precise. The most important characteristic of calibrated measurements is the ability to compare magnitudes of the same object between observations and even instrument systems. This improves the ability to perform change detection, fuse optical observations into multi-sensor SSA networks, and confidently monitor the state of RSOs over long periods of time.

Calibrating photometric measurements has always been a challenge for observational astronomers and the optical SSA community [3]. The atmosphere is dynamic over several timescales, no two instruments are alike, and not only are instruments not perfectly stable over time, but calibration sources typically are not either [4,5]. A particular challenge for optical observations is the spectral component of calibration. Observations are often made with broad filters to maximize sensitivity, but it then becomes complicated to separate color-dependent atmospheric effects from observations, even if the instrument system spectral response is known [6,7]. Although active calibration techniques have been suggested, these are expensive and not practical for the majority of observatories [8]. Unfortunately, because conventional calibration techniques using standard star fields across the sky require valuable telescope time, many observers may not be able to calibrate their data to a standard system on every night of observation.

With the rate-track mode commonly used by OSCOM, hundreds of background field stars are captured as streaks in the 1° field of view of OSCOM's telescopes. Each of these stars are relatively bright by astronomical standards and have had their photometric magnitudes recorded in several standard catalogues. We are working on a software tool to automatically use these field stars to calibrate the instrumental satellite magnitude to a standard system. A similar process has been demonstrated manually for asteroid observations [9]. This technique requires no additional observation time dedicated to observing standard star fields, while correcting for atmospheric extinction as it was at the time of satellite observation. The calibrated satellite magnitudes could then be corrected for range to produce an absolute constant-distance satellite magnitude, and possibly further corrected for solar phase angle during light curve analysis.

Our new software, under development, contains image reduction, streak detection, satellite detection, star identification, and magnitude correction stages. The software is implemented in C++ for speed and is expected to be fully automated using robust streak detection and star identification algorithms. Fig. 3 demonstrates the step by step process for the calibration of a single rate-track RSO frame. First, images are preprocessed to correct sensor bias, pixel-to-pixel variation, and optical vignetting. Next, star streaks are identified in each image, and streak center points are fed into a geometric matching algorithm to identify each of the stars in the field. General knowledge of the telescope pointing and satellite orbit produce a starting point for the algorithm. Once the stars are identified, photometry is performed on each star using an elongated elliptical or rectangular aperture. A weighted regression is then performed between the stellar instrumental magnitudes and catalog magnitudes and errors. Photometry is also performed on the satellite using a circular aperture and the satellite instrumental magnitude can then be put on a standard magnitude scale using the results of the regression. This regression can be performed rejecting outliers, e.g. variable stars, and using catalog magnitudes in multiple filters. The process is automatically repeated for every frame in the sequence of observations.

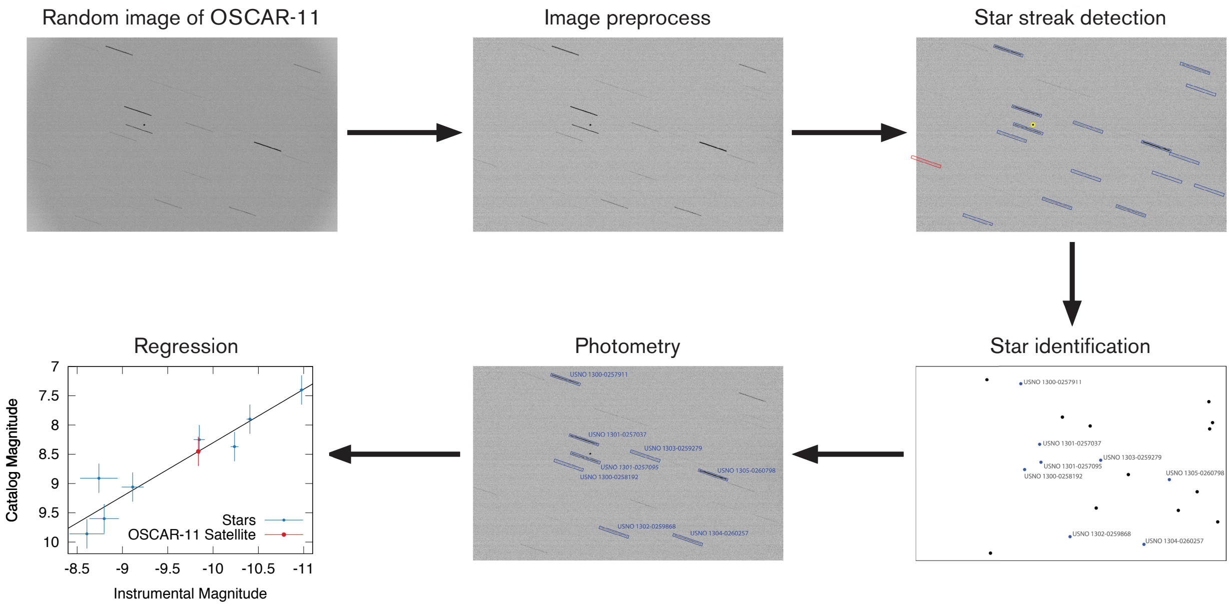

Fig. 3. Sample process of calibrating a single OSCOM satellite photometry frame using background field stars.

4. CONCLUSIONS

OSCOM has demonstrated the ability to produce temporally resolved optical observations of large through small RSOs, as well as simultaneous observations from multiple sites. Ongoing development efforts focus on ensuring data integrity and achieving automated operation. In this paper we have highlighted several examples of these efforts, including our expanded support and evaluation of new hardware, more user-friendly tracking and telescope control software, and an automated photometry analysis and calibration tool. Each of these advancements improve the consistency and regularity with which OSCOM can perform observations in support of small satellite operational missions.

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