Optical Tracking and Attitude Determination of LEO CubeSats with LEDs: A Balloon Demonstration

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ABSTRACT

The use of active illumination on CubeSats allows tracking of low Earth orbit (LEO) satellites during Earth eclipse with simple ground-based instruments. Position, attitude, and telemetry of spacecraft parameters can be determined using light emitting diodes (LEDs) on spacecraft. On the local night of May 10, 2018, the University of Michigan successfully flew and optically tracked a high-altitude balloon payload equipped with light emitting diodes (LEDs) as a prototype mission for a future LED CubeSat mission: Project LEDSAT. We present the results from this flight, which was actively tracked at a range of 54 km using an 85-mm aperture telescope and CMOS detector.

1. INTRODUCTION

The rapidly growing population of satellites in LEO means that new techniques will be needed for tracking, orbit determination, and spacecraft identification. Project LEDSAT will demonstrate the use of LEDs on LEO satellites combined with existing ground based optical telescopes to augment current LEO tracking methods. It is an international effort to evaluate the use of LEDs for position determination, attitude determination, and telemetry. For LEO satellites, the presence of LEDs means that the satellite can be tracked even during eclipse periods, increasing the number and duration of passes that the satellite can be observed. In the case of simultaneous launches of large numbers of CubeSats, LEDs could aid in rapid satellite identification after deployment. The University of Michigan and the University of Rome "La Sapienza" plan to launch separate CubeSats each equipped with LEDs for these purposes.

A description of the use of LEDs on CubeSats for precision positions, attitude determination, and spacecraft identification was outlined by this group in [1]. This work builds on the successful Japanese CubeSat FITSAT-1 [2] which demonstrated that LEDs flown on a 1U CubeSat in LEO could be detected on the ground with small optical instruments. The crucial difference between FITSAT-1 and LEDSAT is that LEDSAT is designed with very accurate and precise timing on the LED flashes for position and attitude determination.

The increasing rate of LEO small satellite deployments is a twofold issue since they orbit at large angular speeds and are generally deployed in large clusters. The fast speeds and low altitude of orbit mean that optical space surveillance assets do not have large windows to acquire information during a track. The optical sensor must be in darkness, while the satellite must be in sunlight. Additionally, when large clusters are deployed simultaneously, it can take ground centers more than 30 minutes to acquire situational awareness and identification of individual satellites in the cluster. Using LEDs with different flash patterns could be used to rapidly identify individual satellites. A simulation of two LEDSATs as they would appear in a wide-field ground-based telescope tracking at the sidereal rate shortly after deployment from the ISS is shown in Fig. 1 (from [1]).

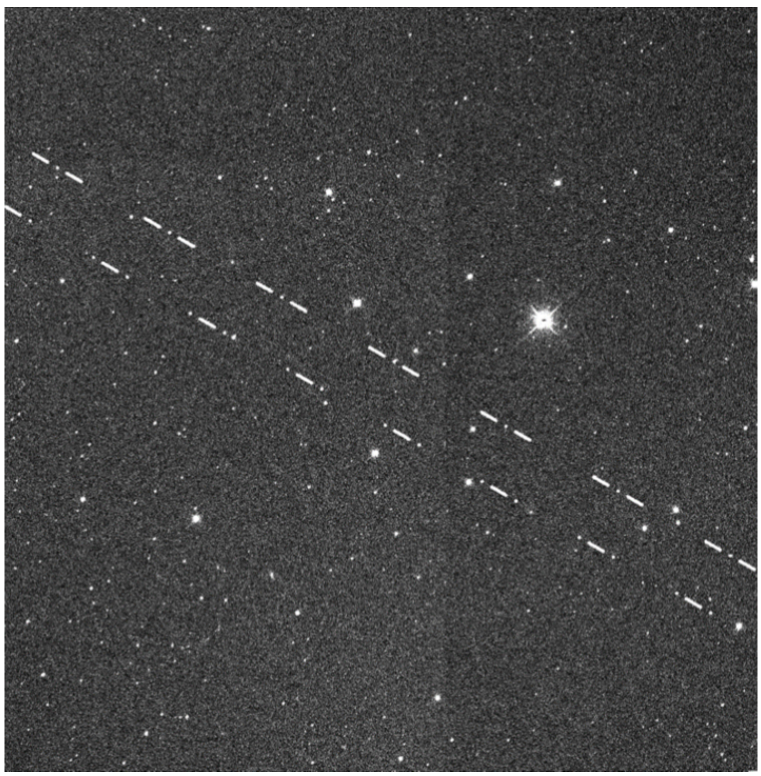

Fig. 1. Simulation of two LEDSATs crossing a starfield shortly after deployment. The upper transmits the Morse letter K, the lower the letter R. The dots are the same width as the stars. From [1].

A group at the Sapienza University of Rome has designed and is in the process of constructing a 1U CubeSat which will implement fully the LEDSAT mission concept [3]. This mission is a finalist in the European Space Agency's (ESA) *Fly Your Satellite* student satellite competition and is expected to fly in 2019 or 2020.

A different technology is also being investigated as a potential solution for in-space identification by the Extremely Low Resource Optical Identifier (ELROI) team at Los Alamos [4]. The difference between the two concepts is that all of the complexity is built on the spacecraft in the case of LEDSAT so that very simple ground-based telescopes and detectors can be used.

The balloon mission was conducted by the Michigan eXploration Laboratory (MXL), a research laboratory of the University of Michigan Aerospace Engineering Department. MXL has flown 7 CubeSats and 30 high-altitude balloon flights as technology demonstrations and science missions in collaboration with organizations such as NASA-JPL, NSF and SRI International. The optical tracking for the balloon mission was conducted by the Department of Astronomy of the University of Michigan, which used telescopes in southeastern Michigan to optically track the balloon payload.

The following sections will describe the design and results of the high-altitude balloon demonstration conducted by MXL and Michigan Astronomy.

2. High-Altitude Balloon (HAB) Mission Overview

The objective of the LED Initial Testing Experiment (LITE) mission was to launch a HAB at nighttime with a blinking LED payload to simulate a LEDSAT in Earth eclipse. The MXL and Michigan Astronomy team then would attempt to track it and capture images with the Angell Hall Observatory's 0.4-m and 85-mm aperture telescopes on the University of Michigan campus in Ann Arbor. Also, if it was possible with the data collected, the team would determine the brightness and attitude of the payload from post-processing captured images of the payload. The findings of this mission would be important because they would be the first field test of the signal-to-noise ratio (SNR) predictions made in the optical link budget estimated prior to the mission. The validation of these predictions would allow the team to determine LED parameters for future space-based missions.

The balloon mission consisted of 4 main elements: the LITE payload, the balloon and supporting equipment, the optical ground station, and chase teams with mobile radio ground stations.

The balloon train layout is shown in Fig. 2. The balloon train consists of a 1600-gram weather balloon, a 6-foot diameter parachute, a main line (laundry-line rope), an omni-directional radar reflector, a Byonics Automatic Packet Reporting Service (APRS) radio position transmitter, a secondary line (paracord), and the LITE payload module.

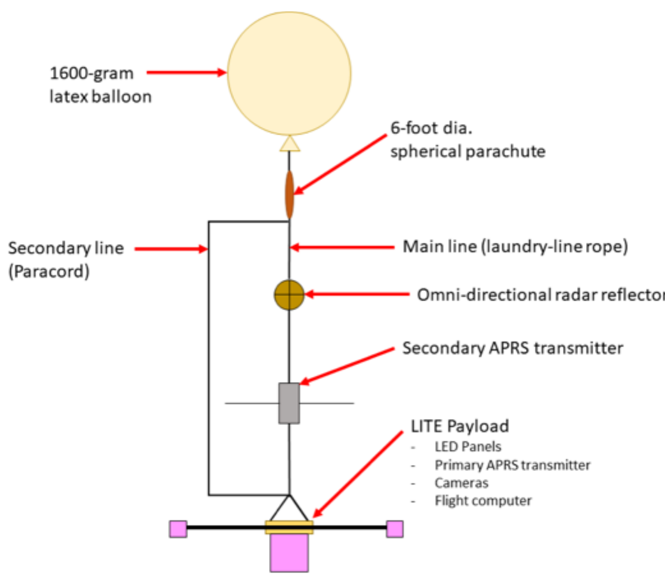

Fig. 2. HAB train layout for the LITE mission.

The LITE payload module, shown in Fig. 3, houses all of the science subsystems: the 2 LED panels, a GPS receiver, the secondary APRS transmitter, a Raspberry Pi flight computer (FCPU), an electrical power system (EPS), an attitude determination sensor suite, Kapton heaters, electrical harnessing, a 3D printed CubeSat-inspired structure, and inertial booms to help to stabilize payload rotation during the flight sequence for improved image quality and to attempt to simulate real in-space rotation rates. Two of the inertial booms housed GoPro cameras at the ends to verify proper payload operation in the event that images of the payload were not captured.

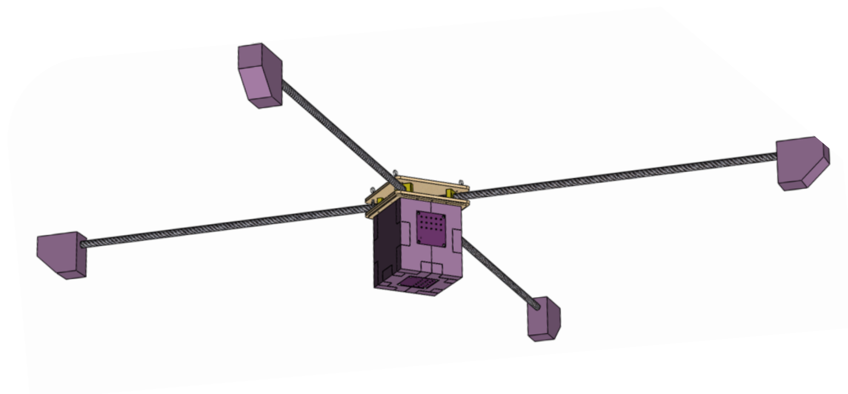

Fig. 3. LITE payload module with insulation and inertial booms.

The 2 on-board LED panels, which can be seen in more detail in Fig. 4, utilize 15 OSRAM JUKQ-1 626-nm (red) high power (1 Watt) LEDs each. The choice for 15 LEDs was made via a low-fidelity link budget analysis prior to the mission. Results from this mission will be used to calculate a higher fidelity link budget for future LEDSATs. The LEDs were arranged in a 5-series, 3-parallel configuration, and operated at 1 amp constant current, controlled with constant current driver circuitry. The panels each flashed a unique blink pattern, see Fig. 5. The blink patterns were chosen so that they would appear as point sources to a distant telescope, allowing for proper photometry and astrometry to be done during post-processing of the image data, the results of which can be seen in Section 3. The panels blink different patterns was so that they could be distinguished from one another in captured images, allowing for attitude determination.

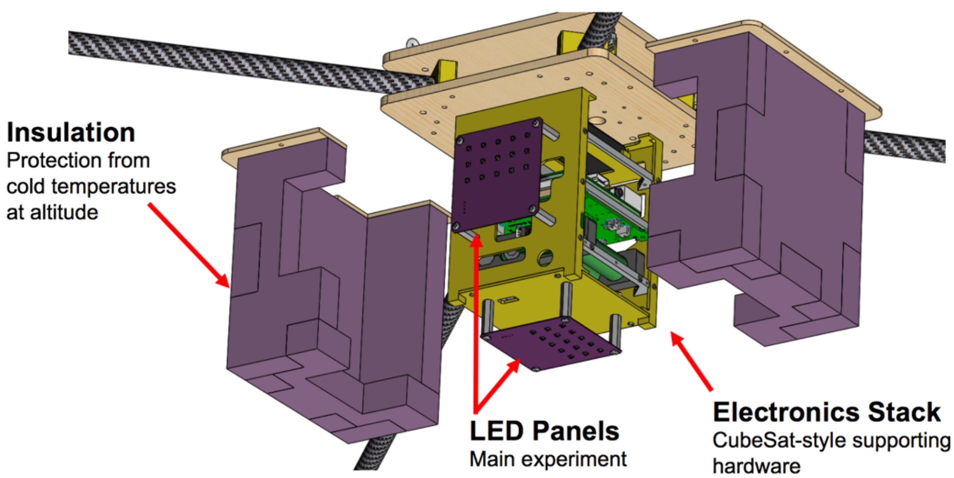

Fig. 4. LITE payload module with insulation pulled out.

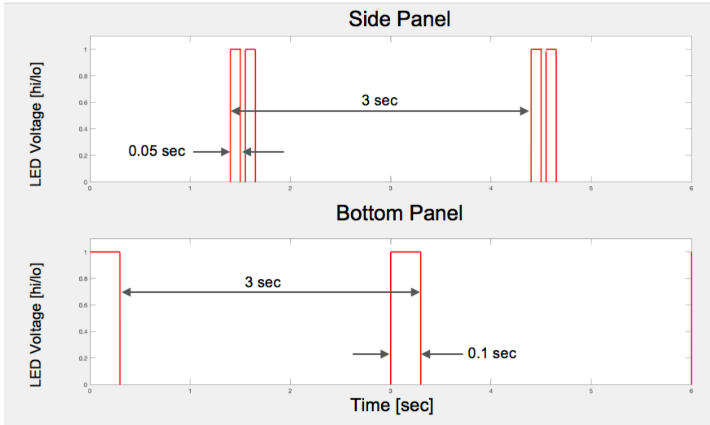

Fig 5. The different LED patterns on one side panel and on the bottom panel.

Also, on board the LITE payload module was a sensor suite operated by the Raspberry Pi FCPU. The suite comprised of a real-time clock module, a 3-axis magnetometer, a 3-axis gyroscope, a 3-axis accelerometer, and a GPS receiver that communicated over I^2C or SPI with the Raspberry Pi. These sensors were chosen so that the estimated attitude of the payload module could be reduced as part of the data post-processing. Each of the 3-axis sensors were logged at 20 Hz and the GPS was logged at 10 Hz. To support redundancy of the live position tracking/beaconing of the APRS tracker on the balloon train, a secondary Tracksoar APRS transmitter (operating with a different call sign) was also part of the sensor suit. An exploded view of the on-board electronics stack can be seen in Fig. 6.

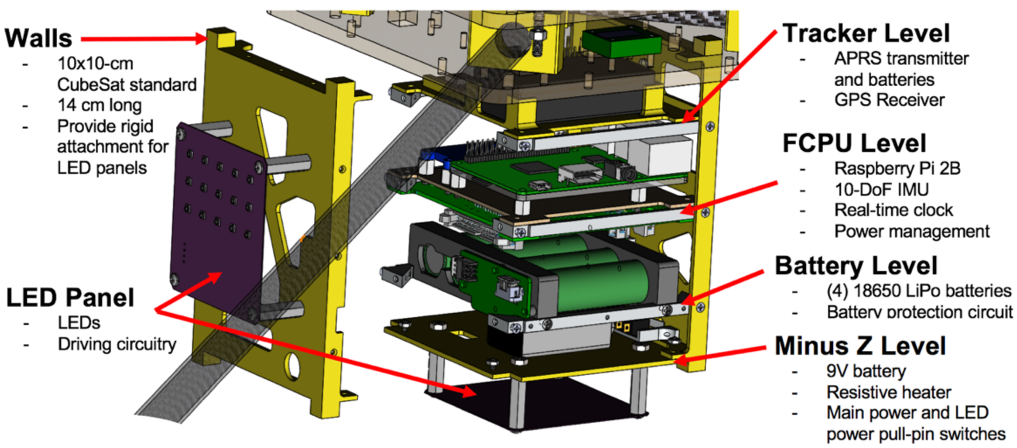

Fig. 6. Inside view of the LITE payload showing the electronics stack on-board the experiment module.

The optical ground station was the Angell Hall Observatory of the University of Michigan located in Ann Arbor, Michigan, seen in Fig. 7. The ground station consisted of two telescopes mounted on the same equatorial mount—a 0.4-m aperture reflector with CCD camera, and an 85-mm refractor with CMOS camera. A custom tracking algorithm interfaced with the telescope control system (TCS) software to point the telescope to the balloon's radio-beaconed location. When imaging, the telescope was stationary, and the balloon drifted across the telescopes' field of view—0.2ºx0.2º in the case of the 0.4-m telescope and 2.1ºx1.7º for the 85-mm telescope.

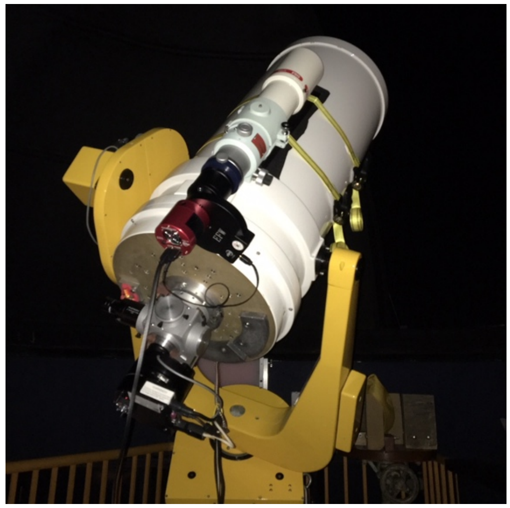

Fig. 7. 0.4-m and 85-mm telescopes inside the Angell Hall Observatory dome (Ann Arbor, MI).

The 3-dimensional position of the payload was transmitted using APRS. The algorithm used in the experiment scraped callsign-specific GPS location packets from the Internet at APRS.fi every 30 seconds and had the ability to switch the targeted call sign in the event of an APRS transmitter failure. It used the GPS position of the balloon payload and the static position of Angell Hall Observatory to calculate the apparent position of the balloon payload with respect to the telescopes. This information was then transmitted to the 0.4-m TCS, which proceeded to point the telescope to the correct location.

3. HAB MISSION RESULTS

On May 11, 2018 at 02:46 UTC, the HAB was launched with the activated LITE payload. Tracking proceeded once the apparent elevation of the balloon was greater than 15 degrees at the telescope. During the flight, optical tracking was successfully achieved at 03:32 UTC from Angell Hall Observatory on the 85-mm telescope, proving optical tracking with LEDs could be achieved. A graphic overview of the flight profile and tracking can be seen in Fig. 8. During the time the optical track was acquired, over 200 images with detections of the balloon LEDs were captured from the CMOS camera mounted on the 85-mm telescope. The individual LED signals captured in the images had a SNR greater than 15. See Fig. 9 for an example of 17 summed consecutive 1-second exposures starting at 03:32:07 UTC. The signals captured existed in at the edges of the field of view of the 85-mm telescope due to the lack of a prediction algorithm, since the telescope pointing lagged the balloon's movement. No detections were found in the data from the narrow field 0.4-m CCD camera.

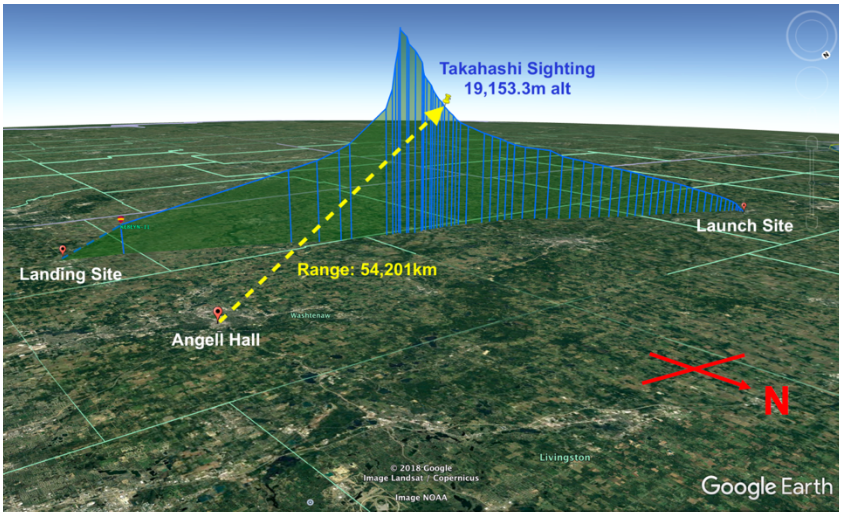

Fig. 8. Flight path of the HAB with labeled position and range with respect to Angell Hall Observatory during the successful optical track. Launch site was in Marshall, MI and the landing site was in Dundee, MI. Compass denotes cardinal North.

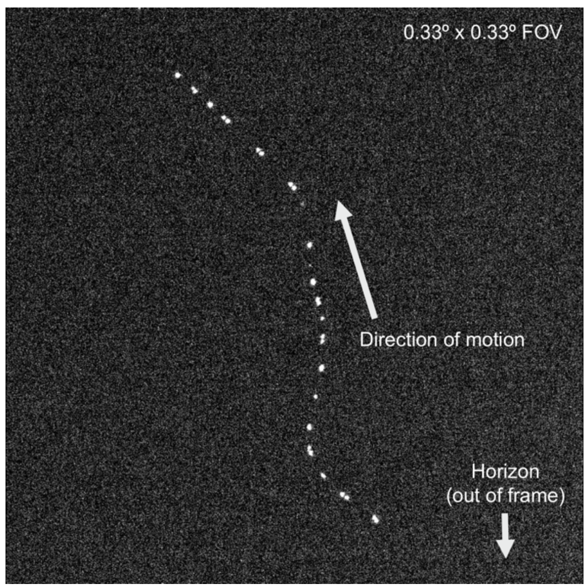

Fig. 9. The sum of 17 1-second exposures from the 85-mm captured during an optical track of the LITE payload. The FOV is 0.33º x 0.33º and denotes the direction of motion and horizon with respect to the telescope. This image was obtained at a range of ~54 km and an observed elevation from Angell Hall of 18 degrees.

Complimentary to the positional information that exists within the captured images, attitude information also exists as seen in Fig. 10, a zoomed in area of Fig. 9. The side panel's double pulse blink and the bottom panel's single pulse blink is clear. Since only two panels were used and the body frame axes of the payload were known, low-precision attitude information can be deduced from the images. If a blink is present within the image, it is facing the telescope aperture, if a blink is not present, then it is not facing the telescope aperture. This information is present within Fig. 9, as denoted by the "Bottom panel no signal" label. This was most likely a result of the payload swaying back and forth due to wind. However, there is a much greater potential for higher-precision attitude reduction from these images by knowing the body frame axes of the payload, the magnitude of the pulse (from post-processing of the image) and knowing the intensity of the light as a result of LED panel's angular displacement. This would allow for analysis of high, medium and low signal pulses such as the one in the bottom right corner of Fig. 10. The LEDs used in this experiment had an intensity attenuation of 50% at 75º angular displacement—which was shown in both the manufacturer's datasheets and laboratory tests.

Useful attitude information was not obtained from the on-board sensors due to noise.

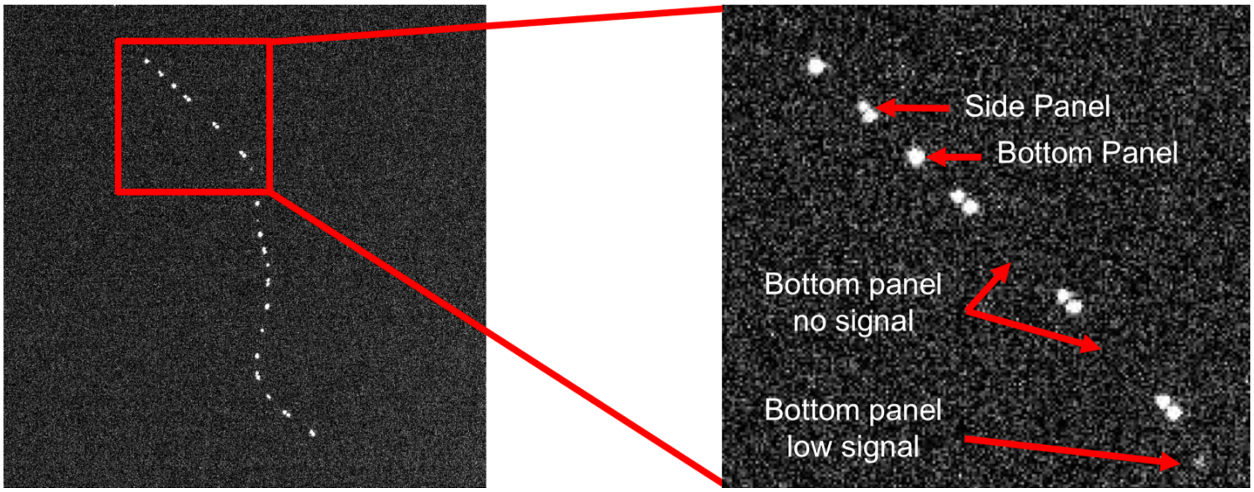

Fig. 10. Labeled signals in zoomed area of Fig. 9.

Positional information can be obtained from the location of the LED flashes with respect to background stars. Photometry can be obtained by measuring the intensity of the flashes and comparing with standard calibration stars. Unfortunately, there were significant clouds during this experiment so only upper limits to the brightness could be measured.

4. SUMMARY AND FUTURE WORK

The balloon mission was a success because it completed its objectives of optically tracking an actively illuminated object at a distance and making significant steps forward towards performing optical attitude determination with captured images. Though the mission was successful, there are many improvements being made for a second flight aimed at launching in fall of 2018 in Michigan. The MXL team plans to improve the onboard sensor system to obtain better attitude and position data to be compared to the captured images from the telescopes in order to perform higher fidelity analysis. The team also plans to improve the tracking algorithm by giving it the ability to predict the balloon payload's future location, move ahead of the payload, and park so that the balloon will drift through the center of the field of view. Finally, the team is trying to organize efforts with local amateur astronomers to utilize different telescopes in different locations in order to confirm results for position and attitude information.

This experiment and its proceeding experiments will be used to advance the research endeavor for Project LEDSAT as the La Sapienza team progresses towards their launch in either 2019 or 2020. This research is also being used to develop the planned PHased ARray Optical Satellite (PHAROS) mission by MXL, a 3U CubeSat to demonstrate LED based optical tracking and attitude determination. It is currently seeking funding for development.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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