Improved Orbit Determination of LEO CubeSats: Project LEDsat

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Abstract

Project LEDsat is an international project (USA, Italy, and Canada) designed to improve the identification and orbit determination of CubeSats in low Earth orbit (LEO). The goal is to fly CubeSats with multiple methods of measuring positions on the same spacecraft: GPS, optical tracking, satellite laser ranging (SLR), and radio tracking. These satellites will be equipped with light emitting diodes (LEDs) for optical tracking while the satellite is in Earth shadow. It will be possible to compare the orbits determined from different methods to examine the systematic and random errors associated with each method. Furthermore, if each LEDsat has a different flash pattern, then it will be possible to distinguish closely spaced satellites shortly after deployment. The Sapienza University of Rome 3U CubeSat URSA MAIOR with LEDs and retro-reflectors was launched in June 2017 and is working on orbit. Sapienza has designed a 1U CubeSat follow-on mission dedicated to LED tracking, which was selected for possible launch in 2018 in the European Space Agency's (ESA) 'Fly Your Satellite' program. The University of Michigan is designing a 3U version with LEDs, GPS receiver, SLR, and radio tracking. The Royal Military College of Canada (RMC) is leading a Canadian effort for a LEDsat mission as well. All three organizations have a program of testing LEDs for space use to predict the effects of the LEO space environment.

1. Introduction

Optical tracking and orbit determination for objects in Low Earth Orbit (LEO) offer a number of challenges that are not present in optical observations of objects at geosychronous orbit (GEO). The angular resolution of optical observations

Primary is that objects in LEO have apparent angular rates as observed from the ground that is much higher than those of objects at GEO. LEO rates can exceed 1 degree/sec.

Passive optical tracking of LEO objects is possible only when the object is in sunlight and the ground-based telescope is in darkness. This limits the tracking windows to a short time after sunset, and before sunrise. For comparison, GEO objects can be tracked all night long except for a brief period (1 hour or less) when they are in Earth shadow.

In [1] we outlined the major advantages in optical tracking of LEO objects that arises from tracking objects that have on-board illumination, and thus one does not depend on the satellite being in sunlight.

1. Equipped with Light Emitting Diodes (LEDs), the spacecraft could be tracked even while in Earth shadow (eclipse).
2. There is now no dependence on topocentric solar phase angle which can cause the object to be several magnitudes fainter at an angle of 90 degrees than at 0 degrees. The apparent brightness of the LEDs as seen from the ground depends primarily on the range, and not on angle.
3. The full optical resolution of a telescope can be used: better than a few arc-seconds.
4. If the telescope is tracking sidereally so stars appear as point sources, and the LEDs are flashed quickly enough (a few millisecond or less), the LED flashes will also appear as point sources. The same algorithms that measure star positions can be used to determine the precise positions of a LEO object measured against the reference star fields. Systematic errors due to the satellite being streaked in the optical images, or conversely the stars being streaked if the satellite is rate tracked, should be minimized.
5. If the accurate and precise timing of the flashes is done on the spacecraft, then one does not need accurate and precise timing on the ground. Simple ground based equipment can be used, which is well within the reach of amateurs and college observatories. All that is required is know what absolute time a particular flash was generated.
6. By proper encoding of the LED flashes, telemetry from the satellite can be transmitted to the ground.
7. If multiple satellites are launched at the same time, then it can be difficult to distinguish and catalog the satellites until they are spatially well separated. But if each satellite has a different flash pattern, then the cataloging and orbit determination can be started immediately after satellite separation from the launch or deployment mechanism. Fig. 1 shows a simulation of two such satellites with different flash patterns. The resolution (a few arc-seconds) is far better than can be achieved with radar or radio tracking. This would be very useful in the case of deployment of a large number of CubeSats at once [2].

Visibility of LEDs from a CubeSat in LEO was demonstrated by the Japanese 1U CubeSat *FITSAT-1*[3], which carried arrays of high powered LEDs and was visible from the ground with small optical systems. *FITSAT-1* demonstrated the proof of concept of the visibility of LEDs on a 1U CubeSat in LEO. LEDsat builds on this and will do science with the signals from LEDs.

First we will outline the advantages of active illumination for orbit determination, then our plans for testing various models of LEDs for their response to the LEO space environment. Then we will review current LEDsat missions that have been launched, are in final design review, or are planned.

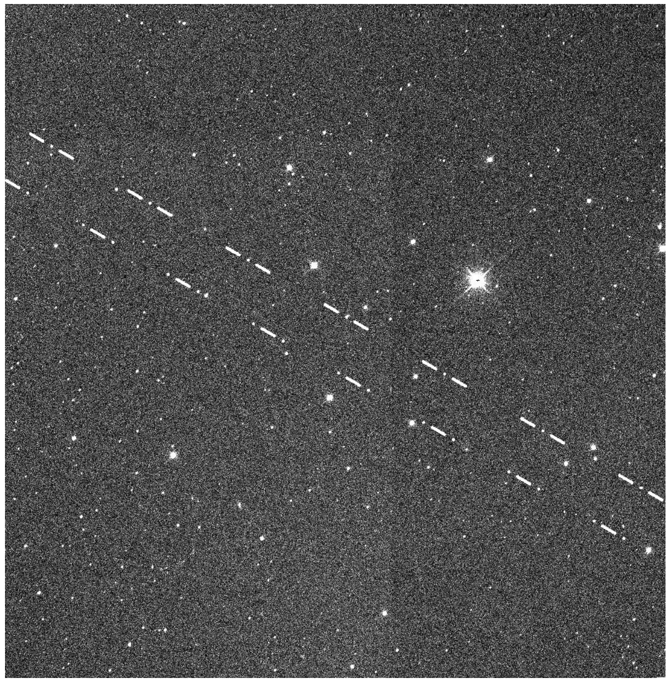

Fig. 1 Simulation of two LEDsats shortly after deployment from the International Space Station (ISS). The upper LEDsat is signaling the Morse K, while the lower one is signaling the Morse R. The shortest flashes – the 'dots' will have the same width as stars and can be centroided to the same accuracy and precision.

2. Orbit determination improvement for optical observations

Typically, non-illuminated sidereally tracked LEO objects do not have a constant magnitude due to tumbling motion, changes in attitude or solar phase angle variation. Therefore, the observed streak might not be constant, and can appear as a series of disconnected flashes. Hence, it is not possible to assign an accurate and precise time-tag to the observed flashes and endpoints. The solution presented here is based on active illumination and on-board timing systems and is designed to solve the problems related to the uncertainty of the generation of the observed flashes to improve orbit determination capabilities. The generated sequence of dots and lines can be used if dots have the same relative size of the stars in the background to assign celestial coordinates with high precision. Telemetry information and the variation among sequences of dots and lines will provide the observer precise information about the time in which the dots signals are generated from the payload. Therefore, ground station tracking data may be obtained without the need of high accuracy timekeeping systems.

The feasibility study of orbit determination has been carried out through the simulation of the celestial coordinates of the satellite and the implementation of a batch filter to process them. In the analysis, measures are collected every 60 seconds during the satellite-ground stations visibility windows. A total period of observation of 12 hours has been considered for a single observatory. It has been demonstrated [5] that the initial state reconstruction in the $r\theta h$ orbital reference system provides accurate results. The main component of the position error is in the $r\theta$ plane (r error below 10 m and θ error below 10^2 m) while the one along the h direction is very small. The derived components of the velocity error are very small and therefore the initial velocity has been reconstructed with high accuracy (v errors below 10^{-3} m/s). Another positive outcome is that if the measurements are performed by a network of observatories distributed worldwide, then precise orbit reconstruction is more precise than measurements from a single observatory.

3. Space Environment Testing of LEDs

To the best of our knowledge there are no LEDs that are currently space qualified. The LEO environment can be quite harsh compared to ground based usage. Therefore we are setting up a testing program of possible flight LEDs both in Europe and North America. This testing program will have two components – radiometric and environmental.

1. Radiometric – how does the LED output compare with the manufacturer's specifications?
    a. Total output as a function of input voltage.
    b. Angular distribution of output illumination.
    c. Spectral output.
    d. Rise/fall time of LED signal.
    e. Temperature dependence of output signal.
2. Environmental:
    a. Change after exposure to strong UV light. This will likely be one of the major reasons for LED signal degradation during the mission. Are certain LEDs more resistant to UV? Clearly anything with plastic in it will suffer greatly.
    b. Radiation testing: we are investigating testing the LEDs in a Cu60 test facility.
    c. Thermal vacuum testing.

Our plans are to do independent testing in some of these areas on both sides of the Atlantic and share the results.

4. Sapienza University of Rome Missions

A group led by Fabrizio Piergentili has started two missions:

The first called *URSA MAIOR* [4] is a 3U CubeSat (Fig. 2) with LEDs, laser retroreflectors, and a deorbit sail for compliance with IADC guidelines on mission lifetime. There are both red and green LEDs on board that were added after construction of the satellite had begun. The CubeSat was successfully launched in June 2017 as part of the QB50 project, is operational on orbit, and is being tested.

Fig 2. A full scale mockup of the 3U CubeSat *URSA MAIOR* with deorbit sail deployed.

The second Sapienza mission is called *LEDSAT*. It is a 1U CubeSat with red, green, and blue LEDs on each pair of opposing faces (Fig. 3), and laser retro-reflectors. In 2017, the mission was selected as a finalist in the European Space Agency's (ESA) *Fly Your Satellite* competition. Out of 30 student entries, it is one of six finalists. If selected for launch, it should fly in late 2018 and be deployed in space from ISS.

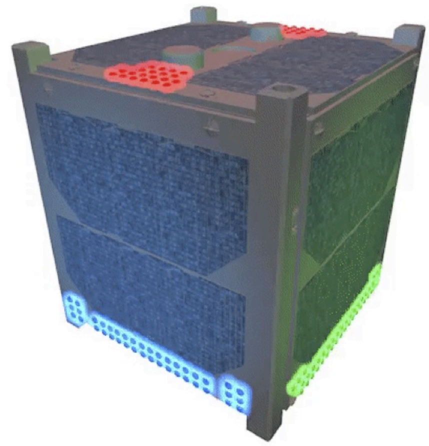

Fig 3. 1U *LEDsat* of Sapienza University of Rome expected to fly in 2018. Opposing pairs of faces have either red, green, or blue LEDs.

The *LEDSAT* payload is designed to be assembled with a total number of 140 LEDs, mounted on the six panels of the 1UCubeSat standard structure. Analysis has been conducted to study the apparent magnitude of the Cubesat as a function of the elevation angle. An altitude of 420 km has been considered equal to the ISS one. The plots presented in Fig. 4 show the total magnitude for each color as function of the total power irradiated and the distance of the satellite from the observer which is a function of observed elevation.

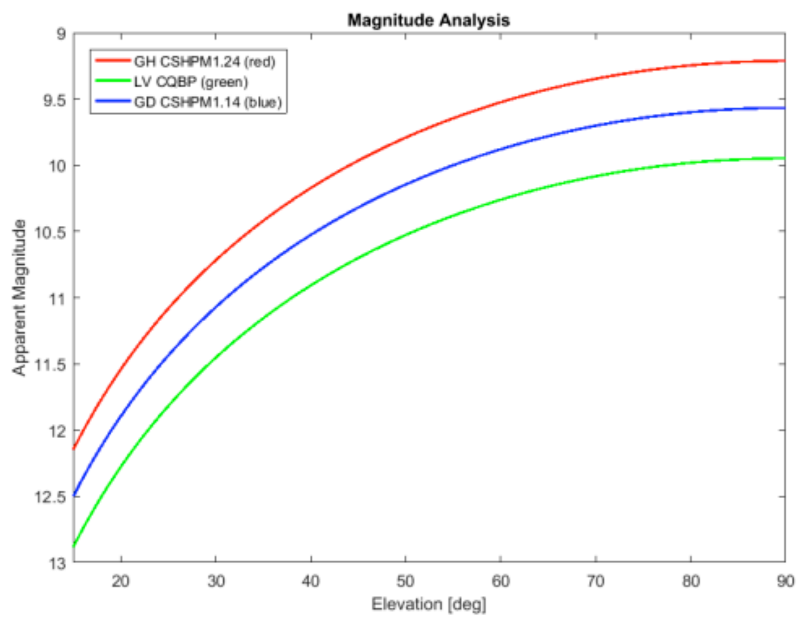

Fig. 4. *LEDSAT* apparent magnitude at an altitude of 420km for a range of observed elevation.

Besides optical tracking, the LEDs will be used for optical communication experiments for transmitting telemetry to the ground. This non-laser optical communication path could be useful in the event of an anomaly in the standard radio telemetry system.

One of the conclusions of the design process and reviews is just how power is required to enable a bank of LEDs to be visible in small telescopes.

5. University of Michigan Mission

Optical observations are only one method of obtaining data for orbit determination. There are others, each with its own advantages and disadvantages. Therefore the University of Michigan is designing a 3U CubeSat called ODsat, for Orbit Determination satellite. Withe the increased power available on a 3U Cubesat, we will be able to have different tracking methods:

- LEDs for optical tracking even in Earth shadow: returns angles and rates.
- Laser retro-reflector: returns range and angles (to less precision than LEDs).
- Radio tracking: returns range.
- GPS receiver: returns full 3 dimensional information and could be the most accurate and precise of all.

With multiple methods on the same LEO spacecraft, it will be possible to investigate the systematic errors between them in one's orbit determination code.

6. Summary

The use of LEDs on spacecraft for tracking and telemetry is in its infancy. The Japanese CubeSat *FITSAT-1* demonstrated that LEO spacecraft could be tracked even with small ground-based telescopes. Follow-on missions as described here will use the LEDs for tracking and identification purposes. The LEDs can even be used for telemetry and optical communication without the use of lasers.

7. References

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