LEDSAT: DESIGN OF A CUBESAT EQUIPPED WITH LEDS AS CALIBRATION TARGET

Patrick Seitzer(1), Fabrizio Piergentili(2), Fabio Santoni(3), James Cutler(4), Heather Cowardin(5), Tommaso Cardona(2), Federico Curianò(2), Alice Pellegrino(2), Andrea Gianfermo(2), Chris Lee(1), Srinagesh Sharma(4).

(1) Astronomy Dept., University of Michigan, 1085 S University Ave, Ann Arbor, MI (USA)
pseitzer@umich.edu; chjlee@umich.edu;
(2) DIMA - Sapienza University of Rome, Via Eudossiana 18, Roma (Italy)
fabrizio.piergenitli@uniroma1.it; tommaso.cardona@uniroma1.it; fcuriano@gmail.com; ali.pellegrino.92@gmail.com; andrea.gianfermo@gmail.com;
(3) DIAEE - Sapienza University of Rome, Via Eudossiana 18, Roma (Italy)
fabio.santoni@uniroma1.it;
(4) Aerospace Engineering Dept., 1320 Beal Ave, Ann Arbor, MI (USA)
jwcutler@umich.edu; srinag@umich.edu
(5) University of Texas El Paso, Jacobs-JETS Contract, NASA JSC, Houston (USA)
heather.cowardin@nasa.gov;

ABSTRACT

The increasing number of small satellite cluster launches (i.e. CubeSats) leads to a greater risk of their confusion and collision after deployment. This encourages the states all over the world to further improve their capabilities in space surveillance. This paper describes "LEDSAT", a jointly project carried on by University of Michigan and Sapienza – University of Rome.

The main aim is to develop and launch at the same time two 1U CubeSats equipped with LEDs (Light Emitting Diodes) for optical tracking with ground-based telescopes. The number of passes in which each CubeSat is visible from a network of ground-based telescopes is increased by having LEDs as an on-board payload to actively illuminate the satellite. Thus, it is possible to increase the accuracy and the precision of tracking objects in LEO (Low Earth Orbit).

Moreover, LEDs flashing with different patterns on each satellite will allow distinguishing them after the in-orbit deployment to minimize the confusion between objects.

This paper outlines the preliminary design of the Sapienza's LEDSAT. The analysis has been performed by using a concurrent engineering activity, a work methodology supported by S5Lab (Sapienza Space System and Space Surveillance Laboratory) research team. The system architecture of the CubeSat with the main mission parameters and design drivers are outlined, with emphasis on its main subsystems. The main features of the on-board LEDs configuration are described by reporting the selected configuration for both space and ground segments.

1 INTRODUCTION

The Inter-Agency Space Debris Coordination Committee (IADC), an international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space, is currently promoting observations for the characterization of orbital debris by using spectro-photometrical and light-curve measurement data analysis [1]. Their goal is also to improve orbit and attitude determination of orbiting objects. For this type of optical observations, the ground-based telescope must be generally in darkness while the satellite must be illuminated directly by the sun. This constraint is particularly binding when the object is in LEO (Low Earth Orbit), where this condition is verified only right after sunset or just prior the sunrise.

The S5lab research group of Sapienza – University of Rome and Astronomy Department of University of Michigan (U-M) decided to cooperate to propose a solution to these limitations, especially with LEO nanosatellites. Active illumination on the spacecraft through LEDs increases tremendously the number of passes in which the object is visible when the ground-based telescope is in darkness by removing the restriction that the satellite shall be in direct Sun.

The performed LEDSAT access simulations over a period of two-weeks show how the potential tracking gain increases by a factor of three due to LEDs on-board the nanosatellite [2].

The idea to way around the light limitations was suggested by the Japanese 1U CubeSat FITSAT-1 (deployed from the ISS on October 5, 2012), which carried high-powered green and red LEDs, and was observed with small ground-based telescopes [3]. FITSAT-1 was operative for 8 months until its re-entry in atmosphere and this mission proved the feasibility of using LEDs to actively illuminate the CubeSat.

This technological strategy will be tested by S5Lab research team with the 3U Cubesat "URSA MAIOR" (University of Rome la SApienza Micro Attitude In ORbit testing) [4] designed and developed in the framework of QB50 [5] that is expected to be launched

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in April 2017. Beyond its main payloads, URSA MAIOR will board two high-power red LEDs on one face and two high-power green LEDs on another one. Hence, it will be a valuable test of the concepts presented in this proposal and it can be considered the precursor of LEDSAT mission.

Additionally, LEDs will be used to investigate the possibility of reconstructing the attitude of the CubeSat.

Sapienza – University of Rome has been involved in the educational projects related to the design, manufacturing, launch and operations in orbit of small satellites since the UNISAT program (from September 2000 with UNISAT1 to June 2006 with UNISAT4) [6]. Moreover, S5Lab is taking care of the IKUNS (Italian-Kenyan University NanoSatellite) [7ref IKUNS] 6U CubeSat, in collaboration with the University of Nairobi (Kenya) and with the support of Italian Space Agency (ASI). Furthermore, S5Lab is currently supporting the development of 1KUNS – 1st University NanoSatellite Precursor. This 1U CubeSat is the first proposal for a small satellite developed by an African country, Kenya, selected by the Japanese Space Agency (JAXA) and the United Nations Office for Outer Space Affairs (UNOOSA) as part of the "KiboCube" program [8].

2 LEDSAT MISSION

LEO objects are very challenging to track by means of large Field Of View (FOV) optical telescopes. Optical tracking can be considered complementary to radar measurements or radio ranging. The angular resolution of a small optical telescope is better than a few arc-seconds because its resolution is proportional to λ/D (where λ is the wavelength and D is the telescope diameter). This is much better than the resolution achievable with even large radio telescopes. To improve optical tracking and the current orbit determination algorithms, we propose to fly a CubeSat equipped with LEDs for observing it on all passes where the station is in darkness. The simulation presented in Figure 1 shows LEDSAT added to an image from the Curtis-Schmidt telescope in Chile.

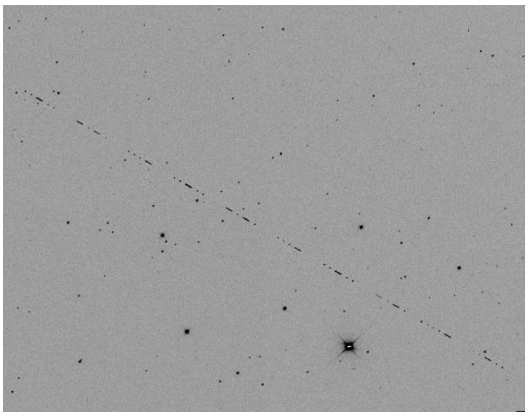

Figure 1. Simulation of a tumbling LEDSAT with different flash patterns on each pair of opposing faces. The LEDSAT signal has been added to a real image from the Curtis-Schmidt telescope in Chile. When each flash is generated will be determined by accurate timing on the spacecraft. Astrometry will be done by measuring the centroids of the shortest flashes ("dots") and compared to the centroids of stars.

By equipping CubeSats with LEDs flashing with different patterns, it would be possible to minimize the confusion among them in case of deployment of multiple objects at the same time, such as large cluster for future LEO CubeSat missions [9].

In fact, they can be distinguished shortly after deployment by using ground-telescope images even if in the same image separated by only few arc-seconds. Currently, JSpOC (Joint Space Operations Center) is requesting markers on each spacecraft in case of large numbers of CubeSats deployed at the same time [10] and the proposed solution of using LEDs will satisfy this requirement.

As mentioned in Paragraph 1, FITSAT-1 proved that a 1U CubeSat with LEDs on-board could be detected from the ground with small telescopes. The LEDSAT 1U CubeSat has been conceived to do science with the light signals, to further investigate the nanosatellite tracking techniques based on optical observations and to explore the potentialities of this technology for other interesting applications. The main difference with FITSAT-1 is in the on-board system that will permit an autonomous satellite orbit and attitude determination. Moreover, the LEDs shortest flash on LEDSAT has been defined around 1 ms to look like stars to be centroided with the same software used for ground-based stellar astrometry. The FWHM (Full Width at Half Maximum) of the LED flashes will be a few arc-seconds or less, comparable to the image quality of small ground-based optical telescopes. By placing the absolute timing of the flashes on the spacecraft itself, there is no need for high timing precision on the ground-based system. Thus, very simple, existing, optical telescopes (like those in the amateur astronomy community) can be used for tracking. The reference frame will be stars, either from GAIA or brighter star catalogues with an accuracy and precision of a few milliarc-seconds. In this way, the telescope will be tracking at the sidereal rate, the usual rate for almost all ground based astronomical telescopes. For LEDSAT travelling at an apparent angular rate of 0.5 degrees/sec, a 1-second timing error in starting the exposure corresponds to an error of 0.5 degrees in acquiring the satellite. For a wide-field telescope of 1 degree or more, the satellite will be anywhere in the telescope FOV.

The main purpose of observation strategies and instrumentations for optical observations is the development of algorithms for orbit determination. The presence of uncontrolled objects in orbit requires the continuous monitoring of the orbits to plan collision

avoidance manoeuvres to avoid impact between operative satellites and debris. The reduction of the uncertainty in the evaluation of the impact risk allows satellite operators to prevent unnecessary collision avoidance manoeuvres. The advantages turn out to be both scientific and industrial: a reduction of the impact risk is guaranteed and this allows taking control on the growth of the number of space debris. Moreover, satellite operators can save propellant to lengthen satellite's operational life.
The activity of the determination of the attitude motion is focused to in-orbit objects, to uncontrolled objects such as upper stages of launchers, through optical measurements. The knowledge of the rotational state of such objects, the angular velocity, is crucial to plan any mission to remove them. The reconstruction of the attitude motion through optical observations is based on the analysis of light curves, the time trends of the intensity of the light radiation received by the observer during the observation.
In fact, satellites and space debris do not have a constant brightness, they give off flashes at typically regular times. This flashing behaviour is caused by the tumbling motion of the object, whose surfaces act as mirrors for the sun (specular reflection). Objects with a diffusely reflecting surface will also show varying brightness since the observer will see a changing amount of light reflecting area of the rocket as it tumbles about in its orbit. The measured period between two flashes or maxima/minima in the light curve can give a good approximation for the satellite's rotation motion.
S5Lab research group has developed a tool [11] that uses the virtual model of the orbiting object, propagated to reproduce its measured light-curve. The differences between the real and the simulated data is used as cost function to be minimized. Crucial part of this process is to recreate an accurate model of the orbiting object that includes all the reflective surfaces and light sources. In this case, both the CubeSat external structure and the LEDs pattern will be simulated in agreement with the real experiment. The reconstructed attitude will be compared with the one obtained from the ADCS (Attitude Determination and Control System) to validate this tool.
For the LEDSAT tracking and the reconstruction of its attitude, three colours of LEDs are recommended on-board (Red, Blue and Green, one colour every two opposite faces). At the beginning of the in-orbit operations, two of the six faces with the same colour will start flashing together by following a pre-loaded pattern and a fixed sequence based on the precise on-board timing. For orbital determination, the satellite will be tracked without filters or with wide filters. This permits to be detected by most of the telescopes.
Starting from six ground stations, the global segment could grow with an increasing amount of tracking information. The optical data collected by the ground segment will be uploaded and shared by using an open source online platform.
During the mission, there will be the possibility of changing flashing data cycle. By changing the time rate and patterns, LEDSAT will simulate different rotating objects in orbit. Consequently, three on-board colours could allow expanding the objectives of the missions by detecting LEDSAT from two telescopes, working with two different coloured filters. In this way, experimental methods, such as the attitude determination of orbiting objects from light-curve measurements, will be tested.

3 SYSTEM ARCHITECTURE

The main elements of the LEDSAT mission are the space segment, the ground segment (composed of the RF, optical and Laser Ranging GS networks) and the user segment. A brief description of the overall architecture of the system is given in Figure 2**Error! Reference source not found.**.

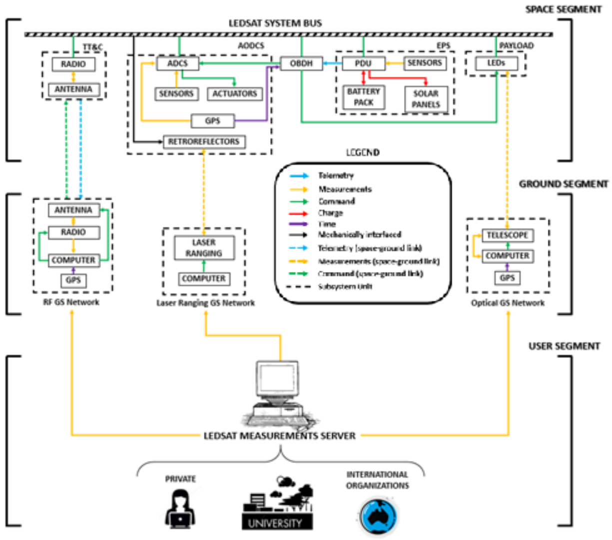

Figure 2. LEDSAT System Architecture.

The main subsystems of the CubeSat are:

- The LED-based payload, able to flash with pre-loaded and commanded patterns with a precise timing;
- The OBDH (On-Board Data Handling) subsystem, to control and tune the payload flashing frequencies and manage the bus and all the operations;
- The ACS (Attitude Control Subsystem), to de-tumble the nanosatellite;
- The ADS (Attitude Determination Subsystem), to collect attitude data to be downloaded to ground;
- The ODS (Orbit Determination Subsystem), to be used to detect the in-orbit position of the nanosatellite in both active and passive methods and to synchronize the on-board OBDH

(composed of GPS and retroreflectors);
- The EPS (Electrical Power Subsystem), able to regulate the battery pack charge and distribute the power to each subsystem;
- The TT&C (Telemetry, Tracking and Command) subsystem, able to receive and transmit command and telemetry.

The exploded view of LEDSAT is given in Figure 3.

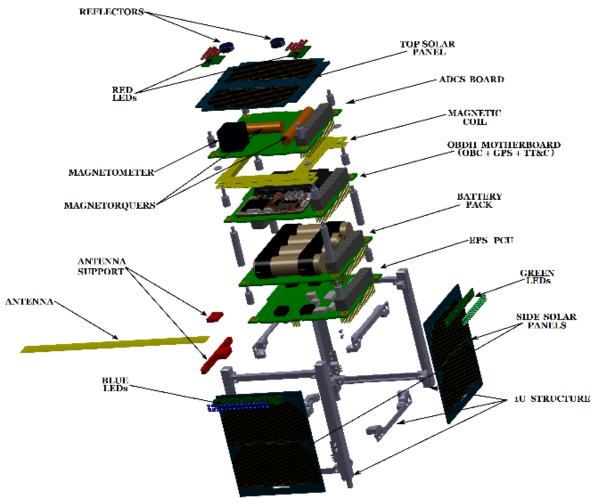

Figure 3. LEDSAT Exploded View Drawing.

4 LED CONFIGURATION

The LEDSAT payload is based on a designed configuration of LEDs to be used as cooperative target on-board the CubeSat for its orbit and attitude determination by means of optical observations. The main drivers considered for the definition of the final payload configuration are the LED Efficiency, their Quantum Efficiency, the available on-board power, the constraints in terms of geometry and weight and the requirement of maintaining low costs. The LED efficiency led their selection among the COTS available devices. Because of the limited on-board power, very efficient LEDs have been identified. The Quantum Efficiency supported the choice of the LED colours. The greater the number of photoelectrons produced for a given photon signal, the higher the Quantum Efficiency – usually higher for Red and Green. A trade-off between the supplied power and the luminous efficiency has been performed to define the number of LEDs, the circuit and the power consumption. The dimensions, the number of LEDs and their configuration are based on the available space on the external 1U structure. For the LEDSAT Payload, three main colours have been selected: Red, Blue and Green (one colour every two opposite faces).
The apparent magnitude has been evaluated in two main cases, with 100% and 50% of the LEDs switched on. Figure 4 and Figure 5 simulate how bright the satellite will appear if one or two of the six faces will be switched on simultaneously. In fact, due to the limited on-board power, if two faces will be switched on together, only half of the LEDs will be used.

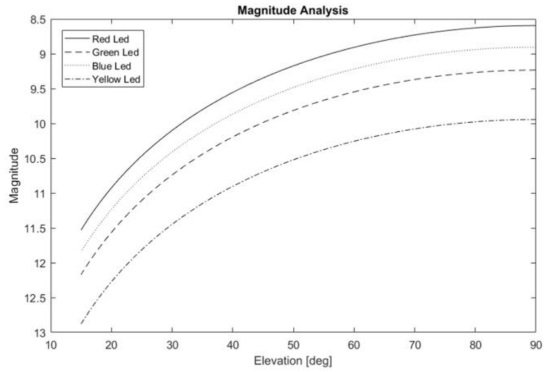

Figure 4. Magnitude Analysis for 100% LEDs.

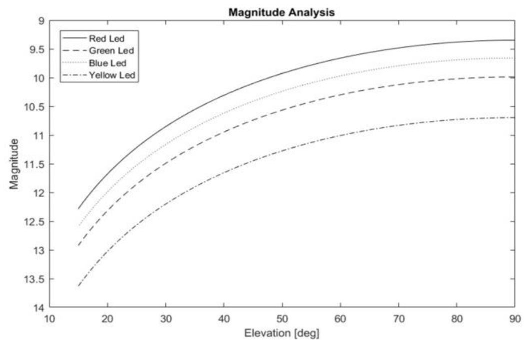

Figure 5. Magnitude Analysis for 50% LEDs.

The Signal to Noise Ratio (SNR) analyses dictate the kinds of binning of the CCDs and the minimum elevation angle considered. The binning will be suited to achieve an acceptable SNR and a good resolution.
To increase the possibility to detect the CubeSat orbit and the attitude determination capabilities, on-board retroreflectors have been included.

5 GROUND SEGMENT

Due to LEDSAT mission, a plan of coordinated observation campaigns will be performed to test the combination of LEDs and retroreflectors for the CubeSat tracking, attitude reconstruction. Commands from the ground will allow changing the payload flashing frequency depending on the mission objective to be tested. Collected information will be analysed to verify the accuracy and the performances of the proposed techniques. Gathered data will be shared into the cooperating observatories network.
S5Lab research team is currently developing a network of optical observatories fully dedicated to space debris observation. Nowadays, the network is composed by: MITO (Midlatitude ITalian Observatory), installed in Rome and already in operative phase; EQUO-OG (Equatorial Italian Observatory On-Ground), installed in

the base-camp of Broglio Space Center (BSC) (Malindi, Kenya) and managed by ASI, in pre-operative phase [12]; EQUO-OS (Equatorial Italian Observatory Off-Shore), in installation phase on the off-shore platform of BSC. Moreover, other four observatories have been selected at different latitudes. More observatories, at both equatorial and medium latitudes, allow a larger flexibility in terms of possible orbital parameters. An analysis about the access times for each ground station has been done to quantify the average visibility time for LEDSAT in its entire lifetime (around 1 year). The main achieved results are summarized in Table 1.

Ground Station	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov
Ann Arbor, USA	198.68 sec	196.97 sec	199.27 sec	199.33 sec
Rome, Italy	180.44 sec	184.44 sec	183.44 sec	182.06 sec
Bern, Switzerland	282.27 sec	281.73 sec	285.20 sec	283.35 sec
Cerro Tololo, Chile	228.23 sec	215.89 sec	219.33 sec	219.87 sec
Malindi, Kenya	142.57 sec	135.29 sec	140.11 sec	139.96 sec
Matera, Italy	170.66 sec	166.72 sec	168.43 sec	166.89 sec

Table 1. Average access times per orbit by considering an orbit like ISS.

The MLRO (Matera Laser Ranging Observatory) located in Matera (Italy) and in Zimmerwald Observatory (located in Bern, Switzerland) will offer support to the LEDSAT team and they will be part of the LEDSAT Laser Ranging GS Network.

6 CONCLUSION

The presented paper outlines the LEDSAT mission idea for the development of a 1U CubeSat equipped with LEDs for optical tracking and attitude reconstruction. The CubeSat has been designed in cooperation between University of Michigan and Sapienza – University of Rome. The main advantage of using LEDS as payload is the gain in number of passes that the spacecraft is now observable with active illumination of the CubeSat. Moreover, in the case of multiple CubeSats being launched in-orbit at once, LEDs would allow the identification of the spacecraft immediately after deployment to assist in cataloguing to satisfy the JSpOC requirements.

This paper deals with the main LEDSAT mission objectives, with special focus on the system architecture including the details on both space and ground segment of the project. The configuration of the on-board payload with the preliminary analyses performed are reported in order to allow a complete understanding of the mission concept and the possible outcomes.

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