THE LEDSAT MISSION: OPTICAL RECOGNITION AND ORBIT DETERMINATION OF A SELF-ILLUMINATING PAYLOAD ON-BOARD A 1U CUBESAT

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ABSTRACT

Satellite optical observations are constrained by lighting requirements, i.e. the observational site at ground shall be in darkness while the target is in penumbra, reflecting sunlight towards the observer. This requirement restrains the observation intervals to few minutes per day. The potential implementation of self-illuminating payloads, such as LED-based boards on the external surfaces of satellites, would extend the observation interval to the whole eclipse phase of each orbit, significantly increasing the number of acquirable measurements. LEDSAT (LED-based small SATellite) is a 1U CubeSat mission aimed at demonstrating a LED (Light-Emitting Diode) -based payload for allowing optical recognition and detection from ground. The spacecraft has been conceived by Sapienza University of Rome and University of Michigan and developed at Sapienza in the framework of the ASI (Italian Space Agency) IKUNS Programme and of the ESA (European Space Agency) Fly Your Satellite! Programme. The CubeSat equips 140 LEDs in three different colors for allowing optical measurements from ground. The LED payloads flashes will allow to recognize the spacecraft after launch and to optically determine its orbit and attitude. The optical measurements will be compared to orbit and attitude sensors data: LEDSAT will equip an orbital GPS receiver for orbit determination and an external IMU (Inertial Measurement Unit) for attitude reconstruction. Specific LED sequences will be dedicated to recognition, orbit and attitude determination for improving the optical measurements precision and their integration at ground. The optical measurements network will be composed of several observatories in three continents (Europe, Africa, America), while it will involve all the other potentially interested optical observatories all around the world.

The LEDSAT flashing patterns have been optimized to guarantee the maximum possible return of information on its orbit and attitude state. The GPS Pseudo Random Number Gold codes have been applied to maximize the self-correlation of the chosen patterns and to minimize their cross-correlation. The pattern will be updated in order to verify the effectiveness of the LED-based payloads for optical tracking. If successful, the LEDSAT investigation could suggest best practices for the implementation of LEDs on-board all future satellites, with particular regards to small spacecraft that are increasingly developed and launched in LEO. The improved optical trackability of LED payloads would support, in case of a wider implementation, Space Situational Awareness and Space Traffic Management and provide a better observability over the spacecraft orbits and attitude states. This paper will describe the LEDSAT mission, with particular regards on the lessons learned during the payload development, integration and testing, in the perspective of a future usage of autonomous illumination payloads, such as LED boards, in tomorrow's small satellites. After a description of the LEDSAT mission, the spacecraft design will be presented as well as the characteristics of the payload, optical link, ground-based observatories. The spacecraft planned operations, i.e. the flashing patterns, their aim and the possible duty cycles will be presented, with guidelines for the future implementation of these payloads on other satellites. Finally, the timeline for the LEDSAT operations will be presented..

1 INTRODUCTION

Satellite optical observations can greatly support the other traditional space debris and satellite monitoring and tracking methods (e.g. radar monitoring), although they are obviously constrained by lighting and weather conditions [1]. Indeed, a visible satellite shall be in sunlight while the observer is in darkness to allow

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optical observability of a satellite. This constraint, jointly with the need of an adequate amount of reflected sunlight and the effective yearly observational window related to good weather on the observatories sites, forces the optical observations to being applied to few passes per day, for a total observable time of maximum 10 minutes per day per visible satellite.

The implementation of autonomous illumination payloads on-board satellites would increase the observational interval to the whole eclipse phase [2], greatly improving the potential impact of the optical observations in the tracking process. The implementation of active systems to illuminate the satellite, though, includes a point of failure in the system that is designed to cooperate. Small active illumination payloads shall be made independent from the satellite if they are needed to support the mission despite the operational status of the satellite, e.g. for space debris monitoring operations. The implementation of this typology of systems can greatly support the Space Traffic Management tasks as improving the monitorability of all satellites.

The demonstration of the self-illuminating system for optical tracking is being carried out by the LEDSAT 1U CubeSat mission [3], [4], conceived by Sapienza University of Rome (S5Lab research team) and University of Michigan. The project is supported by ASI in the framework of the IKUNS Programme and it is part of the ESA Fly Your Satellite! Programme. LEDSAT is going to equip 140 Light Emitting Diodes (LEDs) in three different colors (red, green, blue) on all its external surfaces. The payload has been designed on purpose for a 1U CubeSat as it can be adapted to every small satellite platform. The CubeSat will profit from a launch opportunity offered by the ESA Fly Your Satellite! Programme in 2021. The lessons learned from the hardware development have allowed to propose a generalization of the payload design concept [5]. During the in-orbit operations, the satellite will perform optimized flashing patterns to allow simultaneous orbit and attitude determination of the spacecraft and to test an innovative back-up communication method based on encoded LED flashes. Moreover, the spacecraft will synchronize its flashes to the GPS time to allow precise time referencing for the astrometric measurements obtained by the observational sites.

This paper will present the main features of the LEDSAT CubeSat mission, by providing details on the lessons learned from the hardware and software design, the satellite manufacturing and assembly, the testing phase and operations planning.

2 THE LEDSAT MISSION

LEDSAT is a 1U CubeSat aimed at testing a LED-based payload for ground-based optical tracking and at demonstrating the effectiveness of a tracking and navigation system based on autonomous illumination. The spacecraft design is based on a commercial, flight-proven, bus and on a bespoke payload composed of the external LED boards and a LED controller board. The design shares various components implemented in other missions developed and operated by or in collaboration with the S5Lab research group, as this increases the reliability of the whole production and operations process.

The mission follows a Proto-Flight Model approach, i.e. a single model is manufactured and the flight model itself undergoes functional and environmental qualification. LEDSAT is presented in Figure 1.

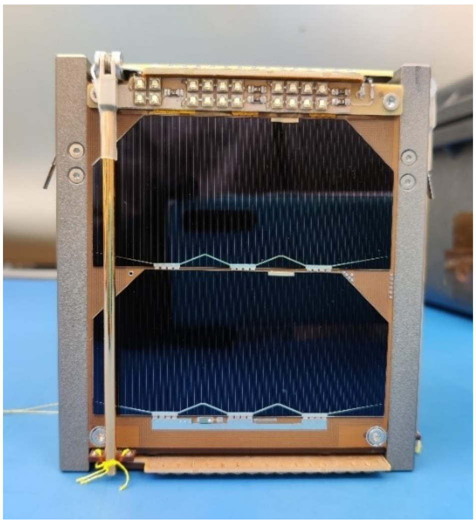

Figure 1: LEDSAT PFM.

The satellite has been assembled in early 2020, it passed functional qualification in October 2020 and it was environmentally qualified between November and December 2020. The project is now facing the final phases of flight acceptance and it will be deployed in orbit in 2021. The primary mission objective is to demonstrate the LED-based payload for orbit determination and to allow the observatories to acquire astrometric data, the second mission objective is related to acquisition of photometric data and attitude reconstruction. The accuracy of the acquired optical data will be verified via comparison with on-board sensors. The third and final mission objective is the test of a back-up communication system based on LEDs encoding their flashes. A more detailed overview of the systems design and the realization of an optical link with optical observatories for space debris will be given in the next section.

3 PAYLOAD FEATURES

The LEDSAT payload is composed of six LED boards in red, green and blue mounted on the external surfaces of the 1U satellite, with the same color of diodes on opposite faces of the satellite. The LEDs have a maximum current consumption compliant with the maximum power exerted by a commercial power system for a CubeSat, by taking into account the vital systems while operating the LEDs. The maximum power consumption of the payload is around 30 W [5]. The possibility to mount six boards on a 1U CubeSat makes this typology of payload applicable to all the small satellite platforms for tracking purposes. Furthermore, the duty cycle of the LED operations can be modulated in line with other payload operations. While in LEDSAT, LEDs are flashing with a relatively high duty cycle, representing the only payload of the mission, LED boards can be applied to other missions and flash with duty cycles close to 1% to achieve trackability of the spacecraft while pursuing their own mission objectives.

For what concerns the needed environmental qualification for the LED-based payloads, tests such as outgassing, UV and Total Ionizing Dose radiation, thermal-vacuum and vibration were performed within the LEDSAT project [4], [6]. All the tests demonstrated survivability of the diodes in-orbit. A picture from the UV testing on diodes dummy boards is depicted in Figure 2.

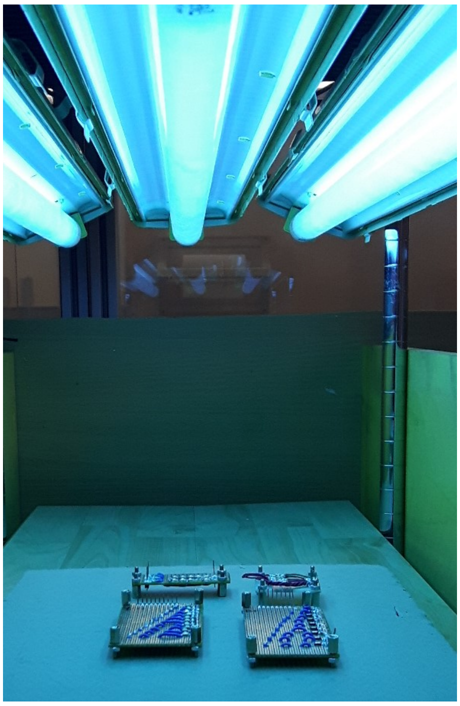

Figure 2: LED boards during UV testing.

The optical link was designed by taking into account the telescopes used by the involved institutions and the observatories owned or operated by Sapienza University of Rome [7]. In general, LEDSAT can be observed by small space debris observatories that can detect objects with magnitude values around 10. Telescopes with this typology of configuration can easily achieve Signal-to-Noise Ratio (SNR) values above 10 for observations above 15-20 degrees of elevation. LEDs designed by maximizing the exerted power can be operated and observed within extended elevation angle ranges up to 700-800 km of altitude [5], [8], thus serving the most populated orbits and the ones most interested by small satellites (International Space Station to Sun-Synchronous Orbits well above 600 km). If implementing LEDs on bigger satellite platforms, the power consumption constraint can be relaxed and observations can be performed at much higher altitudes. When mounting LEDs on such platforms, it will be desirable that the payloads are staying within self-standing independent units in order to allow tracking and observations without any dependency on the central systems, with minimal impacts on the overall spacecraft mass and volume. This would allow to observe the satellite LEDs in case of a loss of control of the spacecraft.

The electrical design of the payload shall preserve the functionalities of the main satellite subsystem, in terms of not exceeding threshold power consumption values, and shall provide sufficient safety and reliability of operations. As an example, the circuitry shall be managed in order to avoid single point of failures in the LED electrical scheme arrangement, and to allow multiple failures before failure of the subsystem (in terms of insufficient radiated flux or actual failure of the board).

The payload of LEDSAT is time-synchronized with an orbital GPS receiver [9] in order to start flashing according to the Pulse-per-Second signal of the GPS. This allows to acquire optical measurements for orbit determination with more precision, by knowing the exact timing of the flashes start. LEDSAT uses both the GPS receiver and a Real-Time Clock with a Temperature Controlled Crystal Oscillator (TCXO) for reducing its power consumption while maintaining a precise time coordination with the observatories. The usage of small GPS units to coordinate the observatories is a very cost-effective and simple feature to include on-board observatories. If implementing the LEDs on other satellite platforms, the usage of LED boards without coordination with GPS still returns significant results in terms of orbit determination and payload identification.

4 PLANNED OPERATIONS

LEDSAT is scheduled to use the LED boards throughout its mission. The satellite observations can be performed through two techniques:

- The sidereal tracking technique, where the telescope moves at sidereal rate, mainly acquiring images. In the acquired images, the satellite appears like a light streak over the

stellar background;
- The target tracking technique, where the telescope and mount are commanded to follow the object pass. This technique is mainly used to acquire videos. In the video frames, stars appear as light streaks since the telescope moves, while the object is staying at the center of the telescope Field Of View (FOV).

Both techniques can be used for observing LEDs. A simulation of the LEDSAT pass over the stellar background in sidereal tracking observations is presented in Figure 3.

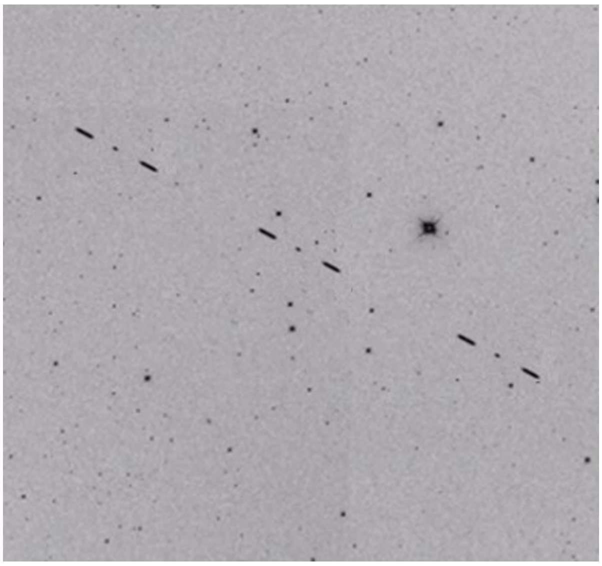

Figure 3: Simulation of LEDSAT pass during sidereal tracking observations [2].

At deployment, LEDs can greatly ease the identification of the satellite. When deployed in large clusters, small satellites are often confused among the available Two Line Elements. In some cases, this prevents complete access to the satellite features for part of the early operations. LEDs can help in achieving a better determination of the satellite identity just by their observations or, when implementing LEDs on multiple satellites, by assigning an identifier pattern (such as a Morse code letter) to each satellite for faster identification. This will allow to obtain more precise orbital elements and a faster identification for all the satellites that are observable. With LEDSAT, the identification will allow to perform part of the technological demonstration of the satellite.

After early operations, the LEDs of LEDSAT will continue to flash to gather information on the satellite orbit and attitude. The patterns of the satellite have been optimized to match the requirements for orbit determination through optical observations and the needs for face recognition aimed at attitude determination. For what concerns the orbit determination, optimal flashes involve both “short” and “long” flashes, visible as “dots” and “trails” in the telescope images. Trails allow for an immediate recognition of the object from the available astrometric software, while dots, if time-synchronized, can return a very precise measurement in terms of right ascension and declination, to be integrated to retrieve the orbital elements. Attitude determination needs either different colors or orthogonal patterns for each face. With different colors, observations can be performed simultaneously by a multiplicity of observatories using color filters. Orthogonal patterns can be resolved by de-convolution in order to retrieve the observed face.

LEDSAT will use the GPS Pseudo-Random Number codes (PRN codes) in order to allow maximum self-correlation and minimum cross-correlation among the patterns. Being composed of long and short flashes, these patterns can satisfy both orbit determination and attitude reconstruction requirements.

The flashing sequences will be composed of 20 chips (bits without informational content) per face in order to allow sufficient flashing times for each face to be recognized [6]. The analyzed acquired luminous flux and patterns detection can lead to a preliminary estimation of the overall tumbling rate of the satellite and to the integration of the acquired data in a more complex model able to retrieve attitude. Simulations on different tumbling rate values foreseen for the mission have shown a 99% detection rate for SNR values above 10, whose value is considered the minimum for carrying out the technology demonstration of the mission and, in general, to achieve good quality of data acquisition for space debris observations.

As final mission objective, LEDSAT is attempting to encode the flashes to transmit low data-rate data to ground. This could help nano-satellite mission that experience a loss of the downlink transmitter (which is responsible for approximately 20% of the CubeSat mission failures) to down link basic data on the status of the CubeSat and its payload.

5 FUTURE DEVELOPMENTS

If successful, the investigation led by LEDSAT could suggest the usage of LED-based payloads on-board all satellites. As previously referred, small satellites released in large clusters could adopt identifier patterns to allow optical recognition shortly after launch, thus solving ambiguities and allowing accessibility and observability of the satellite since the very early stages of LEOP (Launch and Early Operations). Furthermore, the LED-based units would greatly help in improving orbit and attitude determination. Orbit determination could greatly exceed the precision assured by conventional ranging and RF tracking data, thus assuring improved tasks in the framework of future

Space Traffic Management [10], [11] or current Space Situational Awareness operations. Attitude determination is of great help in case of future re-entry trajectory prediction campaigns (as happened, as example, for the Tiangong-1 station in 2018 [12]) or for future Active Debris Removal tasks, where attitude determination is vital to decide in advance the optimal removal method and then to acquire the spacecraft attitude to perform the actual removal tasks. Both these future tasks are mainly addressed to larger platforms and will require autonomous modules. These could be realized through autonomous LED boards connected to stand-alone batteries and small solar panels able to let the tracking system survive even if a loss of control of the main spacecraft happens. The demonstration given by LEDSAT will help understanding the effectiveness of the LEDs and how close we are to introducing this tracking system for a broader usage.

6 CONCLUSIONS

LED-based payloads on-board satellites for ground-based tracking could greatly help in achieving a higher precision of tracking and attitude determination for all satellites. These active illumination devices allow for an extension of the observability window from few minutes per-day, when in penumbra, to the whole eclipse phase of each orbit. LEDSAT is a 1U CubeSat mission, conceived by Sapienza University of Rome and University of Michigan, aimed at demonstrating such kind of payload. The project is supported by ASI withing the IKUNS Programme and part of the ESA Fly Your Satellite! Programme. The satellite has been qualified for flight and it will be launched in 2021. The spacecraft equips 140 LEDs in three different colours on all the CubeSat surfaces. The satellite LED boards have been qualified with a variety of tests carried out between 2017 and 2020 at subsystem and system level. The optical link budget reports that the LEDs, which will consume around 30 W of power, will be observable above 15-20 degrees of elevation and achieving SNR values above 10 with the Sapienza optical network telescopes. The satellite operations involve both sidereal and target tracking operations and will aim at identifying the CubeSat soon after deployment, at improving its orbit determination, at determining its attitude. The final mission objective is related to down link of data through light-based experimental transmission. If successful, the investigation carried out by LEDSAT could be applied on all classes of satellite. With regards to larger satellites, they could mount stand-alone, independent units with power generation and storage systems that are disconnected from the main spacecraft bus in order to preserve their functionalities in case of the satellite failure.

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LEDSAT is part of the second edition of the Fly Your Satellite! Educational Programme, managed by the Education Office of the European Space Agency (ESA). Within the Programme, students design and build their satellite at their universities and benefit from direct knowledge transfer of ESA technical and managerial expertise, as well as access to facilities.

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