LEDSAT: a LED-based CubeSat for optical orbit determination methodologies improvement

Giammarco Cialone*, Paolo Marzioli, Silvia Masillo,
Andrea Gianfermo, Lorenzo Frezza, Alice Pellegrino, Fabrizio Piergentili
Department of Mechanical and Aerospace Engineering (DIMA)
Sapienza – University of Rome
Rome, Italy

Fabio Santoni
Department of Astronautics, Electric and Energy Engineering (DIAEE)
Sapienza – University of Rome
Rome, Italy

*Corresponding author e-mail: giammarco.cialone@uniroma1.it

***Abstract*—LEDSAT (LED-based small SATellite) is a 1-Unit CubeSat that will mount Light Emitting Diodes (LEDs) on its six faces, in order to validate, verify and improve the current methodologies for optical orbit determination. The LEDs will also support the CubeSat identification after deployment from the ISS. The satellite is being produced by the S5Lab research group at Sapienza – University of Rome, and it has been accepted for the European Space Agency Fly Your Satellite! Programme. Currently, the on-board LEDs have been tested for the UV and gamma-ray radiations, proving their survivability in the space environment. This paper describes the aims, the design, the LED-based payload and the expected results of LEDSAT.**

Keywords—CubeSat, LEDs, orbit determination, satellite identification

I. INTRODUCTION

The progressive increase of man-made objects in the Earth orbit, either cooperative (e.g. active satellites) or uncontrolled and uncooperative (defined as space debris), is leading to the need for an accuracy improvement in satellites orbit determination, in order to predict possible collisions among satellites, or between a satellite and space debris. In particular, the increasing number of CubeSats deployed together in single launches [1], as well as mission concepts of large telecommunications micro- and nano- satellite clusters [2] require an improvement in satellite and space debris tracking systems [3]. These would be aimed at preventing collisions and at carefully planning effective collision avoidance maneuvers.

On this purpose, satellite tracking and orbit determination is usually performed, at ground, by radar or laser ranging systems ([4], [5]), and, on-board, by optical sensors and Global Navigation Satellite Systems (GNSS) receivers. The optical observation is often considered as complementary to the described other methods, due to its dependability on the reflective properties of the satellites outer surface, on the observatory atmospheric conditions. Furthermore, optical tracking requires the observables to be in sunlight while the observatory is in darkness. Even if inherently presenting technical challenges for a completion of the observation campaigns, such as the high angular speed of the targets, that may overcome several degrees/second, optical LEO tracking offers the opportunity to improve the satellite position determination to few tenths of arcseconds [6], especially when integrating the measurements performed by multiple observatories (set in different locations). Moreover, the current trend for optical satellite tracking aims at reconstructing the attitude of the observed objects [7], as well as at identifying the single satellites few after deployment into orbit in large clusters [8]. These opportunities are obviously largely increased, when considering the implementation of an active illumination system on-board an orbital platform.

LEDSAT (LED-based small SATellite) is a 1-Unit CubeSat project aimed at testing a Light Emitting Diodes (LEDs) -based payload for the validation, verification and improvement of the current methodologies for optical stand-alone satellite and space debris orbit determination. The CubeSat is currently being developed by the students and the research group of the Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) at Sapienza – University of Rome. The project has been accepted in May 2017 for the second edition of the Fly Your Satellite! Educational Programme, managed by the Education Office of the European Space Agency (ESA). This Programme is aimed at allowing European university students to design and build their satellite and benefit from direct knowledge transfer of ESA technical and managerial expertise, as well as access to facilities. The project is realized under the collaboration of the research team with the University of Michigan, the Astronomy Institute at the University of Bern (AIUB), and the Italian National Institute for Nuclear Physics (INFN), and it is supported by the Italian Space Agency in the framework of the IKUNS Project.

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The satellite project Critical Design Review (CDR) has been successfully concluded in May 2018. The satellite launch is currently scheduled between the end of 2019 and the beginning of 2020, and the mission will approximately last for one year.

The CubeSat will be equipped with LED boards on all of its six faces, in order to be tracked by a network of six observatories spread all over the world. Furthermore, the good visibility of the satellite will allow several other observatories, both professional and amateur, to acquire data and collaborate to the optical data acquisition during the operational life of the spacecraft. The satellite project secondary objectives include the execution of specific LED activation sequences to gather information on the satellite attitude and the test of an innovative light-based back-up communication, potentially applicable to future nano- and pico-satellites missions, in case of a failure of its conventional Radio-Frequency (RF) communication system. The attitude oriented light patterns are currently being defined and studied with the exploit of a simulation model and an optimization algorithm, while the instrumentation needed to maximize the light-based communication data rates is under testing.

This paper will describe the LEDSAT mission objectives and phases, along with a general description of the CubeSat design. Then, an overview on the LED boards will be presented, together with the most recent results on these components qualification for space flight. Finally, an overview of the scientific tasks and expected results will be provided.

II. LEDSAT 1-U CUBESAT

LEDSAT (LED-based small SATellite, [9]–[11]) is a 1-Unit CubeSat equipped with Light Emitting Diodes (LEDs) on all its six faces. The spacecraft is mainly composed by Commercial-Off The Shelf (COTS) components for the bus subsystems and bespoke boards for the payload subsystem. The satellite operations will be managed either automatically, by following an operational calendar defined before launch, or manually, by being directly controlled from the Radio-Frequency (RF) ground stations. The operations will be managed with a fine time synchronization, obtained with an on-board Global Positioning System (GPS) receiver, with precise oscillators and Real-Time Clocks (RTCs) connected to the on-board computer.

The LEDs are mounted on bespoke boards on the top, bottom and side faces of the satellite, with the same diode colors mounted on opposite sides. The LEDs will be observed by six telescope stations, located in Rome (Italy), Ann Harbor (Michigan), Malindi (Kenya), Cerro Tololo (Chile), Matera (Italy) and Bern (Switzerland). For its peculiar mission objectives, the satellite needs to maximize the electrical energy storage to increase the maximum activation time of the LEDs while in eclipse. For this reason, six COTS Li-Ion cells, are installed on two boards along with the Power Control Unit, for a total energy storage of 57 Whr. The satellite solar panels will mount, on their rear side, the magneto-torquers used to reduce the spacecraft angular rate below 2 degrees/second. Laser ranging retro-reflectors will be applied on at least two faces of the satellite, in order to allow the passive orbit determination from the laser ranging stations of Bern, Switzerland, and Matera, Italy. The communications with ground will be allowed by a UHF band transceiver, that will communicate with three RF ground stations, namely in Rome, Italy, in Nairobi, Kenya, and

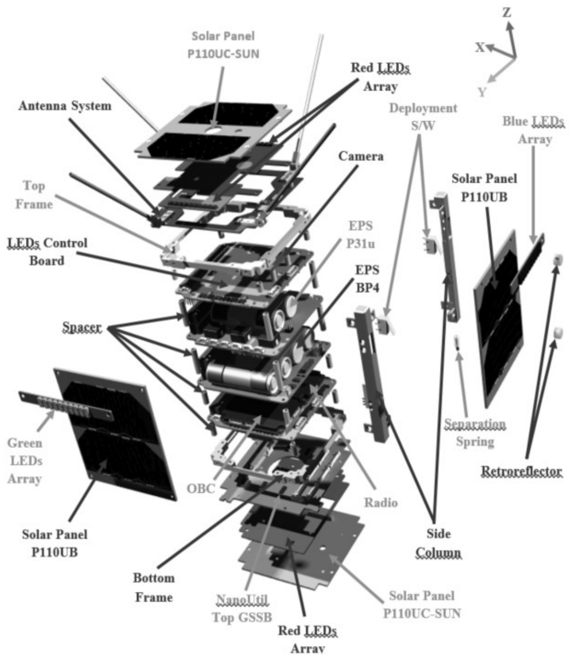

Figure 1: LEDSAT 1U CubeSat exploded view.

in Ann Harbor, Michigan. An exploded view of the CubeSat is shown in Figure 1.

Currently, the project CDR has been successfully finalized and the mission is moving towards the satellite integration and ambient verification. After thorough ambient and environmental testing campaigns of the satellite, LEDSAT will be accepted for launch in quarter 3 (Q3) 2019, launched in Q4 2019 and deployed from the ISS in early 2020.

III. PAYLOAD DESIGN

The innovative concept of a self-illuminated system and the extreme challenging operational conditions make the LEDSAT design one of a kind. The achievement of mission objectives mainly depends on the detectability of the actively illuminated payload from the project telescope stations and the survivability of the selected devices in the space environment.

During the first year of project (2017), the S5Lab research group has focused on photometric and astrometric studies in order to develop a payload configuration able to be tracked in LEO even by amateur telescopes. By considering a limited power budget and mass constraints, high-powered LEDs have been selected among the COTS devices, mostly for their efficiency. The optical instrumentation capabilities of the ground segment have driven the choice of the color and number of LEDs.

LEDSAT payload consists of three colors of LEDs, selected for the proper applicability to operations that require maximum luminous flux with limited power consumption and stringent requirements regarding lifetime. The selected colors are red (660 nm), green (505 nm) and blue (451 nm). The total amount of 140 diodes has been confirmed by apparent magnitude and signal to noise ratio analyses of the luminous flux. The designed configuration ensures a limited current drain suitable for nanosatellite application in LEO.

The selection of the LED Emission Band (EB) considers an average of the Quantum Efficiency highest values (QE) of the sensors mounted on the Couple Charged Devices (CCDs) of the ground observatory network. This has limited the chosen EB to the visible spectrum. The dominant wavelength groups shall guarantee a minimum QE of 30% for each sensor. Moreover, the radiation features of the LEDs shall be almost constant for about the half of the angle of emissivity, in order to guarantee visibility in case of high tumbling rate. The detectability of LEDSAT through optical observations depends on several variables. The main feature is the elevation of the CubeSat pass over the telescope station. This value influences the length of the light path to the observer and the atmosphere thickness interested by the line-of-sight, which characterizes the light flux extinction. The effect of both aspects is an amount of power received at ground, which appears reduced by several orders of magnitude (with respect to the emitted power) and it represents a crucial factor, especially at low elevation values, for determining the chances of observing the CubeSat, by also considering the sky background brightness. The second main feature concerns the observatory instrumentation. In fact, the heterogeneous composition of the ground based observing stations optics and sensors, also when including the involvement of astrophiles and amateur observers in the project, makes an accurate Signal-to-Noise Ratio (SNR) analysis very dispersive. Therefore, by considering the usual detection flux threshold corresponding to a 13-16 magnitude, an apparent magnitude assessment could be sufficient to indicate a likely detectability of the satellite flashes for the large majority of the optics and instrumentation of the possible observers.

The apparent magnitude analysis has been performed for the red LEDs, by considering an altitude of 400 km (the satellite will be deployed by the ISS) and an elevation angle range covering 10 to 90 degrees. The slant range and the atmospheric absorption in

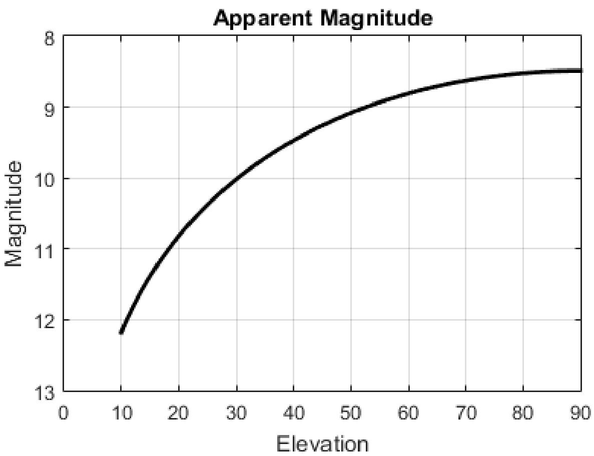

Figure 2: Apparent magnitude of LEDSAT LEDs (on ISS orbit). Both the exponential decay caused by the atmospheric extinction and the slant range variation have been modeled with respect to the elevation angle.

the considered band have been taken into account. By considering the results shown in Figure 2, it is possible to infer that the LEDSAT observability is well assured above the usual minimum elevation angle of 20 degrees.

Critical aspects of LEDSAT mission are correlated to an unexpected degradation of the components in space environment. For the LEDs space qualification, a deep testing campaign has been performed to understand possible change of behavior of the devices. The most common LED failure mode is the gradual lowering of light output and loss of efficiency. Furthermore, if a shift in the bandwidth of the dominant wavelength occurs, it shall be characterized to fulfill mission objectives during the whole duration of the mission.

The environmental testing campaign includes thermal-vacuum, ultraviolet (UV) and gamma-ray radiation exposure. Replicas of the LEDs final configuration, shown in Figure 3, have been manufactured and tested. Prior and after each tests, a complete optical verification and characterization of the models has been made, by thoroughly measuring their total irradiance and the peak wavelength. UV testing has been performed at the Space Systems Laboratory (LSA), at Sapienza – University of Rome facilities on a different set of preliminary test boards shown in Figure 4.

The main criticality has been related to the silicone lens, that covers each LED chip. It has been observed that the degradation

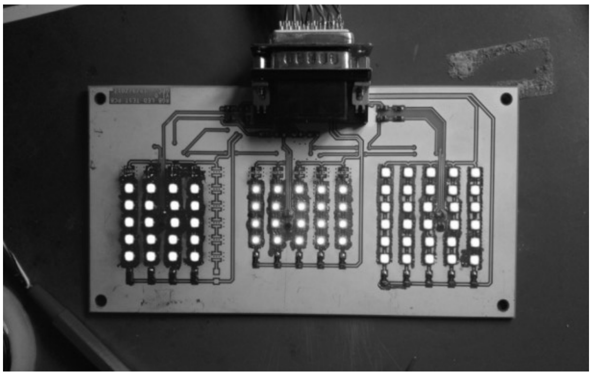

Figure 3. LEDs boards for testing campaign.

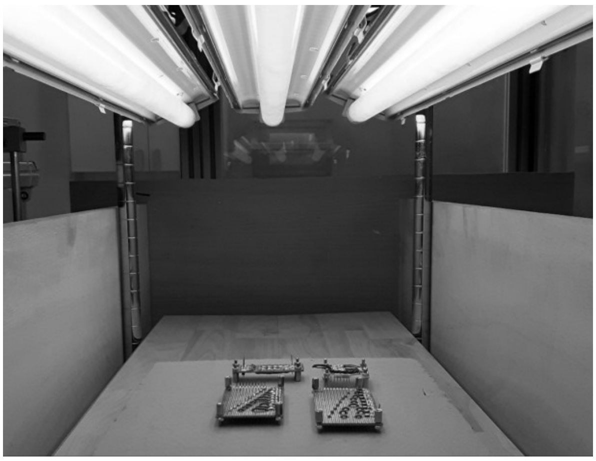

Figure 4. UV radiation exposure tests being performed in the Sapienza LSA facility, Rome.

of the silicone could cause bandwidth shifting. This phenomenon is commonly defined as “yellowing”, due to the shifting toward the yellow (555 nm) wavelength. Therefore, the LEDs test boards have undergone one-month of UV radiation without any a significant change of the radiometric characteristic.

Moreover, by considering that LEDs are potentially sensitive to ionizing radiation, a Total Ionizing Dose (TID) test was performed at the Co60 facility of ESA/ESTEC in Noordwijk, The Netherlands, shown in Figure 5, in a five days testing campaign. The tested LEDs passed the irradiation exposure without showing any degradation in the electrical parameters (current and voltage) or in the light emission performances (irradiance, flux and peak wavelength) up to a TID of approximately 35krad (Si). During the TID tests, the sample was fixed to a stand placed at a determined distance from the radiation source. Each sample has been exposed to a TID of 34.5 krad, divided among 8 steps. The radiometric performances have been measured between each pair of steps, in order to quantify the eventual flux degradation, by means of an irradiance probe, in a provisional camera obscura located next to the testing facility. Half of the LEDs have been tested in biased mode (activated), while the rest of the LEDs have been exposed while being in an unbiased (deactivated).

The results of the TID testing campaign are shown in Figure 6. The irradiance trend of all the boards (all colors, both biased and unbiased, with respect to TID) shows that no degradation occurred during the irradiation doses. The test pass/fail criterion stated that a 40% degradation of the boards was sufficient to qualify the LEDs for the LEDSAT mission.

The functional and environmental qualification was a success for the LEDSAT mission. Moreover, the standard bus components included in the aforementioned and shown design have been selected also for another 1-U Cubesat mission named 1KUNS-PF (First Kenyan University Nano Satellite – Precursor Flight) which has been deployed from the ISS on 11 May 2018 and it is nominally performing its in-orbit operations.

IV. SATELLITE OPERATIONS AND EXPECTED RESULTS

As described before, the capability of actively illuminating the spacecraft extends the optical observability interval of a satellite to the whole eclipse time. The observational

Figure 5. LED boards inside the Co60 Irradiation testing facility at ESA/ESTEC (Noordwijk, The Netherlands).

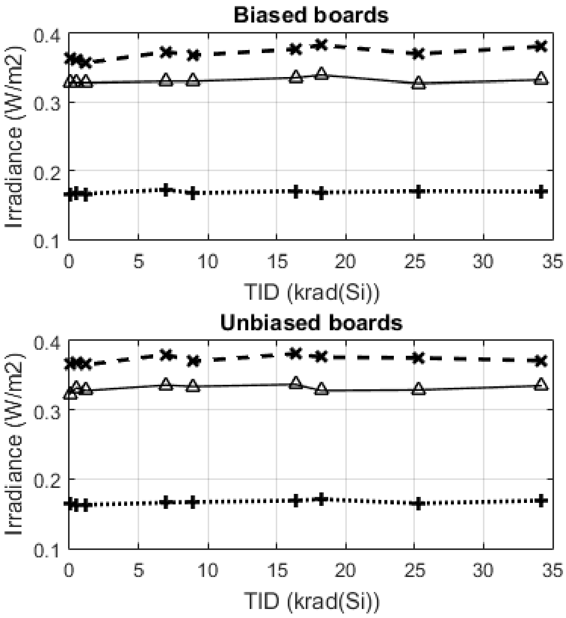

Figure 6. LED board irradiance versus the ionizing radiation dose. Solid lines with triangle markers are referred to the red boards, dashed lines with “X” markers are referred to the blue boards, dotted lines with “+” markers are referred to the green boards. The constant trend of all the plotted data indicate that no degradation occurred as result of the TID tests.

improvements of such kind of active visible light emission system have already been demonstrated by the Japanese FITSAT-1 mission [12], whose LEDs were tracked by the Japanese observatories. Indeed, a fundamental difference is however present between LEDSAT and FITSAT-1 mission. While the Japanese satellite flashing was activated from ground stations, requiring an accurate synchronization between these stations and the involved observatories, LEDSAT will mount precise time-keeping devices that will ensure a precise operational time synchronization, without needing the observatories to be synchronized to a RF transceiver. The schedule will then be made available to all the interested observatories, astrophiles and academic institutions interested in observing the satellite passes. It will also be possible to upload all the collected data on a measurements server managed by the LEDSAT team and hosted by Sapienza - University of Rome. The same tool will also be used as a reference for the satellite Two Line Element (TLE) and angular position in the sky for the astrophiles interested in tracking the satellite flashes. This approach allows to acquire data even from small telescopes, without the need of simultaneous RF commands and eventually making all the data available for the scientific community.

Different flashing patterns in different wavelengths (i.e. colours) will be implemented to maximise the chance to identify the CubeSat position in orbit and to get information about its attitude, since different colours will correspond to different satellite faces. Hence, two different data typologies will possibly be inferred from the optical observation of the light tracklet left by the satellite pass over a specific observatory:

a) the satellite celestial coordinates;

b) the satellite attitude.

The first point is addressed at performing a tracklet identification and centroid computation. This operation does not require the identification of the observed face of the satellite (of a certain colour), since the satellite rotational state is not required to this purpose. Indeed, different patterns can be independently tested to maximize the precision of the achievable satellite position in the sky, both involving all the satellite faces at the same time or different patterns for different faces to optimise the dotted shape of the light curve according to the satellite velocity and the image resolution. The satellite coordinates will then be determined by performing a Field of View (FoV) recognition, by comparing the identified stars in the image with a star catalogue.

The possibility to get information about LEDSAT attitude will instead be investigated by collecting and processing light-curves generated by different LEDs colours and possibly adopting different patterns from each available ground-based telescope.

In general, orbiting objects do not have a constant brightness. They reflect the sunlight and the recorded intermitting tracklet is caused by their tumbling motion. Brightness changes over timescales of a second or less can be investigated by using long exposure images by trailing the target across the star fixed field of view. The result is an image where the target appears as a streak while the background stars appear as dots, since they are tracked by the telescope. The counts distribution in the track-wise direction of the streak is used to detect the primary frequencies of the satellites. The success of the attitude reconstruction procedure mostly depends on the accuracy of the light streak peaks detection. The streak starting and ending point are usually evaluated as the points, in the track-wise direction of the streak, where the total pixel counts are above the sky background level and their accurate determination is crucial for a precise attitude and position reconstruction.

Specific LEDs flashing sequences will be tested for the LEDSAT mission in order to enhance the decoupling of the angular motions around the three satellite axes and determine the attitude. The identification of the observed face is a fundamental requirement to this purpose. The satellite will be commanded to flash with inherently orthogonal patterns, which will allow an easy recognition of the phases, based on Gold codes. The observed light curve, generated by the LEDs, will be autonomously associated to one of the six faces patterns, which are known and determined prior to the satellite operations. Then, the spacecraft rotational state will be derived from a best-fit computation between the model generated and the observed intermittent light pattern, leaving the CubeSat rotational state as a free parameter of the fit. While the satellite is orbiting, the on-board attitude sensors will constantly collect data about the CubeSat angular speed during the nominal operations, when the actuators are switched-off. All the collected data will consequently be downlinked to ground in order to compare these data with the reconstructed attitude. This comparison (between the attitude information collected by the on-board sensors and the results obtained by analysing the optical measurements) will allow to verify the accuracy of this technique. The attitude recognition tasks could allow to acquire information on the satellite attitude during the de-tumbling phase, shortly after deployment, if at least one pass will be performed over one of the optical ground stations.

One of the satellite purposes is also to define an easy and reliable method to identify the small satellites immediately after the deployment. In fact, in the very first mission orbits, the availability of the orbital parameters of the nanosatellites are limited mainly due to the fact that they are usually launched in clusters. Typically, an early RF-based identification of the satellite is very difficult because of the lack of directional information in such kind of communication [13]. Moreover, during the first 30 minutes after the CubeSats deployment, radio silence is mandatory, as it is imposed by the current ISS regulations. To address this problem LEDs could be implemented on such small satellites in order to easily identify them from ground based observing stations just after their release. Specific lighting pattern could be used to discriminate different members of a satellite cluster. Thus, one of the mission aims is to demonstrate the feasibility of this kind of identification method.

Finally, light flashes will be used to verify the possibility to transmit to the ground simple information about the system status as back-up communication strategy. In fact, the failure of the communication subsystem can corrupt the chances of accomplishing the mission. A study performed on the first 100 CubeSats launched within the 2012 proved that an outage in the RF equipment led to the mission failure in the 17% of the examples [14]. A proper strategy to mitigate this problem and to provide an alternative link to transmit housekeeping and scientific data will allow increasing the mission success percentage. To this purpose, both *tracklet observation* (with a fixed stellar field) and *satellite live tracking* (by following the satellite during its pass) methods will be used. For each direct light communication observation, the satellite will be commanded to transmit at different data rates depending on the used observation method. The LED flashes will be detected both by means of Charge-Coupled Devices (CCDs) and Avalanche and P-I-N photodiodes. The satellite will flash to downlink housekeeping data (attitude, temperatures, voltages) or pre-determined messages (to validate the method well-functioning). Data size and precision will be adjusted according to the message allowable size. The reduction will consider pre-determined numeric intervals suitable to evaluate the systems health status only by using the light-based transmitted messages. This system could be of critical importance for future CubeSat and satellite systems, if implementing LED panels, to potentially transmit data even in case of a transceiver failure.

V. CONCLUSIONS AND FUTURE PERSPECTIVES

The design of LEDSAT has been finalized in early 2018 and confirmed with the successful outcome of the CDR in May 2018. The project is now heading to the satellite integration. The satellite launch is currently scheduled in the September-December 2019 window, with the consequent deployment from the ISS to be performed in early 2020.

This 1-Unit CubeSat realized in the framework of the Fly Your Satellite! Educational Programme, managed by the Education Office of the European Space Agency (ESA), aims at improving the capability of performing the ground-based orbit determination and attitude reconstruction procedures by means of optical observations using a cooperative target. Indeed, the implementation of a LED-based active light emitting payload will extend the observability window to the whole satellite pass over the ground stations eventually assuring the quasi-full orbit monitoring coverage with the support of a largely distributed optical monitoring system composed by professional and amatorial observatories spread around the globe. The use of different LED colors will improve, coupled to the exploit of narrow band filters in the observatories, the satellite attitude reconstruction allowing easily identifying the observed Cubesat face. Moreover, the implementation of different timed flashing patterns for each satellite face will guarantee the satellite recognition while performing an observation and a precise celestial coordinates reconstruction based on the images shot with sidereal tracking technique. Furthermore, the flashing patterns, when performed in a specific predetermined sequence will also ease the attitude reconstruction allowing the cube face recognition and the light-curve fitting with a theoretical model.

The results of the environmental testing campaign exposed in this work can be summarized as follows:

1) The tested LEDs showed no degradation after the UV radiation exposure as well as no evidence of yellowing of the silicone cover of the diodes.

2) During the execution of the TID tests performed in Co60 facility at ESA/ESTEC in The Netherlands no effect of the ionizing radiation on the light emitting diodes has been measured. The LEDs boards have been exposed to an amout of radiation (34.5 krad) that will largely cover the flight duration (approximately 19 months for a maximum TID of 21 krad). This result certifies that the severe space environment will not affect the satellite payload and will not cause a space segment failure.

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LEDSAT has been selected for the Second Edition of the Fly Your Satellite! Programme, managed by the Education Office of the European Space Agency. During 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. LEDSAT is also part of the IKUNS (Italian-Kenyan University NanoSatellites) project, managed by the Italian Space Agency (ASI).

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