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The PhotSat mission: Ultraviolet and visible all-sky monitoring with a CubeSat

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Abstract

PhotSat is the first astrophysical satellite developed from design to operations by the Institute of Space Studies of Catalonia (IEEC) and the Catalan industrial ecosystem. The main scientific goal of the mission is to obtain a full sky photometric monitoring of the approximately 10 million brighter astrophysical sources down to magnitude 15. Its main science case is in the support of high-precision programmes of all kinds (transients, exoplanets, solar system, stars, galaxies, ...). By using a CubeSat platform in low-Earth orbit, the PhotSat mission will be able to access both the visible and ultraviolet ranges using two independent telescopes. Thanks to their wide field of view (FoV= 8°) the mission will be able to revisit each sky position with a cadence of only 2-3 days, except for an exclusion region of 32° around the Sun. As the design lifetime is of 2-3 years, the entire sky will be completely observed repeatedly by the end of the mission. PhotSat will provide dense light curves for all bright sources in the sky, simultaneously in three different passbands (one in the ultraviolet and two in the visible) using CMOS detectors. The PhotSat consortium is composed of several institutes, universities and industries in the Catalan ecosystem. In this sense, PhotSat will also help our consortium to establish new collaborations and develop the joint capability of executing science experiments from their initial stages, including preliminary design, construction, launch, and operations; using off-the-shelf NewSpace technologies.

1 Introduction

Performing astronomy from ground-based observatories is hampered by light absorption and image distortion produced by the atmosphere and by the day-night cycle that limits the amount of observable sky and the length of time for which each object can be observed. By avoiding atmospheric effects, space observatories open the possibility of reaching much higher precision in photometry and observing in wavelength regions not accessible from ground.

PhotSat (`https://www.ieec.cat/en/project/64/photsat/`) is the first space mission entirely led by the Institute of Space Studies of Catalonia (IEEC) and dedicated to the field of astrophysics. The main goal of the mission is to develop a small satellite with two telescopes, able to observe astronomical phenomena that cannot be properly characterized from ground, performing photometry of the brightest sources on the sky. Given the development of the NewSpace sector, we also aim at increasing the expertise of the institute and being able to develop scientific experiments with these new platforms. This project will push forward the academic and industrial infrastructure in order to carry out future end-to-end missions and projects using smallsat technology in-house in short development time (<3 years).

2 The satellite

The satellite consists of a 16-unit (16U) CubeSat[1], see Fig. 1. To maximize power and thermal stability and ensure a minimum lifetime of 2 years, it will orbit the Earth at an altitude not lower than 500 km in a Sun synchronous dawn-dusk orbit (SSO), with its solar panels always perpendicular to the Sun. The satellite is expected to be fully operational during year 2026.

With two small telescopes and a rotating mirror mechanism (called siderostat), the PhotSat satellite will be able to observe stars within the visible (VIS) and ultraviolet (UV) wavelength domains, while detecting and warning of possible transient sources. The sky is covered by keeping the satellite in a rigid pointing during each orbit, and using the siderostat, at the entrance of the telescope, to scan a great circle strip. At the following orbit, the plane of rotation of the siderostat is changed by reorienting the satellite and the process is repeated until the full sky is covered in 2–3 days. Using the PhotSat simulator for the effective coverage per month with FoV$=8^\circ$ and siderostat step angle of 4° for an entire year (Fig. 2), we obtain the number of times each zone of the sky is scanned. On average, in a full year of observations, every position in the sky is observed about 400 times, with the region in the ecliptic plane to be the most densely observed (with a maximum of about 1000 times per year).

The satellite has two telescopes (built by ASE Optics Europe) with small apertures ($<$ 70 mm) but with a large FoV each (8° in diameter). The two telescopes are almost identical devices except for their wavelength sensitivity (Fig. 4): the VIS channel (with minimum coverage of 500–840 nm, divided into two bands to increase chromatic information), and UV channel (minimum coverage of 250–300 nm, single band to enhance signal and simplify optics). The two channels consist of custom optics and off-the-shelf detectors (EHD SCA2020-

[1] 16U according to the CubeSat standard: https://www.cubesat.org/

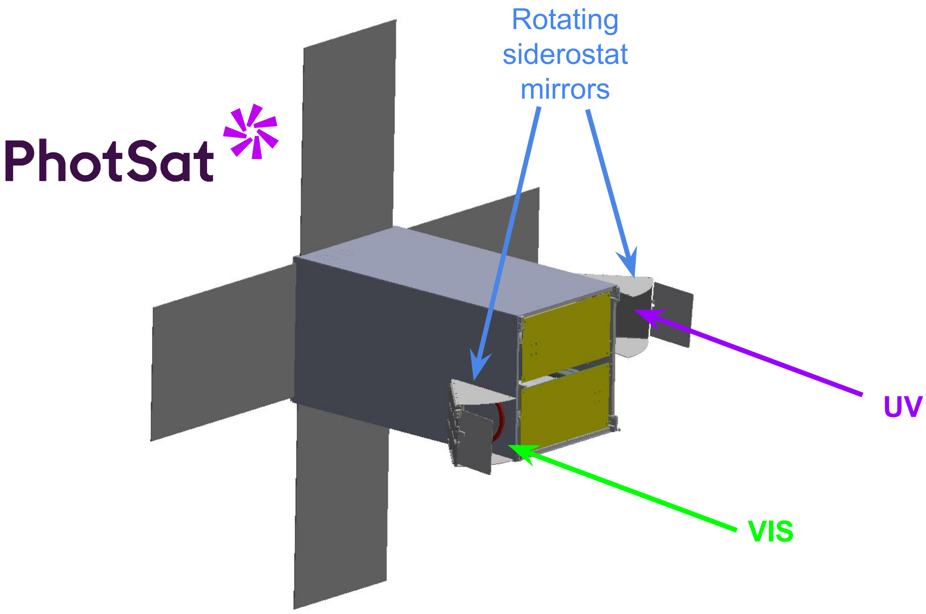

Figure 1: Configuration of the satellite considered for PhotSat mission.

UV-TR, GSENSE2020BSI, CMOS, 2048 × 2048 pixels of 6.5 μm size, corresponding to 14 arcsec/pixel). Each siderostat and telescope are shielded against direct solar light by the solar panels themselves. This also effectively limits the accessible sky to angles greater than 32° from the direction of the Sun (Sun avoidance angle).

The VIS detector is divided into four different sectors covered with two different filters following a chessboard pattern (see Fig. 3). With a siderostat scanning step equal to half of the FoV we obtain semi-simultaneous observations of the full sky in two different passbands. Using the chessboard pattern minimises the effect of the rotation of the siderostat with respect to the detector (see Fig. 3). In the case of the UV detector only one filter will cover the entire detector, effectively doubling the integration time with respect to the VIS telescope. This is convenient as, in general, the UV observations will have significantly lower signal to noise ratios. The observed FoV and the siderostat steps will be the same as in the VIS telescope in order to have simultaneous observations in both ranges.

While the payload will move the siderostats and extract scientific data from the optical system, the platform will be in charge of powering the satellite, controlling its orientation, establishing communications with the ground and managing all data between subsystems, including the astronomy payload. Regarding communications, the plan is to transmit and receive the payload data over an X-band antenna at the Montsec and Svalbard stations. PhotSat is estimated to obtain 2000-3000 scientific coadded images per day. Together with the calibration data needed it means than the spacecraft should send to ground about 15–21 GB/day (assuming no compression). The mission will also be able to alert on some fast transients detected on board to be observed from ground in more detail with quick reaction

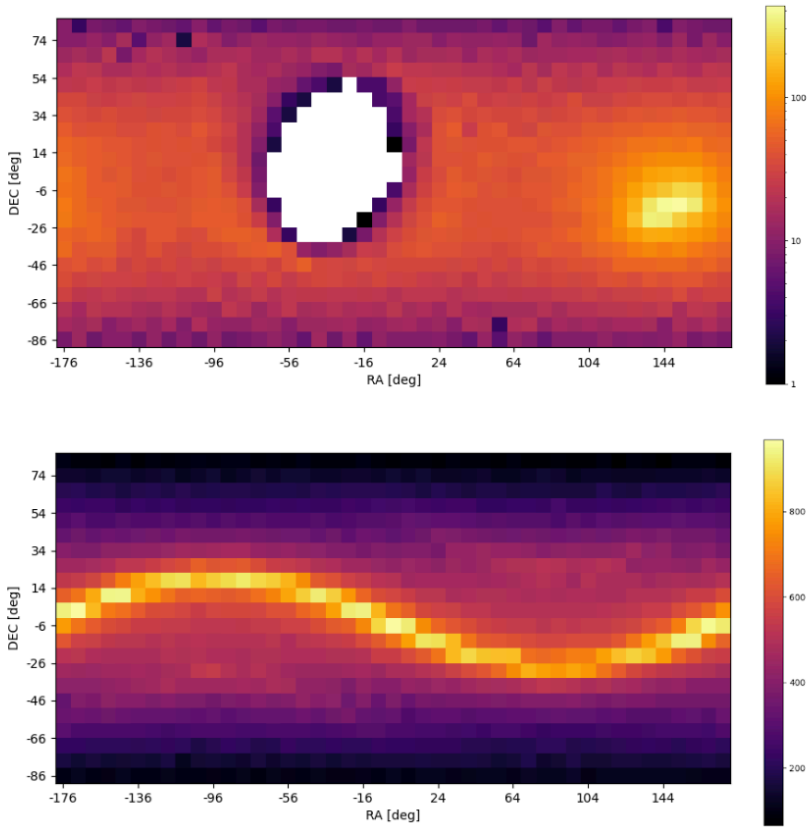

Figure 2: Number of observations in every sky position obtained during a month (top panel, with a gap where the Sun is located) and a full year (bottom panel, with maximum number of observation in the ecliptic plane) of mission. A FoV of 8° and a siderostat angle step of 4° were considered for these simulations.

times. Mission and Science Operations Center (MOC and SOC) will be centralised by the prime contractor (OPEN COSMOS EUROPE SL) and IEEC facilities. The resulting pipeline and data archives will be made available outside the collaboration.

3 PhotSat science

The core science case that defines the mission requirements consists of obtaining images of the full available sky (considering the Sun-avoidance angle) every 2-3 days, reaching a photometric precision of about 1% in the VIS channel at 12^{th} magnitude. Full-frame images will be acquired and downloaded, and therefore sources (stars but also other transient phenomena) of brightness reaching up to 15^{th} mag shall also be detectable at a photometric precision better than 20%. For the UV channel, the magnitude limit is less certain as this is an unexplored domain (both scientifically and regarding the performance of the technology), but we expect

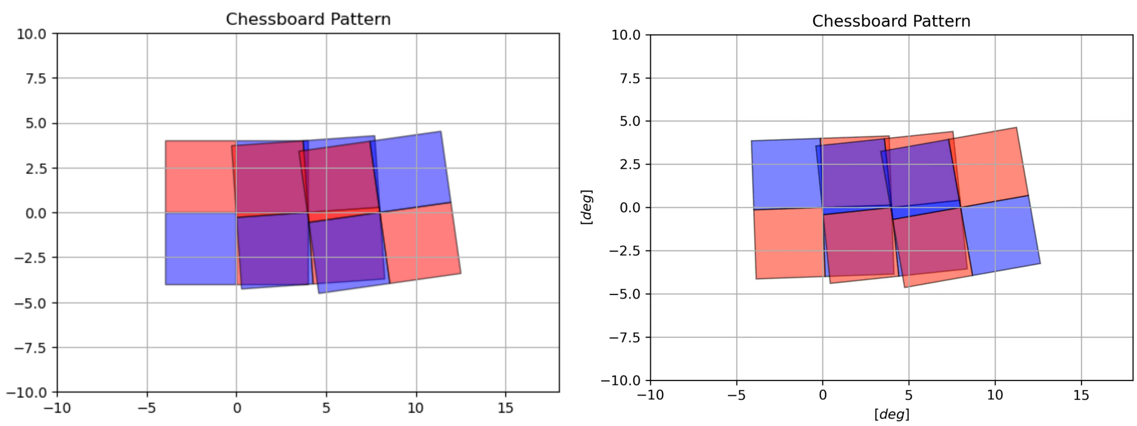

Figure 3: Orientation of three consecutive images obtained by the VIS detector. Different colours represent areas of the detector using different filters. Left and right panels show the same pattern rotated by about 90°.

to reach 1% photometric precision at about 9 mag, and a detection limit at 13$^{\mathrm{th}}$ mag.

The high cadence of observations of the full sky (once every 2-3 days) alongside the full 2-3 years of mission in PhotSat is one of its main advantages. This will allow to study many transient events and variable sources, as well as solar system objects, during the lifetime of the mission. With this survey, PhotSat will monitor the full accessible sky extracting photometry of the brightest stars while detecting and warning of possible transient phenomena. This mini-space observatory will be used for a variety of science cases and can provide supporting data to numerous on-going international programmes (for example, photometric characterization of sources observed by the JWST, cover the bright end of the Legacy Survey of Space and Time, LSST, from the Vera C. Rubin observatory, combine space-based high quality multi-band photometry with ground based observations, among others). These kinds of observations will be relevant to the field of exoplanets, stellar physics, bright transient events (supernova, kilonova and more), variability, solar system objects.

Another strong point of PhotSat mission is its UV detector. There have been only a handful of UV space missions (GALEX, IUE, Swift, HST). Besides, such missions were generally not covering the temporal domain and, furthermore, many of the sources observable by PhotSat are in fact saturated in GALEX. The UV range includes interesting information not accessible from the ground. For example, PhotSat will be able to measure the Balmer jump (364.5 nm) (see Fig. 4). The strength of the Balmer jump is sensitive to temperature for stars hotter than 10 000 K, and to surface gravity for cooler stars.

Transients generally begin their emission in the UV and, thus, PhotSat will allow an early detection. Stellar flares and core-collapse supernovae shock-breakouts last a few hours, these being brighter in the UV. With the high cadence of observations, PhotSat is well posed for the detection of such short-lived events. For thermonuclear explosions, the early detection of a bump in the first few days, would favor one progenitor scenario (single degenerate) over others. This bump would be also brighter in the bluer bands.

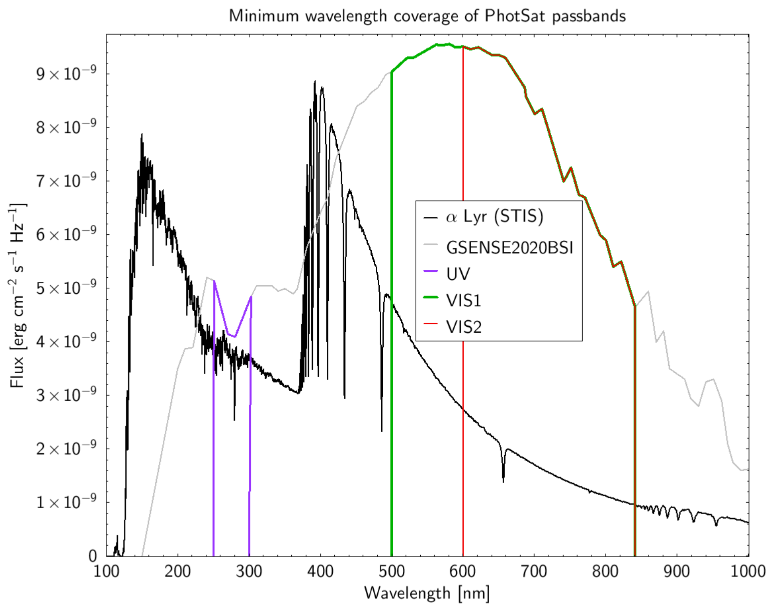

Figure 4: PhotSat photometric passbands requirement (scaled to the same level of the stellar spectra just for visualisation) superimposed to Vega HST STIS spectra [2].

Using photometric transformations between *Gaia* DR3 [3], GALEX [1] catalogues and the PhotSat passbands, we estimate that PhotSat will be able to observe more than 35 million sources with the VIS telescope and about 0.5 million with the UV telescope.

Acknowledgments

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