ON BOARD COMPRESSION OF PHOTSAT MISSION

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Abstract

PhotSat is a satellite mission aimed at exploring deep space through high-resolution imaging using advanced optical sensors. Utilizing a CubeSat platform, the mission seeks to obtain precise astronomical data at a low cost, leveraging miniaturized technologies that reduce complexity while maximizing observational capabilities. The platform is equipped with a high-performance optical system capable of capturing images in two spectral bands (visual and ultraviolet), making it possible to detect transient events such as exoplanets or variable stars. The preliminary design of PhotSat integrates an innovative data compression system based on a binary context-based arithmetic coder, ensuring the preservation of quality in crucial observations while optimizing bandwidth and storage usage. A comparative experiment was conducted with five state-of-the-art codecs, and the results show that the proposed codec outperforms the others in terms of compression efficiency. PhotSat establishes a significant precedent in the field of astronomy with CubeSats, serving as a proof of concept for the feasibility of low-cost scientific missions yielding high-quality results.

Key words: PhotSat; Cubesat; Sky mapping; Data Compression.

1. INTRODUCTION

This paper presents the preliminary on board compression system of PhotSat project, the first space mission entirely led by the Institut d'Estudis Espacials de Catalunya (IEEC) [1] dedicated to the field of astrophysics, in collaboration with the Universitat Autònoma de Barcelona (UAB) [2], the Universitat de Barcelona (UB) [3], the Universitat Politèctica de Catalunya (UPC) [4], and the Consejo Superior de Invesigaciones Científicas (CSIC) [5]. The mission aims to develop and build a nanosatellite designed to monitor the 10 million brightest stars in the sky. This mission offers a unique opportunity for the scientific community, as it will enable the observation of astronomical phenomena that cannot be adequately characterized from Earth, advancing new capabilities in the NewSpace sector and complementing other international space missions. It will be able to perform photometric characterization of sources observed by the James Webb Space Telescope (JWST) [6], cover the brightest range of the Large Synoptic Survey Telescope (LSST) [7], complement the Gaia catalog [8], combine high-quality multiband photometry with ground-based observations, and contribute to fields such as exoplanets, stellar physics, bright transient events (supernovae, kilonovae, and more), the variability of energetic events, and the observation of solar system objects.

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PhotSat will be a space observatory that utilizes an innovative rotating mirror system, allowing its two telescopes to take measurements of nearly the entire sky every two days. The telescopes, each with a diameter of approximately 10 cm, are optimized for observations in a range spanning from ultraviolet to visible light and will be capable of performing high-precision photometry.

The mission will use a 12U CubeSat, composed of 12 units (each measuring $10cm^3$), with a total weight ranging between 10 and 20 kg. This satellite will orbit the Earth at a low altitude of approximately 500 km in a near-polar, sun-synchronous orbit. Data transmission will be carried out through the Teleport of Sant Esteve de la Sarga, located at the Montsec Observatory [9], with a download capacity of 8 GB per day. The amount of data generated daily will vary depending on the final camera configuration. Currently, two options are being considered:

1. **FOV 6° Configuration**: This configuration will generate 2,848 images per day, divided between the two sensors, across 16 daily orbits. With an image resolution of 2048×2048 pixels and a dynamic range of 2 bytes per pixel, a total of 22.25 GB of uncompressed data will be produced.
2. **FOV 8° Configuration**: This configuration, with a lower number of daily images (2,144), will generate 16.75 GB of uncompressed data.

Each image will be created from the average of 50 frames captured with a 1-second integration time per frame. A compression algorithm will then be applied to each averaged image to reduce the data volume before transmission.

In addition to its scientific objectives, the PhotSat project aims to promote the development of local academic and industrial infrastructures in the space sector, laying the groundwork for future missions involving small satellites. PhotSat is expected to be fully operational by 2026, with a minimum operational lifespan of three years.

The mission is funded through the ”Recovery, Transformation, and Resilience Plan - NextGenEU” program, with support from both national and regional funds. Once the astronomical payload is ready, it will be integrated into a platform that will provide electrical power, communication with Earth, thermal control, and orientation capabilities.

This paper is structured as follows: **State of the Art**: A review of other satellite missions focused on deep sky mapping. **Mission**: This section describes the configuration and objectives of the mission, as well as the planned roadmap. It includes details on the design of the satellite, its orbital trajectory, and the requirements of the mission. **Platform**: A detailed description of the information flow process is introduced. **Compression**: A comparative study of different compression techniques that could be applied to the mission is conducted. **Results**: The results of the evaluation of the compression techniques are presented, and the selection of the most suitable algorithm for the PhotSat mission is justified. **Conclusions**: The paper concludes with final remarks on the PhotSat mission.

2. STATE OF THE ART

Similar to PhotSat, there are other satellite missions that photograph the deep sky. A prominent example is the GAIA mission [8] by the European Space Agency (ESA). This mission has revolutionized astrophysics since its launch in 2013, with the goal of creating a three-dimensional catalog of our galaxy by measuring the positions, motions, and distances of one billion stars. Through its high-precision astrometry and photometry, GAIA has provided data for understanding stellar distribution and evolution, as well as for studying celestial objects such as exoplanets and variable stars. Furthermore, it employs advanced on-board data compression algorithms to manage the vast volume of information generated, facilitating efficient transmission to Earth. This mission has set a new standard in deep sky exploration, serving as a reference for future projects like PhotSat.

More recently, the James Webb Space Telescope (JWST) [6], launched in 2021 by NASA in collaboration with ESA and CSA, has enhanced our understanding of the deep sky through its infrared observations. While GAIA focuses on creating a detailed catalog of the Milky Way, the JWST enables the study of the primordial universe, the formation of galaxies, and exoplanets from infrared light. The JWST employs a lossless compression system to manage its data, ensuring efficient transmission to Earth.

CubeSats have become an essential tool in modern astrophysics due to their flexibility, low cost, and rapid development. Missions such as ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) [10] from NASA have demonstrated the viability of using small satellites for detecting stellar variability and exoplanets. The PicSat mission [11], a French initiative, focused on high-precision photometry to observe exoplanet transits, while the Star-Planet Activity

Research CubeSat (SPARCS) [12] explores stellar activity in ultraviolet wavelengths. Additionally, there is CU-E3, which investigates stellar evolution in deep space, and Twinkle [13], a British mission dedicated to the spectroscopic study of exoplanetary atmospheres.

3. MISSION

The PhotSat mission is based on stellar mapping using two sensors of 2048 × 2048 pixels, with a dynamic range of 12 bits. The first sensor operates in the ultraviolet (UV) range, capturing wavelengths between 200 and 350 nm. The second sensor covers the visible range, with two spectral bands distributed in a 2 × 2 grid. The first visible band extends from 500 to 700 nm, while the second band focuses on the range of 600 to 700 nm. Both sensors utilize CMOS technology, enabling the capture of bright stellar objects with a relatively short exposure time of approximately 1 second. For fainter objects, an averaging technique will be applied, which involves combining 50 exposures taken over one minute to generate a single image. This technique will also allow for the monitoring of the Moon and planets in the solar system in both the UV and visible ranges, as well as the detection of transient and periodic astronomical events, such as variable stars and exoplanets.

The mission is planned to last for 3 years. Considering orbital decay, it has been calculated that the initial altitude of the CubeSat must be above 503 km. Furthermore, to ensure a constant power supply to the batteries, a Sun-synchronous orbit is required. This has led to the selection of an orbit at an altitude of 567 km, with an inclination of 97.7º and an orbital period of approximately 96 minutes. This configuration will allow the satellite to complete 16 orbits per day, with an estimated decay of 25 to 30 km over the 3-year mission duration. Under optimal conditions, the maximum mission duration could reach 9.24 years, concluding observations when the orbit descends to 150 km.

The satellite image capture system employs a siderostat that tilts to enable the mapping of the entire visible sky. The analyzed fields of view (FoVs) are 8º, with a shift of 4º between images and 6º with a shift of 3º. This displacement, which is half of the FoV, has been chosen to align the grid of the visible sensors, as illustrated in Figure 1. This configuration will allow each region of the sky to be captured twice, ensuring complete coverage across the various visible spectral ranges. With this system, it is estimated that complete sky mapping can be achieved within a period of 2 to 3 days.

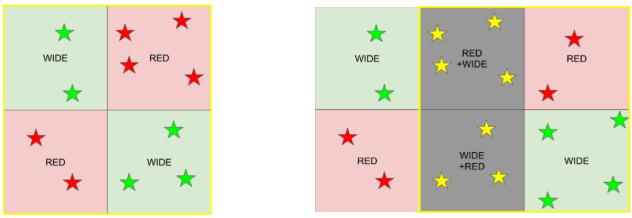

Figure 1: Evolution of Stellar Capture in the Visual Sensor.

The roadmap for the PhotSat mission can be observed in Figure 2. A preliminary design review has already been completed, and the platform procurement has been awarded. In the first quarter of 2025, the critical design review is expected to be completed. By the third quarter of 2025, the assembly, integration, and verification processes are anticipated to be finalized. Finally, at the beginning of 2026, the mission will be launched into space, and a few months later, once the satellite's functionality has been verified, the development phase will be considered complete.

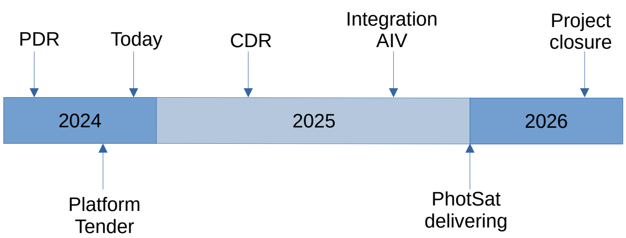

Figure 2: Roadmap of the Photsat mission.

4. PLATFORM

The described situation regarding the integration time and the movement of the siderostat can be simplified into one-minute intervals, with 50 seconds dedicated to capturing frames and the remaining 10 seconds allocated for the movement of the siderostat. Once the capture is complete, the next step involves averaging the images, to which metadata will be added for identification. This metadata, as shown in Table 1, will also be used to prioritize images containing events of high scientific interest.

Table 1: Definition of the packet format to be transmitted.

Field	Description	Size (bits)	Size (Bytes)
PktType	Type of paket	4	1
Priority	Priority of packet	4	
SyncWord	Alignment word	16	2
PktLen	Length of the packet	24	3
Timestamp	Linux epoch in ms	64	8
Compression	flags of compression	16	2
ImgType	Calibration or Field	3	2
Telescope	UV or VIS	1	
Band	UV, VIS1 or VI2	2	
NFrames	Number of stacked frames	7	
Spare	Spare bits for byte alignment	3	
IntegTime	Integration time	8	1
TimeOffs	Time offset between consecutive frames	8	1
AlignInfo	Alignment information	16	2
Image	Compressed image	Up to 8 MB	
Checksum	checksum for all elements of the packet	16	2

Once the averaged images have been obtained, two daily contacts are planned with the Teleport de Sant Esteve de la Sagrera, located at Montsec. Communication will be conducted via the X-band, allowing for data transmission ranging from 4 to 9 GB per connection. This means that a minimum of 8 GB of information can be downloaded each day. However, the volume of data generated daily varies depending on the field of view (FOV), reaching 16.75 GB or 22.25 GB depending on whether a FOV 8° or a FOV 6° is used, respectively. Therefore, in both cases, compression needs to be applied.

To analyze all the data flow generated during the mission, a simulator called PhotSatSim has been created, which is still in the development phase and does not have a public repository. This simulator uses the GAIA catalog to generate a stellar image, simulates cosmic rays and other possible transients, and finally adds the expected noise from the onboard sensor. The noise model is based on the addition of darks (noise due to CMOS heating), flats (vignetting from the camera), and bias (noise from the electronic circuit) to the image. Several dark and flat files previously generated in the laboratory with the sensors are available, and for each image, one dark and one flat file are randomly selected. For the bias, Gaussian noise is simulated with a mean of 187 light measurement units and a standard deviation of 2 units.

5. COMPRESSION

As mentioned earlier, the volume of data generated by the mission exceeds the available transmission capacity to the Montsec station, making the use of compression techniques necessary.

According to the analysis by Maireles-González et al. [14], the codecs with the best performance in terms of compression for integer astronomical images are 5/3 DWT JPEG 2000 [15], 9/7 FAPEC [16], JPEGLS [17], CCSDS 123.0 B-2 [18], and bzip2 [19]. These algorithms, along with a proprietary compression model, have been evaluated for this mission.

The proprietary model is based on the article by Aulí-Llinàs [20], which was used for the first time in remote sensing by Bartrina et al. [21]. The article introduces a model based on a predictor with adaptive weights, similar to that of CCSDS 123.0 B-2, followed by a mapper and a contextual binary arithmetic encoder. Bartrina [21] proposes three different contexts for encoding, of which the context that has proven to be the most suitable for the mission is the context that utilizes adjacent vertical, horizontal, and diagonal pixels. In the proprietary model, fixed weights have been chosen for the predictor to reduce computational load, selected through an empirical study. Figure 3 shows the flow of the acquisition and compression process of the PhotSat mission with the proprietary model.

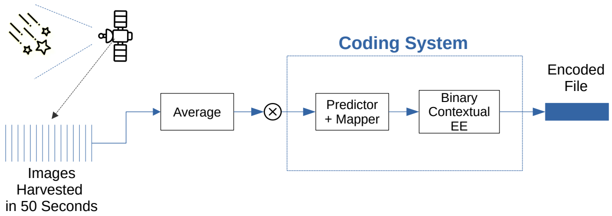

Figure 3: Flow diagram of the image acquisition and compression process with the proprietary encoder.

To evaluate which compressor is the most suitable for the mission, two datasets of images have been created using the PhotSatSim simulator following the methodology described in section 4. Both datasets include 20 UV images since the visible images have not yet been implemented in the simulator. The first dataset contains different regions of the observable sky, while the second focuses on more densely populated areas (figure 4). The datasets used in Maireles-González [14] have also been employed.

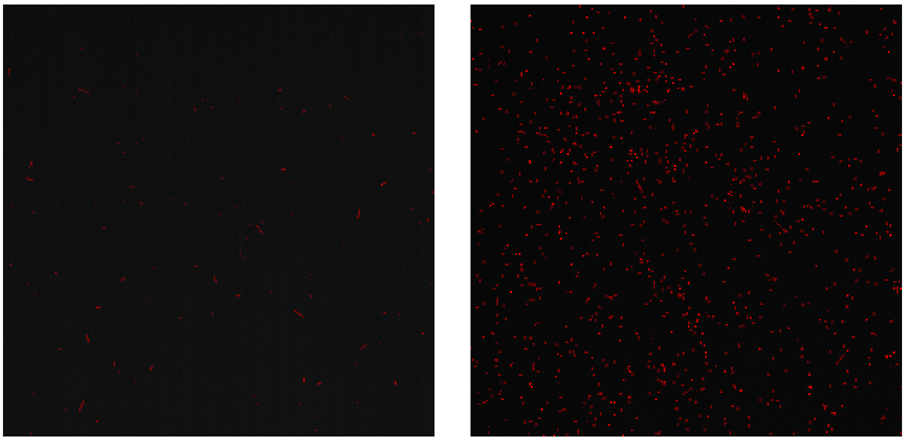

Figure 4: Comparison of the stars observed in the two PhotSatSim datasets. On the left, a crop of 250×250 pixels from an image in Dataset 1; on the right, a crop of 250×250 pixels from an image in Dataset 2.

The compression experiment was carried out using the ENB library [22] in Python. ENB is an experimental environment with specific modules for image compression and includes several plugins for the studied compressors. A custom plugin has been created for the proprietary model.

6. RESULTS

Table 2 presents the compression results of the different corpus and codecs, expressed in bits per sample. The proposed model shows better performance than all others in the real datasets. However, performance varies in the simulated datasets. In the densely populated area dataset, our model yields better results. Conversely, in the observable sky dataset, it performs slightly worse, showing a difference of 0.04 bps compared to JPEG 2000.

Regarding the bandwidth generated per day, as shown in Table 3, all coders produce less than 8 GB daily in the FOV 8° configuration. However, the proposed model stands out for achieving a higher average compression. In contrast, in the FOV 6° configuration, according to Table 4, the 9/7 FAPEC and CCSDS 123.0 B-2 coders do not meet the maximum required. Although the proposed model also meets this requirement in this configuration, the margin relative to the maximum target may not be sufficient in adverse situations during the mission.

Table 2: Results of the compression experiment for the different datasets and codecs, in bits per sample.

	Proposed	5/3 DWT JPEG 2000	9/7 FAPEC	JPEGLS	CCSDS 123.0 B-2	bzip2
Dataset 1	5.35	**5.31**	5.65	5.47	6.16	5.70
Dataset 2	**5.59**	5.68	6.21	5.61	6.48	5.79
INT	**5.30**	5.44	5.53	5.48	5.54	5.56
JKT	**5.57**	5.74	5.82	5.76	5.82	5.99
LCO	**5.52**	5.76	5.81	5.75	5.74	5.85
TJO	**5.51**	5.72	5.76	5.78	5.73	5.86
WHT	**6.03**	6.10	6.19	6.17	6.18	6.35
All	**5.55**	5.68	5.85	5.72	5.95	5.87

Table 3: Expected amount of GB per day based on the dataset and codec for the FOV 8° configuration.

	Proposed	5/3 DWT JPEG 2000	9/7 FAPEC	JPEGLS	CCSDS 123.0 B-2	bzip2
Dataset 1	5.60	**5.56**	5.92	5.73	6.45	5.97
Dataset 2	**5.85**	5.95	6.50	5.87	6.78	6.06
All	**5.73**	5.76	6.21	5.80	6.62	6.02

Table 4: Expected amount of GB per day based on the dataset and codec for the FOV 6° configuration.

	Proposed	5/3 DWT JPEG 2000	9/7 FAPEC	JPEGLS	CCSDS 123.0 B-2	bzip2
Dataset 1	7.44	**7.39**	7.86	7.61	8.57	7.93
Dataset 2	**7.78**	7.90	8.63	7.80	9.01	8.05
All	**7.61**	7.65	8.25	7.71	8.79	7.99

7. CONCLUSIONS

The PhotSat mission, with its innovative approach to deep sky observation, is at the forefront of small-scale satellite missions, following in the footsteps of previous projects such as GAIA, JWST, Twinkle, ASTERIA, PicSat, SPARCS, and CU-E3. Its configuration of two telescopes, one for ultraviolet and another for the visible range, will generate data that will contribute to research in areas such as exoplanets, variable stars, and transient phenomena.

The PhotSat mission on-board compression system effectively addresses the challenges of managing large amounts of daily data with limited bandwidth. By employing advanced lossless compression techniques, the integrity of the data is maintained while reducing file sizes, facilitating efficient transmission to Earth. The results of our comparative experiment show that the proposed codec consistently achieved superior compression ratios across various datasets. It outperformed the other codecs, particularly in terms of bits per sample. The proposed codec results in the lowest amount of data generated per day, both for FOV 8° and FOV 6° configurations, with reductions of up to 5.73 GB/day and 7.61 GB/day respectively.

Overall, PhotSat aims to demonstrate that, despite the technical limitations of CubeSats, it is possible to achieve scientific missions with a significant impact through efficient compression systems that maximize the use of available resources. This implementation sets a precedent for future small-scale space missions, contributing to the development of more efficient technological solutions for deep space exploration.

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