DEVELOPMENT AND IN-ORBIT VALIDATION OF A MULTISPECTRAL AND HYPERSPECTRAL DATA COMPRESSION PIPELINE FOR SMALL SATELLITE MISSIONS

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ABSTRACT

This paper presents a case study of the engineering process of developing, validating, and deploying a multispectral and hyperspectral image compression system for onboard usage on a small Earth Observation satellite, to increase the volume of imagery downlinked to ground. The algorithm was designed for efficient execution on general-purpose CPUs found in typical NewSpace COTS-based onboard computers and supports both lossless and near-lossless compression modes. A further practical challenge addressed during deployment was that the onboard camera produces imagery in a proprietary output format, requiring the development of a preprocessing stage to convert the camera output into the raw BIL format expected by the compressor. The compressor was deployed on the Menut 6U CubeSat as part of the C3SatP payload and has been successfully executed during multiple in-orbit acquisition campaigns, achieving Technology Readiness Level (TRL) 9 through sustained operational validation in orbit. Commissioning results are presented, including lossless compression ratios of 1.85–1.90 at throughputs exceeding 20 MiB/s using a single CPU thread on the Zynq UltraScale+ platform. The paper highlights the engineering workflow—from initial concept through fuzz testing, Engineering Model validation, integration, and in-orbit operation—and discusses practical challenges such as multispectral band misalignment. The engineering methodology and lessons learned are presented as engineering insights for teams developing similar onboard processing systems.

***Index Terms*—** Onboard image compression, Multispectral imaging, Hyperspectral imaging, Remote sensing, CubeSat, Small satellites, Fuzz testing

1. INTRODUCTION

Since the launch of Landsat-1 in 1972, hundreds of spectral imaging satellites have been deployed in Earth's orbit [1], gathering great volumes of highly valuable spectral data. Spaceborne spectral observations are used in a wide variety of applications, from land and resource surveying to climate science and management of natural disasters [2, 3, 4]. These observations would be of little value if they cannot be transmitted down to Earth, and while the amount of data produced by these missions continues to grow, downlink capacity persists as one of the key bottlenecks in imaging operations [5]. Data compression is, therefore, a crucial technology to maximize the returns of Earth Observation (EO) missions.

Data compression technologies have been deployed on board satellites since at least 1980, with SPOT-I including DPCM before transmission [6]. Among the many different compression techniques used over the years, the standards developed by the Consultative Committee on Space Data Systems (CCSDS) [7, 8, 9, 10] are highlighted. These are used in a variety of missions that capture spectral data, including Sentinel-2 (2015) [11], EnMAP (2022) [12], and JUICE (2023) [13]. Other techniques such as Rice coding are also relevant, used in missions such as Landsat 8 (2013) and Landsat 9 (2021) [14, 15].

For many years, these compression systems were deployed in dedicated hardware implementations, such as ASICs and FPGAs [6], a paradigm that influenced the design of these techniques and standards. For example, the CCSDS 123.0-B-2 standard [10], a current international reference for lossless and near-lossless compression of multispectral and hyperspectral imagery, is largely designed with dedicated hardware implementations in mind. In recent years, however, a new approach to Space technology has emerged which emphasizes Commercial Off-the-Shelf (COTS) components: the NewSpace paradigm. Onboard image compression that can run within the limited computational resources of typical COTS-based onboard computers is, therefore, essential for modern EO missions.

The *Menut* mission (2023) serves as a case study on the practical challenges of deploying spectral data compression. Menut was the first EO mission deployed within the framework of the NewSpace Strategy of Catalonia [16], which included the provision of an EO data service over Catalonia's territory and an In-Orbit Demonstration (IOD) service. The mission was based on the Menut 6U CubeSat, which carries a primary payload based on a multispectral VNIR camera with 7 spectral bands in the 400–1000 nm range, and a secondary payload consisting of a multi-purpose high-performance onboard computer, developed in-house by the IEEC, named C3SatP.

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Fig. 1. Example multispectral acquisition acquired by the Menut primary payload over Cerdanyola del Vallès, where the Universitat Autònoma de Barcelona (UAB) is located. The figure shows an RGB composite generated from three of the seven spectral bands captured by the onboard camera.

The IOD service consisted of demonstrating in-orbit the capabilities and behavior of C3SatP, which has run the FFLX compression algorithm, inspired by the CCSDS 123.0-B-2 standard, throughout the mission's operational phase to compress data captured by Menut. FFLX was designed to run efficiently on general-purpose CPUs, making it hardware-independent and easily deployable on the COTS processors commonly used in NewSpace missions. This portability and ease of integration are key engineering characteristics of the approach.

In this paper we provide a deep dive on the end-to-end development, integration, validation, and in-orbit demonstration of a multispectral and hyperspectral image compressor, framed as a case study from which other teams can extract transferable knowledge. We delve into some of the practical challenges encountered, such as band alignment issues or parsing the proprietary camera output into the raw BIL image format required by the compression software.

The remainder of this paper is organized as follows. Section 2 describes the satellite mission and onboard platform. Section 3 describes the software implementation approach. Section 4 explains the image data preprocessing pipeline. Section 5 details the validation and robustness testing campaign. Section 6 covers integration, flight deployment, and in-orbit commissioning results. Section 7 provides a discussion of operational challenges, engineering insights, and practical guidelines. Section 8 concludes the paper.

2. MISSION AND ONBOARD PLATFORM

The work described in this paper was carried out within the Institute of Space Studies of Catalonia (IEEC), a public research institution that promotes and coordinates space science and technology activities in Catalonia. The FFLX compression algorithm was developed and validated as part of the IEEC's NewSpace activities and integrated into the C3SatP, IEEC's multi-purpose onboard computer, for in-orbit demonstration.

The compression algorithm was deployed on the secondary payload of the Menut 6U CubeSat (NORAD ID: 55010), introduced in Section 1. Menut was launched on 3 January 2023 into a Sun-synchronous low Earth orbit (SSO-LEO) at approximately 550 km altitude with 97.5° inclination. The mission operational phase started in June 2023 and ended in June 2026. The satellite was designed, manufactured, and operated by the company Open Cosmos, while the mission is coordinated in collaboration with IEEC, with the technical support of the Cartographic and Geological Institute of Catalonia (ICGC). The onboard compression experiment simultaneously validates both the onboard computer platform and the image compressor under operational in-orbit conditions.

The onboard data flow during a compression campaign is illustrated in Figure 2. Each acquisition follows a consistent cycle: image acquisition by the primary payload (a multispectral VNIR camera with 7 spectral bands in the 400–1000 nm range and 12-bit radiometric resolution), transfer of the raw image from the platform OBC to the C3SatP via USB 2.0 using Ethernet-over-USB, execution of the preprocessing script, execution of the compressor, transfer of the compressed data back to the platform OBC, and downlink via X-band for ground analysis.

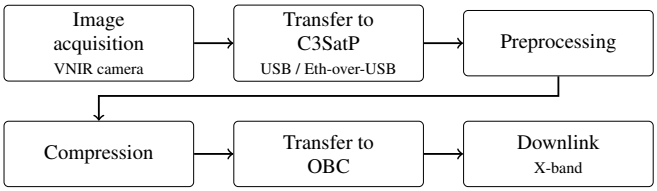


Fig. 2. Onboard data flow during a compression campaign: camera acquisition, transfer to C3SatP, preprocessing, compression, transfer back to the platform OBC, and downlink via X-band.

The platform characteristics that defined the engineering constraints for this deployment are summarized in Table 1.

Table 1. Mission platform characteristics and engineering constraints.

Parameter	Value
Processor	ARM Cortex-A53 (quad-core)
Operating system	GNU/Linux (PetaLinux)
Camera spectral range	VNIR, 400–1000 nm
Spectral bands	7
Radiometric resolution	12 bit
Ground sampling distance	5 m at 500 km
Image format (camera)	Proprietary format
Image format (compressor)	Raw BIL

The compression experiment is run on the C3SatP payload, a multi-purpose onboard computer developed by IEEC and hosted as a secondary payload on Menut [17]. The C3SatP comprises three stacked subsystems in a 0.5U form factor: an OBC motherboard based on an ATSAMV71 microcontroller, an OBDH daughterboard based on a Xilinx Zynq UltraScale+ MPSoC running GNU/Linux, and a software-defined radio daughterboard (not used in this mission). The Zynq UltraScale+ MPSoC features ARM Cortex-A53 processors and serves as the primary computation platform for the compressor. The FPGA fabric is available but is not used in this work; all compression is performed on the CPU.

A key aspect of the C3SatP payload is its use of Commercial Off-the-Shelf (COTS) components not specifically rated for space applications—such as the Zynq UltraScale+, SD card, and DDRAM—that have not been characterized for radiation susceptibility. One objective of the mission is therefore to validate this COTS-based onboard computer in orbit. Prior to flight deployment, all compressor operations were validated on a ground-based Engineering Model (EM) of the C3SatP with equivalent functional characteristics, enabling thorough testing under representative conditions.



Fig. 3. C3SatP 2.0 Flight Model. The payload comprises a motherboard (OBC) and a daughterboard (OBDH with Zynq UltraScale+ MPSoC).

3. SOFTWARE IMPLEMENTATION

The multispectral and hyperspectral image compressor presented in this work, FFLX, was developed by the GICI group at UAB. This section describes the software engineering approach; the internal compression algorithm is not discussed as it is proprietary.

3.1. Implementation Approach

FFLX was designed from the beginning for highly efficient CPU execution. The implementation philosophy prioritizes portability and performance on general-purpose processors rather than dependence on specialized hardware accelerators. This approach enables deployment across a wide range of COTS onboard computers without modification.

Key engineering aspects of the implementation include efficient memory usage achieved through careful buffer management and avoidance of unnecessary data copying, optimized memory access patterns that respect cache hierarchy characteristics of modern ARM processors, and utilization of SIMD instructions where applicable to accelerate the most computationally intensive operations. The implementation is written in C and has been structured to facilitate cross-compilation with minimal dependencies.

For this mission, the compressor was compiled using the C11 standard, targeting the ARM Cortex-A53 CPU of the Xilinx Zynq UltraScale+ MPSoC available on the C3SatP payload. The compressor itself was designed to support a much broader range of missions and configurations than those used in this specific deployment.

The compressor is invoked from the command line and accepts the image dimensions (width, height, and number of spectral bands), the input file name, an optional set of quantization parameters controlling the near-lossless error bound, and the output file name.

3.2. Operating Modes

The compressor supports two operating modes. In lossless mode, the decompressed image is bit-identical to the original. In near-lossless mode, the user specifies a maximum absolute error tolerance, allowing higher compression ratios while guaranteeing bounded reconstruction error. Multiple configurations are available, controlled by a parameter that adjusts the prediction context, trading compression efficiency against throughput.

4. IMAGE DATA PREPROCESSING

An important practical aspect of the integration process is the image data preprocessing pipeline. The compressor expects input in raw BIL format; however, the satellite camera does not produce raw BIL files directly. Instead, the camera generates images in a proprietary mission-specific format that includes metadata alongside the pixel data. This is a common situation in small satellite missions, where camera instruments vary and raw format output is not guaranteed.

A preprocessing script was developed to extract relevant image information from the proprietary camera format, separate metadata from pixel data, and convert the pixel data into raw BIL format. The full data pipeline is illustrated in Figure 4.

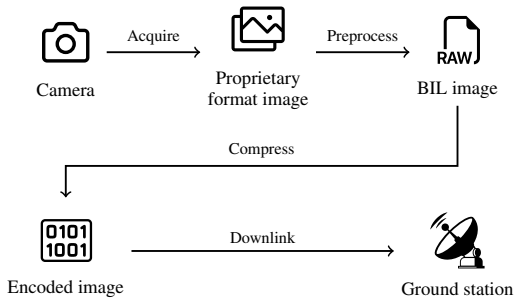


Fig. 4. Image data preprocessing pipeline, illustrated as the transformation of the image object through each stage: a camera acquires a proprietary format image, which is preprocessed into a raw BIL image, compressed into an encoded image, and downlinked to the ground station.

The preprocessing stage was validated by compressing the preprocessed BIL images on the ground and comparing decompressed results against the original camera output. This format adaptation is a general engineering challenge: every mission uses different camera instruments, and adapting the image format is a necessary practical step whenever the camera output is not already a standard raw format.

5. VALIDATION AND ROBUSTNESS TESTING

The validation of the multispectral and hyperspectral image compressor followed a systematic process spanning implementation, fuzz testing, Engineering Model validation, flight deployment, and in-orbit operations, designed to ensure robustness and reliability before deployment.

5.1. Fuzz Testing

After reaching a stable implementation, the software underwent extensive fuzz testing using AFL++ [18], a coverage-guided, mutation-based fuzzer. The purpose was to guarantee robustness before deployment by eliminating unexpected software failures once in orbit, where physical intervention is impossible.

Harness design. A dedicated fuzzing harness was written to reconcile AFL++'s single-input-file model with the compressor's multi-parameter command-line interface. The harness reads the first bytes of each fuzzer-generated file as the image dimensions and treats the remaining bytes as raw pixel data, then calls the compressor as a function with these parameters. This design, where

fields of a single file are reinterpreted as structured parameters, is a general strategy applicable to any command-line program. Figure 5 illustrates this process.

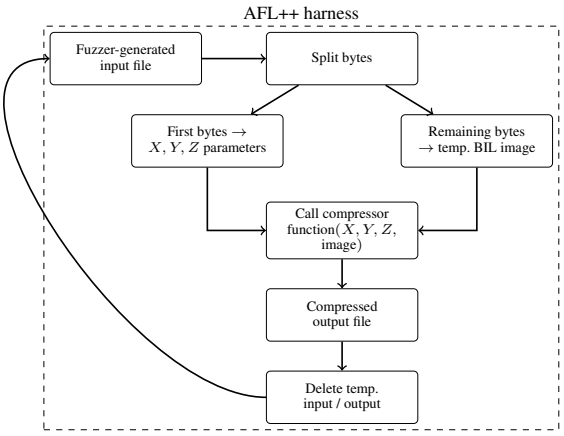


Fig. 5. Fuzzing harness process: AFL++ generates an input file whose leading bytes the harness reinterprets as the image dimensions (X, Y, Z) and whose remaining bytes become the raw pixel data; the compressor is invoked as a function with these parameters, and the temporary files are removed before the next iteration.

Seed corpus and coverage-guided search. The fuzzing campaign was seeded with minimal inputs known to exercise representative code paths. AFL++ instruments the compressor binary to track branch coverage and guides a genetic search, retaining mutations that reach previously unexplored code.

Iterative bug-fixing process. The fuzzer ran in extended sessions of several hours to several days. Each crash was logged, replayed, and traced to its root cause; after fixing each underlying defect, the harness was rebuilt and the campaign restarted until sessions of several days produced no further failures. Fuzzing sessions were run on a workstation, while functional tests were also performed on a Raspberry Pi 3 Model B+ sharing the same ARM Cortex-A53 CPU as the C3SatP. The result was a compressor implementation robust against malformed inputs—an essential property for autonomous space operation.

5.2. Engineering Model Validation

Following fuzz testing, the validated software was tested on the ground-based C3SatP Engineering Model. This stage verified correct functional operation across all compression modes, runtime measurements for each configuration, system stability during sustained operation over extended periods, correct interfaces between the compressor and the payload data handling system, and compatibility with the operational scripts used for flight activities.

6. IN-ORBIT COMMISSIONING RESULTS

Following successful EM validation, the compressor binary was generated and uploaded to the spacecraft. The binary was statically linked to ensure no runtime library dependencies on the target system. Deployment was coordinated with Open Cosmos, which operates the Menut satellite, following the established Secondary Payload Activity Request (SPAR) procedure [17]. The binary integrity was verified after upload using checksums before the first execution.

6.1. Measurement Methodology

The commissioning campaign was performed during Phase 1 of the C3SatP in-orbit demonstration operations [17]. Images of approximately 35 Mpix across 7 spectral bands with 12-bit radiometric resolution were acquired over Catalonia. Each image was compressed onboard using multiple compressor configurations. Runtime was measured using the system clock available on the Zynq UltraScale+ platform. Compression ratio was computed as original file size divided by compressed file size. After each compression, the correctness of the compression was validated using the ‘ls‘ and ‘md5sum‘ commands, whose outputs –the file size and MD5 checksum– were downlinked and compared against ground-computed reference values. In total, 105 GiB of data were compressed in 217 in-orbit executions between October 2023 and June 2026.

The CNES implementation of the CCSDS 123.0-B-2 standard was run on the same platform under identical conditions to provide a performance baseline.

6.2. Commissioning Results

Table 2 summarizes the commissioning results, comparing FFLX against the CCSDS 123.0-B-2 reference. All throughput measurements correspond to single-threaded execution on a single CPU thread unless otherwise stated. FFLX achieves slightly higher lossless compression ratios than the CCSDS 123.0-B-2 reference (1.88–1.90 vs. 1.86) while delivering substantially greater throughput—20.32 MiB/s compared to 3.54 MiB/s for the fastest lossless configuration, representing a 5.7× improvement. In near-lossless mode, throughput exceeds 20 MiB/s while compression ratios reach up to 4.16 (max error=6), reducing data volume by approximately 76%. These results illustrate the benefit of a CPU-optimized compressor design on the COTS embedded platforms characteristic of NewSpace missions. Two independent FFLX instances running concurrently on separate CPU cores achieved a 1.78× increase in aggregate throughput, demonstrating efficient multicore scalability.

Table 2. Commissioning results (throughput in MiB/s) for 35 Mpix, 7-band, 12-bit images. Speedup is relative to the CCSDS 123.0-B-2 lossless baseline.

Mode	CR	Throughput	Speedup
CCSDS 123.0-B-2 Lossless	1.86	3.54	–
FFLX Lossless	1.88	20.32	5.74
FFLX Lossless (higher compression)	1.90	8.47	2.39
FFLX Near-lossless (max error=2)	2.89	20.39	5.76
FFLX Near-lossless (max error=6)	4.16	20.47	5.78
FFLX Lossless (2 parallel instances)	1.88	36.19	10.22

7. DISCUSSION AND ENGINEERING INSIGHTS

7.1. Technology Readiness Advancement

The technology progressively advanced through successive Technology Readiness Levels. Initial laboratory testing on representative ARM platforms demonstrated feasibility at TRL 3–4. Fuzz testing and Engineering Model validation on flight-like Zynq UltraScale+ hardware confirmed robustness, timing, and system compatibility, reaching TRL 5–6. Flight deployment and repeated successful in-orbit executions, together with resolution of an initial limitation via the operational feedback loop, culminated in operational validation at TRL 7–9, reinforced by the use of COTS components typical of the NewSpace ecosystem.

7.2. Spectral Band Misalignment

The spectral bands of the multispectral imager were not perfectly aligned, and the distortion pattern varied across acquisitions, precluding a single geometric correction. Since predictive spectral compressors rely on inter-band correlation to achieve high compression ratios, this spatial misalignment reduces prediction accuracy and consequently compression efficiency. Despite this challenge, the compressor operated successfully and achieved the compression ratios reported in Section 6. The results suggest that improved geometric calibration or onboard band registration at the instrument level would likely improve compression performance, underscoring the importance of considering instrument characteristics when designing onboard compression systems.

7.3. Practical Insights

The following recommendations emerged from the development and validation process. First, fuzz testing complemented traditional verification methods by exploring input regions that human-designed tests typically miss; it should be integrated early in the development cycle and continued until a stable plateau in bug discovery is observed. Designing a harness that reinterprets the bytes of a single fuzzer-provided file as the several structured parameters expected by a command-line program is a general and reusable strategy for applying coverage-guided fuzzers such as AFL++ to programs that were not originally designed with fuzzing in mind. Second, validation on the Engineering Model identified timing and interface issues not observable during workstation-based testing; the EM should match the flight unit in processor architecture, clock speed, memory configuration, and operating system version. Finally, image format adaptation—conversion of camera-specific output to raw BIL—is a common requirement; the preprocessing stage should be designed for verifiability through ground-based round-trip testing and should handle edge cases gracefully.

8. CONCLUSION

This paper has presented the engineering process of developing, validating, integrating, and demonstrating a multispectral and hyperspectral image compressor for a small EO satellite. The compression algorithm FFLX successfully completed software implementation, extensive fuzz testing, hardware validation on an Engineering Model, flight deployment, and repeated in-orbit execution on the Menut CubeSat mission running the C3SatP payload, ultimately achieving TRL 9 through sustained operational use in orbit. It achieves lossless compression ratios that outperform CCSDS 123.0-B-2, while its near-lossless mode provides additional data reduction with bounded error. The compressor also demonstrates much faster runtime than CCSDS 123.0-B-2 across the evaluated configurations. Designed for efficient execution on general-purpose CPUs, it is readily deployable on the COTS-based platforms typical of NewSpace missions. The engineering experience gained throughout this work highlights the importance of representative ground validation, robust software testing practices, and consideration of instrument-specific characteristics when developing onboard image processing systems for future space missions.

9. REFERENCES

[1] ESA Space Debris Office, "Space Environment Report," Tech. Rep. 9, European Space Agency (ESA), 2025.

[2] Li Zhizhong et al., "A review on the geological applications of hyperspectral remote sensing technology," in *2012 4th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)*, 2012, pp. 1–4.

[3] Yang Song et al., "Land cover classification for satellite images through 1d cnn," in *2019 10th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS)*, 2019, pp. 1–5.

[4] Dario Spiller, Stefania Amici, and Luigi Ansalone, "Transfer learning analysis for wildfire segmentation using prisma hyperspectral imagery and convolutional neural networks," in *2022 12th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS)*, 2022, pp. 1–5.

[5] Nelson J. G. Fonseca, Maxime Romier, Michele Del Mastro, and Nicolas Capet, "Data downlink antennas for small satellites in the newspace era: Review and perspectives," in *2024 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, 2024, pp. 17–22.

[6] Kristian Manthey, David Krutz, and Ben Juurlink, "A new real-time system for image compression on-board satellites," *ESA/CNES On-Board Payload Data Compression (OBPDC), Venice, Italy*, 2014.

[7] Consultative Committee for Space Data Systems (CCSDS), *Lossless Data Compression - Recommended Standard CCSDS 121.0-B-3*, August 2020.

[8] Consultative Committee for Space Data Systems (CCSDS), *Image Data Compression - Recommended Standard CCSDS 122.0-B-2*, September 2017.

[9] Consultative Committee for Space Data Systems (CCSDS), *Spectral Preprocessing Transform for Multispectral and Hyperspectral Image Compression - Recommended Standard CCSDS 122.1-B-1*, September 2017.

[10] Consultative Committee for Space Data Systems (CCSDS), *Low-complexity Lossless and Near-lossless Multispectral and Hyperspectral Image Compression - Recommended Standard CCSDS 123.0-B-2*, February 2019.

[11] F. Gascon et al., "Copernicus sentinel-2a calibration and products validation status," *Remote Sensing*, vol. 9, no. 6, 2017.

[12] Luis Guanter et al., "The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation," *Remote Sensing*, vol. 7, no. 7, pp. 8830–8857, 2015.

[13] Ralf Jaumann et al., "JANUS on the JUICE Mission: the Camera to Investigate Ganymede, Europa, Callisto and the Jovian System," *European Planetary Science Congress*, 09 2013.

[14] USGS, *Landsat 8 Data Users Handbook*, 2019.

[15] USGS, *Landsat 9 Data Users Handbook*, 2022.

[16] Institut d'Estudis Espacials de Catalunya (IEEC), "Menut, the Second NewSpace Strategy of Catalonia's Nanosatellite, is Successfully Launched," 2023, Online.

[17] Marc Ortega-Playà et al., "In-Orbit Demonstration Operations of the High-Performance On-Board Processing Capabilities of C3SatP," in *75th International Astronautical Congress (IAC)*, Milan, Italy, 2024, pp. IAC–24,B1,2,x89378.

[18] Andrea Fioraldi, Dominik Maier, Heiko Eißfeldt, and Marc Heuse, "AFL++: combining incremental steps of fuzzing research," in *Proceedings of the 14th USENIX Conference on Offensive Technologies*, USA, 2020, WOOT'20, USENIX Association.