Unchaining Hyperspectral Imaging with Quantum-Inspired Compression (UHIQIC)

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ABSTRACT
With hyperspectral imaging, image content can be identified based on fine spectral details related to chemical composition. Immediate applications in smart agriculture and environmental monitoring have the potential for strong societal benefits. However, the technology struggles with the vast amount of data that it produces, in particular when deployed on satellites. The current movement towards increased use of lossy compression is highly risky, because even careful and tedious parameter tuning cannot guarantee that no applications are compromised. We implemented and validated a compression method that simultaneously provides a strong data reduction and preserves analysis results for all possible applications.

Keywords: hyperspectral imaging; machine learning; earth observation; satellites; compression.

1. INTRODUCTION

The urgent need for sustainable solutions is driving a rapid adoption of smart environmental monitoring and diagnostics technologies across several major industries, including forestry and agriculture. The ability to optimise the use of resources including water and fertilisers, early detection of crop diseases and pests, as well as prediction of crop yield, enables the farmers to produce food in a more efficient, profitable and ecological manner. In this endeavor, the combination of spaceborne hyperspectral imaging with artificial intelligence constitutes an exceptionally effective technique for advanced environmental monitoring and resource management. Fig. 1 illustrates the advantage of high-quality spectral data. This is particularly important for satellite-based imaging, where higher spatial resolution can only be achieved at immense cost, while hyperspectral sensors are relatively cheap. Nevertheless, several challenges remain for large scale utilization. First, the vast amount of data generated by these sensors is currently incompatible with the frequent observation of large areas because of limited on-board storage and downlink bandwidth. Second, the real value of having up-to-date spatial imagery at hand at practically all times can only be unlocked if it can be processed promptly. This requires automated processing, where in particular machine-learning based algorithms have delivered astonishing results in recent years. However, the characterization of the reliability of these algorithms and their robustness to natural and artificial variations in the image data, such as noise and processing, remains challenging. As a consequence, the adoption and monetization of spaceborne hyperspectral imaging for a broad range of applications is only hesitant.

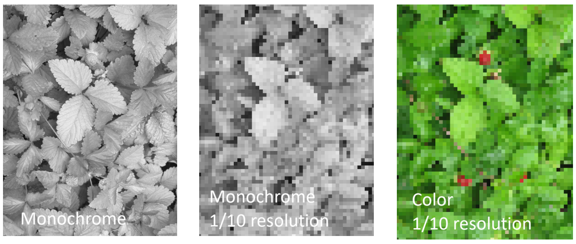

Fig. 1. Spectral information facilitates object recognition. A high-resolution monochrome image (left) allows to identify the depicted plants as strawberries, and even count the fruits with some effort. At lower resolution (middle), this becomes a daunting task. The addition of color information (right) makes it almost trivial.

We have developed a method for quantifying the reliability of machine learning-based algorithms in the presence of noise and other artefacts that may have been introduced during acquisition or preprocessing. Using this method, we validated a compression algorithm that was specifically developed for machine-learning contexts and can significantly reduce the strain on on-board storage and downlink. Tests and simulations demonstrated that the method is compatible with direct integration on satellite hardware. These results were obtained partially in collaboration with other projects and partners, including the European Space Agency (ESA), the Swiss Space Office (SSO) and Swiss research institutions in the field of biomedical imaging and microscopy.

Our results simultaneously solve the challenges of data congestion and data reliability for large-scale utilization of hyperspectral satellite image data for environmental monitoring, in particular in the context of automated processing powered by artificial intelligence.

2. STATE OF THE ART

Image compression has always been essential in maximizing the yield of satellites, and even more so for multispectral or hyperspectral data [1]. Large quantities of information about earth are collected this way, and data integrity is essential. Hence, lossless compression methods are used in the majority of cases [2,3], but there is a trend towards increased use of lossy compression to better accommodate spacecraft downlink limitations [4]. The compromise is typically the following: *Either* use lossless compression to guarantee data quality, but accept a limited data throughput due to low compression factors around 2 to 3 [2]; *or* use lossy compression to achieve a 10-fold or higher data reduction, but accept the risk of inferior data quality. The choice is made even more difficult by further important considerations: Compression speed must be sufficient to not impose a bottleneck on data acquisition, and hardware requirements and power consumption must be low for satellite operation. Finally, it must be noted that it is common to process the image data on the ground and recompress with a different method before the data is made available to end users. As a result, comparing different compression methods is difficult, because the input data may have undergone different degrees of processing. Even worse, the space and on-ground compression methods may interact in ways not foreseen and introduce artefacts that are more severe than when used individually.

The state of the art is well-reflected in the recommended standard CCSDS 123.0-B-2 [5]. It gives specifications for low-complexity lossless and lossy compression. Both methods make use of numerous parameters, which adds a certain flexibility, but also leaves room for errors, as no guidelines are given on how to choose those parameters, and a non-ideal choice can negatively affect data quality.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

We have approached the data problem of spaceborne imaging from the application side by asking the question what a lossy compression method must fulfil to enable maximum value extraction from the decompressed image, in particular in view of the rapidly expanding domain of machine-learning based algorithms. This led us to the concept of *steganographic* compression, that is, a method of compression that is lossy, but seems lossless for all practical purposes. We note that this concept is much stronger than that of *visually* lossless compression, as summarized in Tab. 1. Visually lossless compression methods, such as the widely adopted JPEG standard, were specifically developed and optimised to preserve the image quality, as perceived by the human eye. This compression approach, however, can be the cause of severe loss of information that is incompatible with AI-based analysis and interpretation, as illustrated in Fig. 2. Steganographic compression yields statistically equivalent results to non-compressed images or lossless compression, independent of which kind of processing is applied.

Tab. 1. Comparison of typical characteristics for different compression concepts for raw single-band image sensor data. Visible artefacts can be revealed by human inspection. Invisible artefacts are compression errors that have a measurable effect on image processing.

Compression concept	Compression factor	Visible artefacts	Invisible artefacts
Lossy	20 - 100	Yes	Yes
Visually lossless	10 - 20	No	Yes
Lossless	2 - 3	No	No
Steganographic (this work)	5 - 10	No	No

In order to validate the compression, we developed a novel method to quantify the reliability of machine-learning algorithms by investigating the statistics of algorithm results in the presence of noise and pre-processing. Since noise is unavoidable in image acquisition, algorithms must be designed or trained such that they are resilient to its presence. One of the requirements for steganographic compression, which can be considered a form of pre-processing, is then that processing algorithms show statistically identical results whether or not compression was applied.

We implemented steganographic compression in software and as a satellite-compatible FPGA core. The implementations reached excellent compression ratios and performance. In addition, the compression was proven to give statistically identical results with respect to raw data in more than 50 systems and 230 quantitative

Fig. 2. Sentinel-2 images processed by AI-based 4x upscaling of the uncompressed (left) and JPEG compressed (right) original. While the original images (not shown) appeared identical, the upscaled version of the JPEG image exhibits significant artefacts.

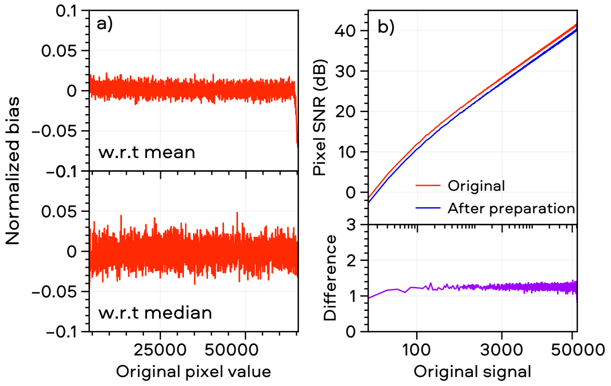

Fig. 3. Performance of the image preparation step as measured on a series of flat-field images acquired with drone camera using a Sony IMX183 image sensor. a) The preparation introduces negligible bias when normalized to the inherent measurement uncertainty of the sensor. b) The signal to noise-ratio is uniformly reduced by about 1.2 dB over the whole signal range, corresponding to increasing the ISO by 24%.

analysis pipelines, many of which including machine learning.

4. PROJECT RESULTS

The key ingredient in our steganographic compression is an initial image preparation step which requires a mathematical model of the image sensor's response to illumination. The model is constructed through a detailed sensor calibration procedure. It allows to replace most of the noise in the image data with pseudo noise. The input noise has, in general, a signal-dependent component originating from photon shot noise and a signal-independent component due to electronic noise. The truly random nature of this noise limits lossless compression to a factor of about 2. The pseudo-noise, on the other hand, is based on pseudo-random numbers and designed to closely match the characteristics of the input noise. This noise can be perfectly subtracted at a later stage, provided that the parameters of the pseudo-random number generator are known. The preparation is guaranteed to keep pixel-value modifications below the noise level, does not introduce artefacts and is proven to preserve mean and median values to an excellent degree, as shown in Fig. 3a. Since the amount of input noise cannot be exactly known for each pixel, the noise replacement reduces the signal-to-noise ratio of the image data by about 1.2 dB, see Fig. b, which is equivalent to increasing the ISO by 24%.

After the image preparation, the actual compression is lossless. This relieves the users of the image data of the worry that (re-)compression may somehow affect their data or processing results. The data of Fig. 3 was obtained in collaboration with an ESA GSTP project with the aim of validating an information-preserving image compression method for monochrome satellite images. In the framework of the same collaboration, we implemented encoders and decoders in both software and hardware. The performance of the coders was evaluated on a data set of 12 representative drone images, where the drone was configured to closely emulate the optics of state-of-the-art earth-observation satellites in terms of ground sampling distance, magnification and extent of the point spread function. The sample images contain mixtures of urban and rural environments for different weather and lighting conditions, as would be typical for satellite images. The performance of the software coder is shown in Fig. 4. On a 3.5 GHz Intel Xeon CPU, the compression rate reaches 140 Mpx/s, which appears to be an order of magnitude faster than a representative implementation of the CCSDS 122.0-B-1 standard

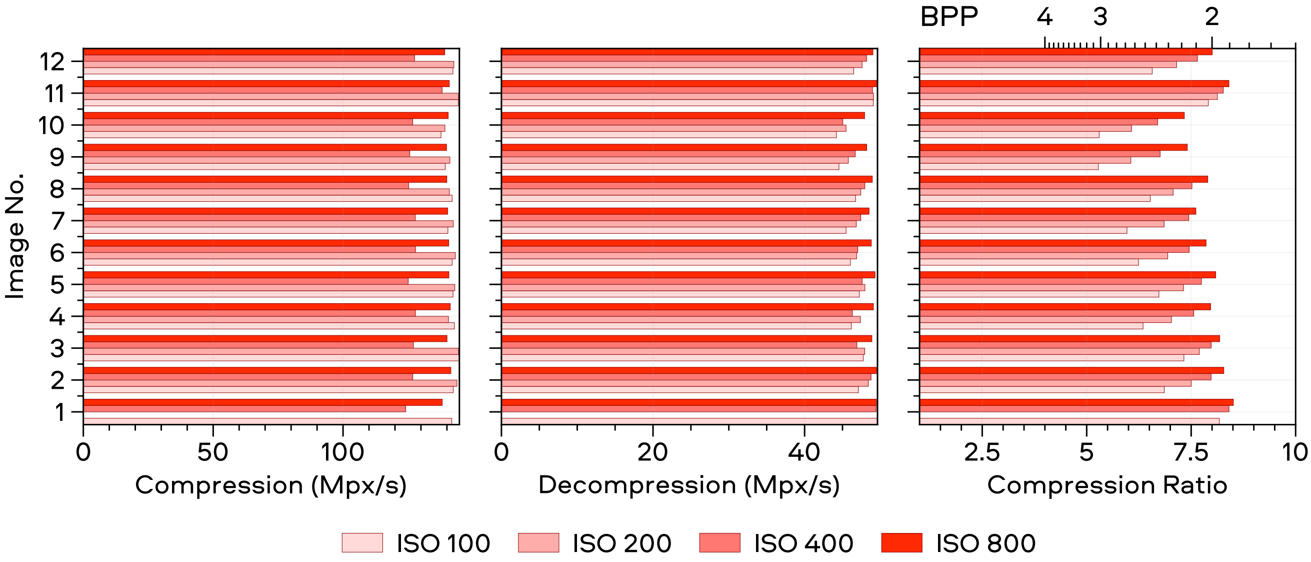

Fig. 4. Performance of a software implementation of steganographic compression evaluated on a single core of an Intel Xeon processor running at 3.5 GHz. The image set consists of monochrome drone images that emulate typical scenes for earth-observation satellites.

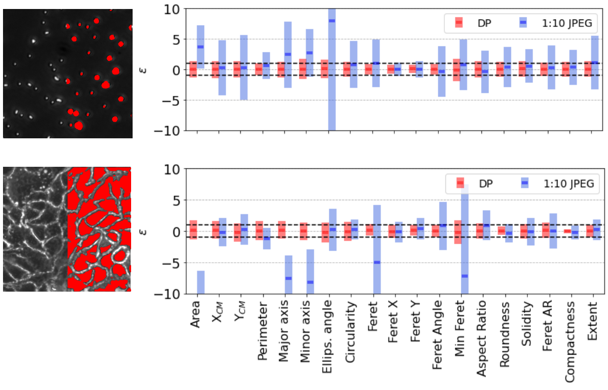

Fig. 5. Benchmarking compression quality with machine learning-based image segmentation. Raw microscope images of microspheres (top left) and mouse kidney collecting duct cells (bottom left) and resulting segmentation maps (right halves, in red) were analysed to extract parameter distributions for various segment parameters, shown on the right. The distributions were normalized such that uncompressed raw images yield zero mean and unit standard deviation, indicated by the dashed lines. The distributions obtained with steganographic compression ("DP", in red) produce identical results as originals, while JPEG compression (blue) can significantly broaden and shift the distributions.

running on similar hardware [6]. The compressed image size was 2 to 3 bits per pixel. For comparison, JPEG2000 lossless compression, which for single-component images achieves compression ratios that are comparable to that of the CCSDS standard, of the same images results in file sizes between 9.8 and 10.8 bits per pixel.

The hardware encoder was implemented for an FPGA of type Xilinx KU040, for which a space-compatible version exists. The encoder was run in simulation rather than on real hardware, which allowed to assess resource utilization, performance and power consumption without unnecessary overhead. The implementation reached an operating frequency of 180 Mpx/s at a power consumption of 760 mW or 4.2 nJ/px and utilizing only about 1% of the available resources, except for input/output lines where 10% were occupied.

To further test the reliability of the compressed data, in particular in the context of machine learning, we collaborated with an Innosuisse project investigating compression for biomedical imaging [7]. In biomedical imaging and many other fields, it is a pressing matter to be able to quantify the confidence levels of machine learning predictions. In [7], we propose a method that uses the inherent noise in otherwise identical images to assess the predictive uncertainty in machine learning task in optical microscopy. The thus established uncertainty serves as a reference value to study the tolerability of distortions introduced by pre-processing the images, e.g. using compression: Distortions are tolerable if they on average lead to identical results and less or equal uncertainty compared to the unprocessed images. Fig. 5 shows an example, where the method was applied to an image segmentation task on microscope images. A 10-fold JPEG compression of the image data is seen to introduce significant distortions, while results for the steganographic compression (labelled "DP" in the figure) are practically identical to that of original data (dashed lines).

5. FUTURE PROJECT VISION

During the course of this project, we have developed and implemented and tested steganographic compression. The implementation satisfies the requirements for on-board operation on satellites and achieves 3 to 5 times better compression ratios than lossless compression. Most importantly, it is information preserving in the sense that it guarantees that any kind of processing will give results that are statistically identical to those of uncompressed images.

In the future, we want to move towards a fully-fledged service for satellite-based smart agriculture and environmental monitoring, with hyperspectral data that covers all of Europe and is updated on a daily basis. Users of the service can either have direct access to the image data or subscribe to a number of algorithms powered by artificial intelligence that provide analysis and guidance.

5.1. Technology Scaling

The compression technology has been extensively validated in the lab for single-band image data. The path for extension to multi-band image data is clear, and the technology can be considered to be at technology readiness level (TRL) 3 to 4. To scale the technology, our FPGA implementation will be realised in hardware and connected to a state-of-the-art optical payload designed for a CubeSat earth-observation satellite. With extensive on-ground testing, the system will reach TRL 6. The culmination of the technology will be the actual launch and successful operation of the satellite in space.

5.2. Project Synergies and Outreach

Compression is only one out of many components in the ambitious project vision, and a strong consortium will be required for its realization. During the course of this project we have had the chance to cooperate with ESA and Airbus, and have also established good relations with a number of other potential partners, who already expressed strong interest in a collaboration, such as MediaLario (specialist in optical systems for space applications), GammaEarth (newly-founded company specializing in artificial intelligence for earth-observation) and GomSpace (manufacturer of nanosatellites). From the ATTRACT portfolio, the project HyPeR may be interested in joining the consortium with its quest for remote sensing of marine plastics.

To facilitate outreach and public dissemination for the ATTRACT consortium, we will assign a dedicated outreach officer with a background in marketing to the project.

5.3. Technology application and demonstration cases

The ATTRACT Phase 2 project will focus on environmental monitoring and agriculture. Examples are the monitoring of emissions and pollution in industrial areas, detection of marine plastics, as well as yield forecasting, harvest optimization and optimization of the use of fertilizers and pesticides in agriculture. With ESAs help, imaging data can be made available to research institutions. Scientific collaborations can be established to further the development of algorithms to extract maximum value from the data available.

5.4. Technology commercialization

Commercialization of the technology will be based on subscription fees for data and service access. GammaEarth has experience in generating revenue from machine-learning based data analysis. Dotphoton, currently selling image compression solutions for industry, research and consumers, has developed several business models adapted to different markets; while a license per system makes sense for manufacturers and integrators, a different license is necessary for data end-users to reduce the cost of data storage and transfer. Dotphoton is now for the third year in a row among the Swiss top 100 startups [8] and will soon officially announce a 7 digits pre-series A round from private investors.

5.5. Envisioned risks

The market for hyperspectral products and solutions is rapidly expanding, which has triggered vast efforts in research and development in this field. There is a risk of arriving on the market too late, but a potential phase 2 project would allow too keep the momentum and stay ahead of competition.

Another general potential risk is an underestimation of the development challenges, which can be significant in particular in the space sector. We will make use of the specific expertise of our consortium partners to devise detailed development plans that allow rapid switching between different strategies in case of unforeseen failures. While this means that more time must be invested in the initial stages of the project, it increases the chance for success.

5.6. Liaison with Student Teams and Socio-Economic Study

Student teams will be ideally suited to explore ideas and develop prototypes for services that make use of the large amount of hyperspectral data. The designated outreach officer will be responsible for managing relevant contacts and producing explanation materials. In this task, he be assisted by the many experienced scientists on the team. Similarly, the outreach officer will be in regular contact with the ATTRACT consortium to develop materials for the benefit of the socio-economic study.

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7. REFERENCES

[1] I. Blanes et al., 2019. *Performance Impact of Parameter Tuning on the CCSDS-123.0-B-2 Low-Complexity Lossless and near-Lossless Multispectral and Hyperspectral Image Compression Standard*, Remote Sens., 11: pp. 1–16.

[2] I. Blanes et al., 2014. *A Tutorial on Image Compression for Optical Space Imaging Systems*, IEEE Geosci. Remote Sens. Mag., 2: pp. 8–26.

[3] A. Zemliachenko et al., 2017. *Lossy Compression of Hyperspectral Images Based on JPEG2000, 2017 4th International Scientific-Practical Conference Problems of Infocommunications. Science and Technology (PIC S&T)*, Vol. 3 (IEEE), pp. 600–603.

[4] A. Kiely et al., 2018. *The New CCSDS Standard for Low-Complexity Lossless and near-Lossless Multispectral and Hyperspectral Image Compression*, *Onboard Payload Data Compression Workshop* p. 1.

[5] CCSDS Secretariat, editor , 2019. *CCSDS Recommended Standard for Low-Complexity Lossless & Near-Lossless Multispectral & Hyperspectral Image Compression*, July 2019 (National Aeronautics and Space Administration, Washington, DC, USA).

[6] S. C. Ramanarayanan et al., 2015. *High Performance CCSDS Image Data Compression Using GPGPUs for Space Applications*, 26. GI/ITG Work. Parallel - Algorithmen, -Rechnerstrukturen Und - Systemsoftware (PARS), Univ. Potsdam, Potsdam, Ger., 32: pp. 49–58.

[7] E. Pomarico et al., 2020. *Quantifying Predictive Uncertainty in Machine Learning-Powered Optical Microscopy from Raw Statistical Noise*, Work. Pap.,.

[8] https://www.top100startups.swiss