Compression of multispectral and hyperspectral images is becoming more and more important as the spatial and spectral resolution of the instruments keep increasing. New techniques are therefore needed to cope with such high data rates. Predictive compression has always been considered an attractive solution for onboard compression thanks to its low computational demands and the ability to accurately control quality on a pixel-by-pixel basis. Traditionally, predictive compression focused on the lossless and near-lossless modes of operation where the maximum error can be bounded but the rate of the compressed image is variable, while fixed-rate is considered a challenging problem due to the dependencies between quantization and prediction in the feedback loop, and the lack of a signal representation that packs the signal’s energy into few coefficients as in the case of transform coding. In this paper, we show how it is possible to design a rate control algorithm suitable for onboard implementation by providing a general framework to select quantizers in each spatial and spectral region of the image and optimize the choice so that the desired rate is achieved with the best quality. In order to make the computational complexity suitable for onboard implementation, models are used to predict the rate-distortion characteristics of the prediction residuals in each image block. Such models are trained on-the-fly during the execution and small deviations in the output rate due to unmodeled behavior are automatically corrected as new data are acquired. The coupling of predictive coding and rate control allows the design of a single compression algorithm able to manage multiple encoding objectives. We tailor the proposed rate controller to the predictor defined by the CCSDS-123 lossless compression recommendation and study a new entropy coding stage based on the range coder in order to achieve an extension of the standard capable of managing all the following encoding objectives: lossless, variable-rate near-lossless (bounded maximum error), fixed-rate lossy (minimum average error), and any in-between case such as fixed-rate coding with a constraint on the maximum error. We show the performance of the proposed architecture on the CCSDS reference dataset for multispectral and hyperspectral image compression and compare it with state-of-the-art techniques based on transform coding such as the use of the CCSDS-122 Discrete Wavelet Transform encoder paired with the Pairwise Orthogonal Transform working in the spectral dimension. Remarkable results are observed by providing superior image quality both in terms of higher SNR and lower maximum error with respect to state-of-the-art transform coding.
The compression of hyperspectral images on-board satellites is at the same time a challenge and a necessity whose importance is currently growing as the resolution of the sensors tends to increase. Consequently, hyperspectral image compression has become a very popular research topic, which has motivated the proposal of different compression algorithms with diverse compression efficiency and complexity. On-board compression algorithms have to meet additional requirements, which are specific to the space environment such as low complexity and error resilience. The available processing power on a satellite is limited, hence most usual data compression algorithms used on ground cannot be applied to space data systems. Nevertheless, to actually benefit from on-board compression, not only efficient algorithms are needed; it is also essential to provide physical implementations of those algorithms, which can operate on-board. In 2012, the CCSDS issued a recommendation for lossless multispectral and hyperspectral data compression, the CCSDS 123, which is based on the Fast-Lossless (FL) algorithm developed at JPL and is based on the prediction paradigm. The predictor uses adaptive linear prediction based on values of nearby samples in a small three-dimensional neighbourhood. Afterwards, the residuals of the prediction are mapped and entropy coded. Experimental results have demonstrated that the CCSDS standard is competitive with other state-of-the-art algorithms, providing the best trade-off between coding performance and computational complexity. The CCSDS 123 algorithm has been already implemented in software for its execution on CPU and GPU. However, none of these implementations are suited for on-board use. This work presents a low complexity hardware architecture of the CCSDS 123 algorithm which can be implemented on a space-qualified FPGA with low hardware occupancy. The compressor’s architecture is carefully designed taking into consideration the impact in terms of compression efficiency and implementation complexity of the different user-defined parameters allowed by the CCSDS 123 standard. The resulting design is the basis of an IP core named HyLoC, which is described at RTL level using VHDL, and then implemented on a space-qualified RTAX100S FPGA. HyLoC is fully compliant with the CCSDS 123 standard, allows the adjustment of the user-defined parameters and is technology independent. The synthesis results show a resource occupancy of 34 % and a maximum frequency of 43 MHz, yielding a throughput that allows for on-line compression.
Proposal for IASI onboard data compression

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The Infrared Atmospheric Sounding Interferometer IASI system is implemented on the Metop satellite series as a result of a cooperating agreement between CNES and EUMETSAT. CNES has the responsibility for the instruments development, and EUMETSAT is responsible for operating, storage and distribution of IASI data. While the instrument data production rate is 45 Megabits/s, the transmission rate allocated to IASI measurements is 1.5 Megabits/s. Therefore, it is necessary to implement – on board the instrument – a significant part of the IASI data processing. An inverse Fourier transform and a radiometric calibration is performed on board in order to decrease the size of the IASI data to be transmitted. Next, the spectra data are encoded before transmission. This part of the processing chain is known as level 0. The spectra data are sent to ground in the form of a bit-stream where each sample is quantized then coded as a natural number using a fixed amount of bits (6 to 10) depending on the spectral range. This method has the advantages of its simplicity and a fixed bit-rate output but its performance is suboptimal and with risks of overflow. In this paper we consider the modification of the level 0 processing chain such that improved data transmission rate is provided. We investigate first the information statistics of IASI L0 data before being sent to ground. We analyze order-0 entropy, order-1 conditional entropy and order-2 conditional entropy, where conditional entropies assess both the spatial and the spectral joint information. According to preliminary results, order-0 entropy already suggests that at least one pixel per sample might be spared if a variable block length coder is employed. Then, we also investigate the actual performance of the latest Recommended Standard for Lossless Multispectral & Hyperspectral image compression, CCSDS-123, on these IASI L0 data. CCSDS-123, approved in 2012, is a prediction-based coding technique specially designed to operate on-board of satellites. CCSDS-123 operates in a two-stage mode. In the first stage, an estimate of the current pixel is performed and used to compute a prediction residual. In the second stage, this prediction residual is encoded with a Golomb code. CCSDS-123 coding technique provides a competitive performance with a low computational cost for a large variety of multi-, hyper-, and ultra-spectral data. Experiments are performed on a set of 8 IASI volumes from EUMETSAT. Each volume is stored in 16 bits per pixel unsigned integers although samples have a real bit-depth precision of 6 to 10 bits. Each volume has 8359 bands, 60 columns and a variable number of rows. CCSDS-123 lossless coding technique is applied using different configuration settings. Experimental results indicate that IASI Level 0 data can be coded by a compression ratio about 2.5:1. This research suggests that, by applying off-the-shelf existing communication standards, transmission rate for IASI Level 0 data could be further decreased, or that some more data could be transmitted at the original transmission rate.
On the Hardware Complexity of the Arithmetic Elements of the Pairwise Orthogonal Transform

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While the resolution of the sensors in remote-sensing space missions tends to increase, the bandwidth of the communication channels remains comparatively stable. As a consequence, the reduction of the captured data volume on board satellites by means of compression is becoming even more important, in particular for multispectral and hyperspectral sensors, where the amount of data captured is substantial. Although lossless compression methods have been traditionally preferred to preserve all the information in an image, current bandwidth and on-board storage restrictions make it compelling to resort to lossy compression in order to reduce the data volume appropriately. To address the compression of multispectral and hyperspectral data, the CCSDS published in 2012 the recommended standard CCSDS 123.0 for lossless compression, and it is currently working towards the definition of a lossy compression standard as an extension of the existing CCSDS 122.0. The latter is a 2D image coder that combines a wavelet transform with a bitplane encoder, and that, if coupled with a spectral transform, would take advantage of the spectral correlation present in multispectral and hyperspectral data. Whenever new algorithms are proposed for on-board compression, the complexity of the resulting hardware implementation of the algorithm has to be considered, since the computational power on a satellite is limited due to the existing limitations of the hardware technologies that can be used on-board. Most of the times, the algorithm is implemented as an ASIC or on an FPGA. Therefore, low-complexity is mandatory to achieve efficient implementations in terms of area and throughput. Among the possible spectral transforms, the pairwise orthogonal transform (POT) has been demonstrated to be a good candidate for spectral decorrelation. The POT is a KLT derivative that, while not matching the coding performance of the KLT, provides significantly lower complexity. This work aims at validating that the low complexity of the POT makes it feasible for a space-qualified FPGA implementation. An RTL description of the main arithmetic stages of the POT, namely the mean subtraction and the balanced and unbalanced pairwise operations are provided, with the aim of achieving a low occupancy of resources and making it possible to synthesize the design on a space-qualified RTAX2000S. In order to accomplish these goals, the operations of the POT are fine-tuned so that their implementation footprint is minimized while providing equivalent coding performance. Most computationally demanding operations are solved by means of lookup tables, which are optimized to achieve the best compromise between occupancy of the FPGA resources and memory access latency. In addition, a bit-exact description of the mathematical equations that are part of the transform is provided, in such a way that they can be solved with integer arithmetic and the implementations are easily cross-validated. Experimental results are presented, on one hand to validate the implementation, showing that the changes applied to the POT do not affect its compression efficiency, and on the other hand, to provide the synthesis results on an RTAX2000S FPGA.
Impact of near-lossless compression of IASI L1C data on statistical retrieval of atmospheric profiles

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The Infrared Atmospheric Sounding Interferometer (IASI) sensor is implemented on the Metop satellite series. Products obtained from IASI data are a significant improvement in the quality of the measurements used for meteorological models. In particular, IASI collects rich spectral information to derive temperature and moisture profiles, which are essential to the understanding of weather and to derive atmospheric forecasts. IASI data are processed through an on-ground processing chain before being considered as end-user products. IASI L0 products are the first data on-ground, sent to reception stations from the satellite, and are not considered as end-user products. Level 1A processing comprises the following steps: decoding spectra, spectral calibration, radiometric post-calibration, IASI/AVHRR/3 co-registration, location and dating. Level 1B consists of resampling the spectra, and Level 1C processing performs an apodization function and analysis of AVHRR/3 radiance levels in IASI pixels. Finally, level 2 processing involves temperatures and water vapor profiles. All L1 and L2 products are also available to end-users. Here, we investigate the near-lossless compression of IASI L1C data, by employing compression processes which upper-bound the maximum absolute error introduced. We look for the level of compression acceptable in IASI L1C products such that it has a negligible impact on the physical measurements. Specifically, we apply the M-CALIC compression process on IASI L1C data, and then we apply nonlinear statistical retrieval methods to derive atmospheric properties, with emphasis on the retrieval of temperature, humidity, and ozone atmospheric profiles. In order to do the nonlinear retrieval, we employ the Kernel Ridge Regression (KRR) algorithm, which has shown good performance in order to predict such variables using IASI L1 data in previous works. We will analyze the KRR performance for different compression strategies. We have selected M-CALIC for the compression since it provides a competitive performance when spectral correlation is high. This is the case for IASI products which contain over 8000 spectral highly correlated channels. M-CALIC is a prediction-based coding technique that estimates the intensity of the pixel to be encoded based mostly on the intensity of co-located pixels in previous components, i.e., pixels at the same spatial position but in components with a lower index. In fact, it is the prediction error that is encoded. These prediction errors are quantized guaranteeing that all distortion errors fall below a given threshold. Using a small threshold ensures a near-lossless compression. Experiments are performed on a set of 6 IASI volumes from EUMETSAT. Each volume is stored in 16 bits per pixel signed integers. Volumes are of size 8461 bands x 1530 rows x 60 columns. M-CALIC is applied for 6 different peak absolute errors. Extensive results on the robustness of KRR to several degrees of compression levels will be shown at the time of the conference. This research can benefit the development of new IASI sensors, as it illustrates that retrieval methods may operate on data that do not have the same quality precision of the originally provided IASI L1C products.