8th INTERNATIONAL WORKSHOP ON ON-BOARD PAYLOAD DATA COMPRESSION (OBPDC 2022)

28-30 SEPTEMBER 2022

A SMART COMPRESSION APPROACH BASED ON THE CCSDS 123.0-B-2 STANDARD FOR CHIME

Antonio Sánchez(1), Diego Ventura(1), Yubal Barrios(1), Luis Berrojo(2), Celia Carrasco(2), Filip Veljkovic(2), Pedro Rodríguez(2) and Roberto Sarmiento(1)

(1)Institute for Applied Microelectronics (IUMA), University of Las Palmas de Gran Canaria (ULPGC)
35017 Las Palmas de Gran Canaria, Spain
Email: {ajsanchez, dventura, ybarrios, roberto}@iuma.ulpgc.es

(2)Thales Alenia Space (TAS) in Spain
28760 Tras Cantos, Madrid, Spain
Email: {luis-rafael.berrojovalero, CeliaCarrascoBraojos, filip.veljkovic, pedro.r}@thalesaleniaspace.com

ABSTRACT

The Copernicus Hyperspectral Imaging Mission for Environment (CHIME) is introduced by ESA in the future Copernicus 2.0 program to provide routine hyperspectral observations for the monitorization of natural resources, including applications such as sustainable agricultural and biodiversity management, soil properties characterization, sustainable mining practices and environment preservation [1]. CHIME shall provide continuous spectral data in the range between 400 and 2500 nm at input data rates up to 2 Gbps.

A mission requirement is to employ adaptive compression, detecting clouds in the scene and introducing in those pixels a higher level of losses. This is relevant because clouds, which it is estimated that cover more than 54% of the Earth's land area and 68% of the oceans, make more than half of the acquired scenes unusable for scientific applications. The solution adopted for CHIME is to modify the CCSDS 123.0-B-2 Low-Complexity Lossless and Near-Lossless Multispectral and Hyperspectral Image Compression [2] to achieve this goal, while at the same time a low-complexity algorithm is provided, capable to compress in lossless and near-lossless modes.

In the CHIME pre-development phase (A/B1), a proof of concept was developed and tested [3]. This solution, developed following an HLS workflow, do not achieve the goals in terms of throughput defined for the mission. Besides, different modifications to the standard were analysed at algorithmic level in [4], in order to remove clouds from the acquired scenes. From this study, it was concluded that the Different Absolute Error (DAE) strategy provides promising results for selective compression in terms of both compression ratio (a data reduction between 20% and 35% compared to the compliant CCSDS 123.0-B-2 algorithm for cloud coverage around 40%) and image quality after decompression.

Cloud detection is also performed by a Support Vector Machine (SVM) approach that allows identifying each pixel of the image as ground or cloud. These 2 classes are used to drive the selective compression with DAE settings for cloud and ground pixel classes. The algorithm is divided in four steps: Spectral Band Selection for performing cloud detection; Top of Atmosphere conversion of the pixels from the selected bands; SVM processing; and Morphological Cloud Map filtering.

This work presents a VHDL-made hardware solution, based on the CCSDS 123.0-B-2 standard and including cloud detection and the DAE approach, to efficiently compress hyperspectral images acquired by the CHIME instrument. Only the prediction features that maximize the throughput under BIL order are implemented. As for the HLS design, the block-adaptive alternative is used for entropy coding. The inclusion of the DAE approach implies that the IP core is able to compress clouds present in the scene with a higher level of losses than the rest of the image and thus improving the compression ratio. Architecture and behaviour of the proposed IP core are detailed, and preliminary results in terms of area footprint and throughput are presented.

INTRODUCTION

Hyperspectral sensors are devices which capture image data in hundreds of different wavelengths. Because of this, they are suitable for multiple applications, including Earth Observation (EO) and deep space missions, where this kind of sensors are being incorporated for detection, identification, navigation, and surveillance purposes. The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) or the Hyperspectral Precursor and Application Mission

(PRISMA) are examples of active space missions embarking hyperspectral sensors [5]. And new missions are constantly being planned, such as the Copernicus Hyperspectral Imaging Mission for Environment (CHIME).

However, hyperspectral sensors produce a vast amount of data which must be somehow handled. This becomes even more demanding with the increasing resolution of last sensor generations. As an example, the hyperspectral sensor for CHIME mission will capture data with a rate of approximately 2 Gbps. Handling such volume of data is particularly challenging for space missions, considering the limitations in computational and storage resources on-board, as well as the limited transmission bandwidths with ground stations. Thus, compression of hyperspectral data becomes mandatory in this kind of missions.

In this context, the Consultative Committee for Space Data Systems (CCSDS), an international organization devoted to the development of communications and data systems standards for spaceflight, has published a data compression standard [2] specifically thought for hyperspectral image data, and aimed at a low computational complexity. The last issue of such standard, the CCSDS 123.0-B-2, incorporates a near-lossless compression mode, which allows for high compression ratios at the expense of introducing losses to the data, in a degree configurable by users.

A distinctive characteristic of the image data captured in EO missions is the presence of clouds. Clouds cover more than half of the Earth's surface and may interfere with data captured by image sensors, either by attenuating or absorbing light at certain wavelengths. This may render big portions of captured images unusable, depending on what information is of interest. Because of this, and considering the hardware limitations on-board, EO missions should consider filtering somehow these uninteresting regions.

BACKGROUND

The CHIME Mission

CHIME is part of the future Copernicus 2.0 programme. It is aimed at providing routine hyperspectral observations for the management of natural resources, assets, and benefits to support new and enhanced services for food security, agriculture, and raw materials [1]. With this goal, hyperspectral sensors will provide continuous spectral data in VNIR and SWIR spectral domains (with a maximum of 256 bands between 400 and 2500 nm) at input data rates close to 2 Gbps. This implies a raw data memory volume in the order of magnitude of Terabits. Therefore, on-board optimized data compression shall be applied.

Data compression for CHIME mission shall be based on the CCSDS 123.0-B-2 Compression Standard but applying selective compression. The idea is achieving an improved data reduction by allowing higher losses for uninteresting image regions, i.e., those covered by clouds. Thus, a compression chain comprised by cloud detection plus selective compression stages shall be implemented, as shown in Fig. 1. The cloud detection stage generates a *cloud map* indicating whether each input pixel is cloud or not, which is provided along the image to compress. This compression chain shall provide real-time processing, being able to process 1 sample per clock cycle at an operating clock frequency of 125 MHz [3]. The processing chain will be implemented on a Xilinx Kintex UltraScale FPGA, the KU060.

CCSDS 123.0-B-2 Compression Standard

The CCSDS 123.0-B-2 Compression Standard [2] is an algorithm specifically designed for the compression of hyperspectral image data with low complexity, enabling implementations with low area footprint, well suited for space missions. It falls under the category of predictive compression algorithms, which means that the pre-processing stage is a predictor. Pre-processed samples are then sent to an entropy coder, which generates the proper codewords that conform the compressed bitstream. The CCSDS 123.0-B-2 algorithm performs compression in a single pass, i.e., every input sample is processed just once.

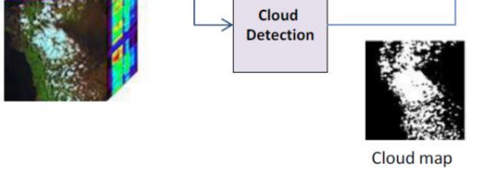

Fig. 1. Compression scheme for CHIME mission [4]

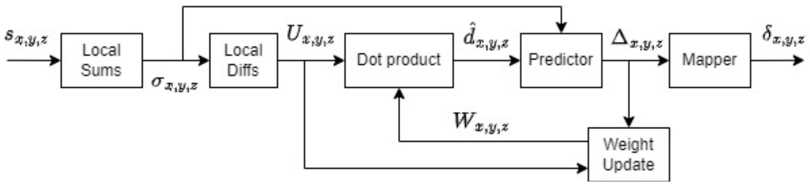

Fig. 2. CCSDS 123.0-B-2 lossless compression mode

The CCSDS 123.0-B-2 predictor estimates the value of every input sample by using previously processed samples in a 3D neighbourhood. From them, a series of *local sums* $\sigma_{x,y,z}$ and *local differences* are computed, from which a *local differences vector* $U_{x,y,z}$ is built. A dot product of this vector with an internal *weights vector* $W_{x,y,z}$ is computed, which in turn allows to compute the *predicted sample*. In lossless mode, the difference between the predicted sample and the input sample value, i.e., the *prediction residual* $\Delta_{x,y,z}$, is mapped into an unsigned integer $\delta_{x,y,z}$ and then sent to the entropy coder. At the same time, the internal weights vector is updated using the prediction residual and other subproducts. This process is depicted in Fig. 2.

In near-lossless mode (see Fig. 3), losses are introduced by applying quantization to the prediction residuals. This allows for higher compression ratios by increasing the uniformity of pre-processed samples. The compression standard allows to apply absolute and/or relative errors. *Quantized prediction residuals* $q_{x,y,z}$ are then sent first to the mapper and later to the entropy coder. At the same time, *sample representatives* $s''_{x,y,z}$ are computed based on the quantized prediction residuals. These are the values of the input samples which will be recovered at the decompressor side, and they are used to compute the local sums and differences instead of the original samples as they will not be available at the decompressor, due to the inclusion of losses. In addition, a subproduct of the sample representatives computation $s'_{x,y,z}$ is used to update the internal weights vector instead of the prediction residual.

As it can be seen, the inclusion of the near-lossless compression mode introduces more computational complexity and additional data dependencies, which must be considered for an efficient hardware implementation. In this sense, some options foreseen in the standard are aimed at reducing these data dependencies, enabling high performance implementations. Such is the case of the narrow mode of local sums computation.

Regarding the entropy coding stage, the CCSDS 123.0-B-2 Compression Standard allows using up to three options: the sample-adaptive encoder, the block-adaptive encoder, and the hybrid encoder. Among them, we focus on the block-adaptive encoder, which is the one implemented for the CHIME mission. This is a universal data encoder defined in the CCSDS 121.0-B-3 compression standard [6]. It incorporates several compression options, all of them based on Rice codes. Input samples coming from the predictor stage are grouped in blocks of fixed size. For each block, all compression options are computed concurrently, and the one which produces the shortest output is chosen, including an identifier to denote the compression option applied.

For every compressed image, the bitstream includes a header to denote the value of the algorithm parameters applied to generate the compressed data. Configuration options are multiple and can be consulted in [2]. In addition, the algorithm offers the possibility of including some image ancillary data to the compression header, in the form of supplementary tables with a pre-defined format.

Cloud selective compression

The CCSDS 123.0-B-2 Compression Standard, in near-lossless compression mode, allows to define per-band error limits. In addition, it allows to periodically renew the error limits every certain number of spectral lines. In the limit case, it is possible to provide a new set of error limits with every line. However, even if both features are combined, it is not sufficient to reach the CHIME mission requirements in terms of selective compression granularity. The mission requires to determine the pixel class, and hence apply the proper error limit, on a pixel-by-pixel basis.

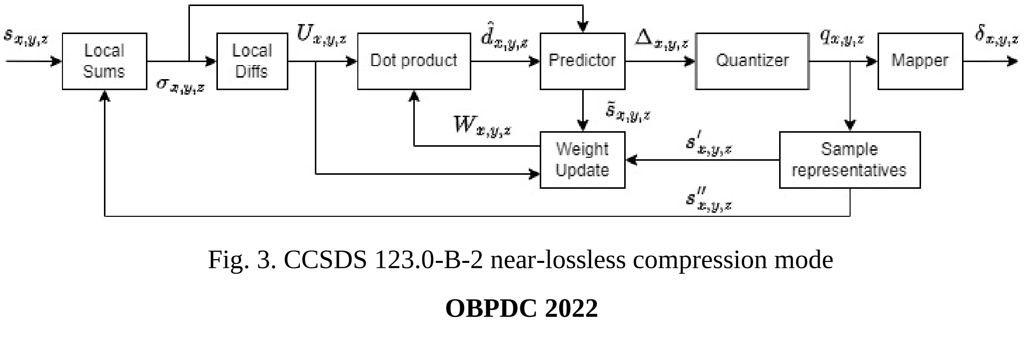

Fig. 3. CCSDS 123.0-B-2 near-lossless compression mode

To achieve this goal, an ad-hoc modification of the CCSDS 123.0-B-2 Compression Standard is proposed in [4], known as Different Absolute Error (DAE). In DAE approach, we assume that every pixel belongs to one out of two possible classes, here denoted as *cloud* and *ground*. The compression algorithm incorporates two configurable per-band error limit vectors, one for each pixel class (only absolute errors are considered). The cloud map received along with the input image denotes the class of each pixel. The image is then compressed according to the CCSDS 123.0-B-2 Compression Standard but applying an absolute error limit determined by the band and pixel class of each sample.

The DAE approach has been chosen among different selective compression options as it provides a good trade-off between compression ratio and image distortion after decompression [4]. Furthermore, such trade-off can be thoroughly adjusted through the selection of adequate error vectors for each pixel class. As main drawback, this approach is not fully standard compliant, requiring ad-hoc implementations on both compressor and decompressor stages. In addition, both error vectors as well as the cloud map used to compress a hyperspectral image must be provided to the decompressor, so it can properly decompress the image.

Several cloud detection strategies are analysed in [4] for implementing the cloud detection stage. Among them, cloud detection based on Support Vector Machine (SVM) is selected for CHIME mission due to its low false positive rate, good performance and low complexity, which makes it suitable for an on-board implementation. The SVM parameters are expected to be stable, so they can be determined through a training stage on ground.

COMPRESSION SOLUTION FOR CHIME

CCSDS 123.0-B-2 tailoring for CHIME

First, we focus on the decisions taken at algorithmic level to adapt the CCSDS 123.0-B-2 Compression Standard for CHIME mission, incorporating the DAE approach.

The CCSDS 123.0-B-2 implementation proposed in this work selects a subset of configuration options which better adjust to the mission requirements. Thus, Band-Interleaved by Line (BIL) is the chosen processing order, and the block-adaptive encoder is used for the entropy coding stage. Our implementation always works in near-lossless mode with per-band absolute errors, and without periodic error limit updating. It must be noted that lossless compression can still be done by setting an error vector of all zeroes. Narrow neighbour-oriented local sums and reduced prediction modes are used to favour a pipelined hardware implementation. Custom weight initialization as well as weight exponent offsets are discarded. Finally, band-independent values are used for the sample representatives tuning parameters. Other configuration settings are summarized in Table 1, specifying if they are fixed or configurable within a range of values.

Table 1. Set of CCSDS parameters used in CHIME compressor

Parameter category	Parameter name	symbol	type	Allowed value(s)
Image parameters	X size	N_x	Dynamic	[1:1536]
	Y size	N_y	Static	64
	Z size	N_z	Dynamic	[1:256]
	Dynamic range	D	Static	16
Predictor parameters	Number of prediction bands	P	Static	3
	Register size	R	Static	48
	Weight component resolution	Ω	Static	19
	Weight update scaling initial/final parameters	ν_{min},ν_{max}	Dynamic	[-6:9]
	Weight update scaling exponent change interval	t_{inc}	Dynamic	$[2^8, 2^9, 2^{10}, 2^{11}]$
	Absolute error limit bit depth (ground class)	D_{AG}	Static	8
	Absolute error limit bit depth (cloud class)	D_{AC}	Static	10
	Sample representative resolution	Θ	Static	4
	Sample representative offset/damping	ψ_z, ϕ_z	Dynamic	[0:15]
Entropy coder parameters	Block size	J	Dynamic	[32, 64]
	Reference sample interval	r	Static	4096
	Output word size	B	Static	4 (32 bits)

In addition to these parameters, the DAE approach requires non-standard settings: the cloud map and the error vector for the cloud class. It must be noted that ground class error is considered as part of the standard settings. These additional settings must be also provided to the decompressor side, so it can properly regenerate compressed images. To ensure the self-containment of the compressed bitstream, it is proposed to encode this additional information in the compression header as supplementary information tables. In addition, a third element is proposed to be encoded in a supplementary table: an identifier for the combined set of configuration parameters for the hyperspectral image compression plus the cloud detection stages. As a result, the image compressor for CHIME will generate 3 supplementary information tables in the compression header, with the characteristics shown in Table 2.

Table 2. Supplementary information tables defined for CHIME

Table type	Table structure	Number of elements	Element size	Element type
Cloud map	2-dimensional *xy*	$N_x \cdot N_y$	1	unsigned integer
Cloud errors	1-dimensional	N_z	D_{AC}	unsigned integer
Configuration ID	0-dimensional	1	32	unsigned integer

It has been decided that the hyperspectral compressor for CHIME will enable a configuration option to choose if the DAE compression is applied or not. When DAE is disabled, the whole image is compressed by applying the error limits of the ground class. However, in this case the cloud map is still generated, as it can be of scientific relevance on ground. The user-defined data field of the cloud map supplementary table is used to distinguish if DAE is applied or not.

Hardware Implementation

The compression solution for CHIME is comprised by a pair of soft IP cores (see Fig. 4), described in VHDL: a pre-processor, which is a custom implementation of the CCSDS 123.0-B-2 predictor supporting the DAE approach, and the SHyLoC 2.0 CCSDS121IP [7] as block-adaptive entropy coder. The SHyLoC CCSDS121IP is a hardware implementation fully compliant with the CCSDS 121.0-B-3 compression standard, which belongs to the portfolio of ESA IP cores for space missions. For CHIME mission, the SHyLoC CCSDS121IP core has been taken as-is but constraining the runtime configurable parameters to match the specifications of Table 1. Both IP cores provide an AMBA AHB slave interface for runtime configuration on-board. In addition, both IP cores have ad-hoc compatible I/O interfaces with a simple handshake mechanism.

The custom CCSDS 123.0-B-2 predictor IP for CHIME is comprised by a configuration core and a prediction core, as shown in Fig. 5. On the one hand, the configuration core receives the IP configuration from the AHB interface and generates most of the CCSDS 123.0-B-2 compression header, including the supplementary information tables for CHIME mission. This header is then passed to the CCSDS121IP, which completes the header by appending the section corresponding to the entropy coder configuration. On the other hand, the prediction core performs the pre-processing stage of the CCSDS 123.0-B-2 compression standard, including the DAE approach. With this aim, input samples are accompanied by a side input indicating the pixel class of the incoming sample, i.e., the corresponding bit of the cloud map. The cloud map is not internally stored, so it must be received twice during the compression of an image: once for generating the compression header, using the same input port than the input samples, and another time during the proper image compression step, through the cloud flag side input. To distinguish between both steps, an extra side input is used. In addition, the prediction core interfaces with an external memory to store some intermediate results, using a simple handshake mechanism.

The prediction core is comprised by several logic modules, implementing each one of the steps of the CCSDS 123.0-B-2 pre-processing stage (see Fig. 6). The design also incorporates three main storage elements: one to store per-band weight vectors, another for local difference vectors, and the last one for sample representatives. This last memory element is the largest one in the design, demanding approximately a full line of samples with all their bands. To reduce the memory consumption of the design, a large fraction of this memory region is allocated externally. This external memory acts as a large FIFO which holds the sample representatives until they are required by the prediction core.

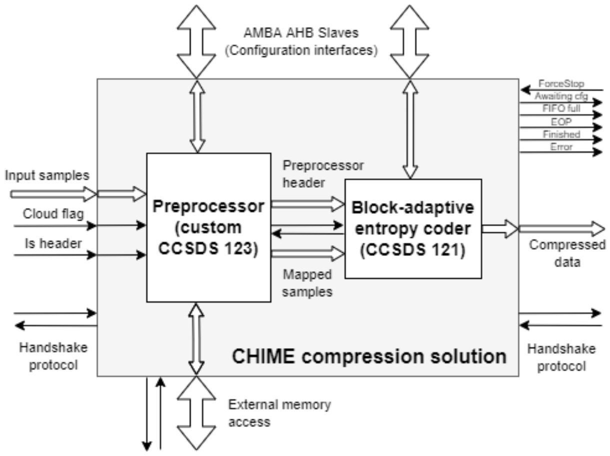

Fig. 4. Proposed compression solution for CHIME mission

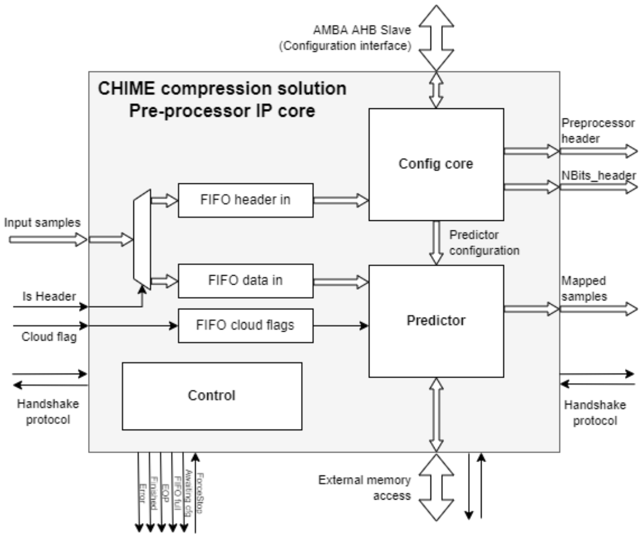

Fig. 5. Overview of the custom CCSDS 123 pre-processor IP for CHIME

A big challenge of this compression solution is reaching a performance high enough to meet the CHIME mission requirements, i.e., being able to process a sample per clock cycle with a minimum clock frequency of 125 MHz. While the SHyLoC CCSDS121IP easily meets this requirement, the custom predictor requires a careful design. Two are the main bottlenecks here: on the one hand, the integer division in the quantizer and mapper modules, an operation which is costly to implement in hardware; and on the other hand, the data dependencies present in the CCSDS123 pre-processing stage may severely slow down the datapath. Both issues are next addressed.

Integer divisions *A/B* are implemented as multiplications between *A* and *1/B*. Considering the operator sizes required by the compression algorithm, these “divisions” can be performed in a single clock cycle and implemented using the DSP resources of the target FPGA. In addition, integer divisions in both quantizer and mapper modules share the same divisor *B*. *1/B* values, which depend on the error limits applied to quantize each sample, are precomputed and stored in a Look Up Table (LUT), which is addressed using the error limit corresponding to the current band and pixel class. A proper sizing and rounding of these *1/B* values is chosen to ensure that the result of the multiplication, performed with fixed-point precision, always coincides with the integer division result.

Regarding the compressor data dependencies, we rely on the analysis conducted in [8]. For BIL processing order, there are two sources of data dependencies: those originated by the sample representatives and weights feedback loops. The dependency on sample representatives is strongly affected by the local sum and prediction modes. A proper selection of

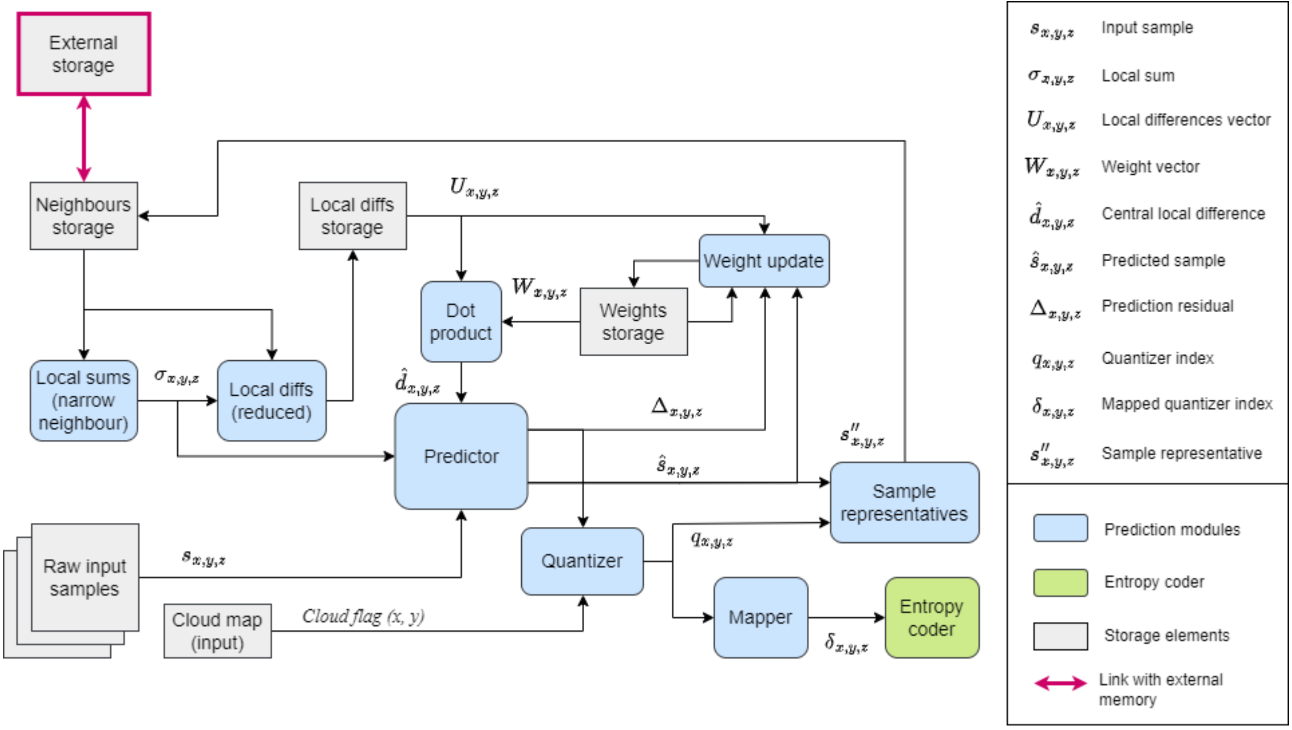

Fig. 6. Architecture of the CCSDS 123.0-B-2 predictor chain for CHIME

these modes loosens this data dependency up to the point it does not represent a limiting factor, provided that images to compress are large enough in the spatial dimension. Dependency on weights is still present, though.

If we stick to the CCSDS 123.0-B-2 compression standard, the feedback loop of weights is comprised by 5 steps: dot product, predictor, quantizer, sample representatives and weights update. In the general case, the weights update step of a sample must be computed before the dot product for the next sample. This imposes an unacceptable performance penalty for the CHIME mission. However, a combination of optimization strategies allows minimizing such penalties [8]. First, the sample representative's subproduct used in weights updating is replaced by using outputs of the prediction module, thus supressing the quantizer and sample representative steps from the feedback loop. As demonstrated in [8], this change is mathematically equivalent to the standard formulation. And second, eager execution is applied to the weights update step to speed up computations. This way, both positive and negative increments of the weights vector components are computed in parallel and in advance, by replicating the weights update module. The right updated weight vector is chosen a posteriori. By applying both strategies, a highly optimized pipeline is implemented which is able to operate with a throughput of one sample per clock cycle. As a remarkable fact, this high throughput is achieved using a standard processing order (BIL), thus avoiding any reordering steps upstream or downstream.

Validation and Implementation Results

The proposed compression solution has been verified in logic simulation against a software implementation of the CCSDS 123.0-B-2 compression standard with DAE compression developed for the analysis conducted in [4]. A total of 57 testcases have been tested, considering a variety of input images and cloud maps, as well as diverse configurations of the developed compression solution, including several error vector settings. Input images, representative of the acquisitions from CHIME sensors, have been generated by OPSI, a simulator developed by TAS under the CHIME development activities. For all this testcases, the output of the compression solution coincides bit-by-bit with the bitstream generated by the reference software.

Implementation results of the compression solution for the Xilinx Kintex UltraScale XQKU060-1i FPGA are reported in Table 3, distinguishing between the pre-processing and entropy coding stages. These results have been obtained by performing synthesis using Synopsys Synplify Premier P-2019.09-SP1 and implementation through Xilinx Vivado 2019.1. For the shake of comparison, results given in [3] for the implementation of the CHIME pre-processor in HLS for Xilinx Kintex UltraScale KU040 FPGA are given. As it can be seen, the VHDL design is able to meet real-time processing requirements of the CHIME mission, where HLS development fails. In addition, the proposed compression solution has a low area footprint, so plenty of logic resources are left to implement the cloud detection logic and incorporating protection measures against Single Event Effects (SEEs). With respect to the HLS design, the VHDL predictor has a noticeable lower memory consumption, because a big fraction of the memory is allocated externally. It is also worth to mention the reduced consumption of other logic resources, particularly Flip-Flops (FFs) and LUTs, with respect to the HLS design, even if some modules have been replicated to support the high-performance pipeline.

Table 3. Implementation results of CHIME compression solution for XQKU060-1i

Resource	**CHIME predictor (HLS) [3]**	**CHIME predictor (VHDL)**	**CCSDS121IP (block-coder)**
BRAM_18K	333 (28%)	8 (0.7%)	3 (0.3%)
DSP48E	40 (2.1%)	37 (1.3%)	5 (0.2%)
FF	6589 (1.4%)	4926 (0.7%)	2085 (0.3%)
LUT	9218 (3.8%)	8492 (2.6%)	5904 (1.8%)
Clock frequency (MHz)	125	125.2	125.7
Throughput (clock cycles/sample)	7	1	1

CONCLUSIONS

With acquisition data rates close to 2 Gbps, the CHIME mission requires an efficient data compression solution which provides real-time processing capabilities, thus considering both the on-board storage resources and transmission bandwidth limitations. To further boost data reductions, the mission requires to apply selective compression, allowing higher compression ratios for uninteresting parts of the acquired images, i.e., those covered by clouds.

This work proposes a compression solution for CHIME mission. It is comprised by two parts: a pre-processor, which is a custom implementation of the CCSDS 123.0-B-2 compression standard, and the SHyLoC CCSDS121IP as entropy coder. The pre-processor incorporates the DAE approach to enable selective compression, in which the degree of quantization applied to each sample depends on the pixel class determined by a cloud map, an additional input which is provided by a previous cloud detection stage. A highly optimized pipeline is implemented in the pre-processor, achieving a throughput of one sample per clock cycle at an operating clock frequency of 125 MHz. The compression solution has been verified against a reference software, and the implementation results demonstrate the goodness of this approach.

Next step will consist in performing a more extensive validation of the proposed compression solution, corner cases included, in preparation for next phases of the CHIME project.

REFERENCES

[1] J. Nieke and M. Rast, “Status: Copernicus Hyperspectral Imaging Mission For The Environment (CHIME),” in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, 2019, pp. 4609–4611.

[2] Consultative Committee for Space Data Systems, *Low-Complexity Lossless and Near-Lossless Multispectral and Hyperspectral Image Compression, CCSDS 123.0-B-2*. CCSDS, February 2019.

[3] Y. Barrios, P. Rodríguez, A. Sánchez, M. González, L. Berrojo, and R. Sarmiento, “Implementation of cloud detection and processing algorithms and CCSDS-compliant hyperspectral image compression for CHIME mission,” in *7th International Workshop on On-Board Payload Data Compression (OBPDC)*, September 2020, pp. 1–8.

[4] D. Lebedeff, M. Foulon, R. Camarero, R. Vitulli, and Y. Bobichon, “On-board cloud detection and selective spatial/ spectral compression based on the CCSDS 123.0-B-2 for hyperspectral missions,” in *7th International Workshop on On-Board Payload Data Compression (OBPDC)*, September 2020, pp. 1–8.

[5] S. -E. Qian, "Hyperspectral Satellites, Evolution, and Development History," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2021, vol. 14, pp. 7032-7056

[6] Consultative Committee for Space Data Systems, *Lossless Data Compression, CCSDS 121.0-B-3*. CCSDS, August 2020.

[7] Y. Barrios, A. Sánchez, L. Santos and R. Sarmiento, “SHyLoC 2.0: IP cores for on-board data and image compression on future space missions”, in *IEEE Access*, 2020, vol. 8, pp. 54269-54287.

[8] A. Sánchez, I. Blanes, Y. Barrios, M. Hernández-Cabronero, J. Bartrina-Rapesta, J. Serra-Sagristà and R. Sarmiento “Reducing Data Dependencies in the Feedback Loop of the CCSDS 123.0-B-2 Predictor”, unpublished.