CODING PERFORMANCE IMPACT ON A CONSTANT-WEIGHT PREDICTOR FOR CCSDS 123.0-B-2

Joan Bartrina-Rapesta[1], **Miguel Hernández-Cabronero**[1], **Antonio Sanchez**[2], **Yubal Barrios**[2], **Roberto Sarmiento**[2], **Joan Serra-Sagristà**[1], **and Ian Blanes**[1]

[1]*Dept. of Information and Communications Engineering*
Universitat Autònoma de Barcelona
Campus UAB, 08193 Cerdanyola del Vallès, Spain
Email: {joan.bartrina, miguel.hernandez, ian.blanes, joan.serra}@uab.cat
[2] *Institute for Applied Microelectronics (IUMA)*
University of Las Palmas de Gran Canaria (ULPGC)
35017 Las Palmas de Gran Canaria, Spain
Email: {ajsanchez, ybarrios, roberto}@iuma.ulpgc.es

Abstract

In 2019, the 123.0-B-2 standard titled "Low-Complexity Lossless and Near-Lossless Multispectral and Hyperspectral Image Compression" was presented. It introduced a near-lossless operation mode and a new state-of-the-art entropy encoder to provide efficient coding of the low-entropy data often produced by the new in-loop quantizer included in the standard. This article shows that tunning properly some parameters during the coding process, the weight update stage of a CCSDS 123.0-B-2 predictor can be bypassed, yielding a faster encoder at expenses of likely compression ratios. Experimental results show the coding performance penalization bypassing the weight updating, compared with a regular coding process –when the weights are updated-, for lossless and near-lossless compression. Coding performance analysis is provided for Hyperion, Aviris, Modis and Airs instruments. Results suggest that, bypass the weight updating produces a lossless coding performance penalization about 4%. For near-lossless, a higher coding penalty is produced as the step size, in the inner loop quantizer of the predictor, is larger.

Key words: CCSDS 123.0-B-2; fast compression; data compression,; low computational predictor.

1. INTRODUCTION

Remote sensing imagery is becoming an invaluable tool for governments, rescue teams and aid organizations to manage infrastructure and natural resources, to appraise climate changes, or to give support when natural disasters strike. In 2019, Consultative Committee for Space Data Systems (CCSDS) Multispectral and Hyperspectral Data Compression (MHDC) working group developed the Issue 2 of CCSDS-123.0-B-1 [1], the CCSDS 123.0-B-2 standard, titled "Low-Complexity Lossless and Near-Lossless Multispectral and Hyperspectral Image Compression" [2]. Since remote sensing images tend to be very large, high-performance and high-throughput compression techniques are of paramount importance. As witnessed by the amount of recent publications in the last five years [3, 4, 5, 6, 7, 8, 9, 1]. However, it is worth noting that, most of these contributions are aimed to improve the lossless or near-lossless coding performance and are compared with coding techniques defined by the CCSDS. But, none of them is aimed to increase the throughput of the recently presented CCSDS 123.0-B-2 standard. This paper presents an strategy to increase the coding throughput of CCSDS 123.0-B-2, and still generating a compliant CCSDS 123.0-B-2 codestream.

The strategy presented in this document is based in that, tuning properly some user-defined parameters, the weight update stage of the CCSDS 123.0-B-2 predictor may be bypassed. Thus, the compressor is faster at expenses of small penalties in terms of coding performance (bits per sample). We named this strategy "Fast Mode", and requires of exogenous techniques. In this case, exogenous strategies consist into train the weights –employed in the prediction stage of the CCSDS 123.0-B-2– outside the compression pipeline, and use these weights to compress the desired scenes. To ease the reading of this contribution, authors employed the notation of [2]. The motivation and the exogenous strategies employed are described in Section 2 and 3, respectively,

The rest of the paper is organized as follows. Section 2 shows how the weight update may be bypassed, Section 3 provides description of the dataset employed, different exogenous strategies employed and analyze their performance. Finally, 4 ends this work.

2. CCSDS 123.0-B-2 WEIGHT UPDATE BYPASS

CCSDS 123.0-B-2 standard designed to be executed on-board payload processing systems is mainly constituted by a predictor followed by an entropy encoder. Additionally, the CCSDS 123.0-B-2 standard incorporates a near-lossless operation mode and a new state-of-the-art entropy encoder, denoted as hybrid encoder. This novel entropy encoder provides efficient coding of the low-entropy data often produced by the new in-loop quantizer included in the prediction stage. The predictor used assumes spatial similarity between pixels to predict the current pixel. However, usually this estimation is not accurate enough to estimate the actual sample. Therefore, the difference between the current pixel and the estimation is tracked and stored in a local difference vector. The local difference vector is further scaled with a weight vector through an inner product. The weight vector is denoted as $\omega_z^i(t)$, i makes reference to the N, W, NW pixels, z to the band to be encoded, and t to the index of the pixel which is being encoded in a band, where $0 \leq t \leq \text{columns} \times \text{rows} - 1$.

One of the most expensive operations is in charge of update the weight vector during the coding process CCSDS 123.0-B-2, which is yield through the vector product to get the proper $\omega_z^i(t+1)$ vector from $\omega_z^i(t)$. This, may hinder efforts due to a strong data dependency in the processing of two consecutive input samples. Thus, a possible strategy to reduce this data dependency and in consequence yield faster compressors is bypassing this stage. With the aim of speed up the coding process, this update operation can be ignored, since these weights remain constant when tuning smartly some parameters, allowing to bypass this stage. Let us to explain further, to skip this stage the weights must remain unaltered, I.e., it is necessary that

$$\begin{gathered} \omega_z^{(i)}(t+1) = \omega_z^{(i)}(t) \ \ \forall i, \\ \omega_z^{\mathrm{N}}(t+1) = \omega_z^{\mathrm{N}}(t), \\ \omega_z^{\mathrm{W}}(t+1) = \omega_z^{\mathrm{W}}(t), \text{ and} \\ \omega_z^{\mathrm{NW}}(t+1) = \omega_z^{\mathrm{NW}}(t). \end{gathered} \tag{1}$$

Under certain encoder configurations, it can be guaranteed that such conditions always hold. In what follows, we obtain a set of standard-compliant encoder configurations under which the weight update stage is effectively bypassed.

First, we derive a simplified mathematical formulation under which weights remain constant. Next, we derive a configuration under which the previous formulation holds.

2.1. Constant weight condition

As all four constraints in (1) are analogous, we follow with the case of central weights, and omit the cases of directional weights. According to equation 51 in CCSDS 123.0-B-2 [2], central weights are updated as follows:

$$\omega_z^{(i)}(t+1) = \text{clip}\left(\omega_z^{(i)}(t) + \left\lfloor \tfrac{1}{2}(\text{sgn}^+[e_z(t)] \cdot 2^{-\left(\rho(t)+\varsigma_z^{(i)}\right)} \cdot d_{z-i}(t) + 1)\right\rfloor, \{\omega_{\text{min}}, \omega_{\text{max}}\}\right).$$

From equation (2.1), can be derived a set of restrictions under which $\omega_z^{(i)}(t+1) = \omega_z^{(i)}(t)$ holds.

First step is to assume that the clip function to be the identity function. When not accounting for the clip function, having $\omega_z^{(i)}(t+1) = \omega_z^{(i)}(t)$ requires that

$$\left\lfloor \frac{1}{2}\left(\text{sgn}^+[e_z(t)] \cdot 2^{-\left(\rho(t)+\varsigma_z^{(i)}\right)} \cdot d_{z-i}(t) + 1\right) \right\rfloor = 0. \tag{2}$$

While the clip function in (2.1) may loosen somewhat the previous requirement, it mostly applies for extreme weight values that provide compression performance penalization.

Defining f as

$$f(x) \stackrel{\text{def}}{=} \left\lfloor \frac{1}{2}(x+1) \right\rfloor, \tag{3}$$

can be seen that

$$f(x) = 0 \iff 0 \leq \frac{1}{2}(x+1) < 1, \tag{4}$$

and that

$$f(x) = 0 \iff -1 \leq x < 1. \tag{5}$$

For convenience, the only considered restriction is

$$f(x) = 0 \impliedby |x| < 1, \tag{6}$$

and hence by combining (2) and (6) it is required that

$$\left| \text{sgn}^+[e_z(t)] \cdot 2^{-\left(\rho(t)+\zeta_z^{(i)}\right)} \cdot d_{z-i}(t) \right| < 1. \tag{7}$$

Knowing that

$$-1 \leq \text{sgn}^+[e_z(t)]) \leq 1, \tag{8}$$

then (7) can be reduced into

$$\left| 2^{-\left(\rho(t)+\zeta_z^{(i)}\right)} \cdot d_{z-i}(t) \right| < 1. \tag{9}$$

At this point a sufficient condition that, when it holds, guarantees constant weights.

Note that, it is not a necessary conditions due to the introduced simplifications regarding the clip and floor operations.

2.2. Equivalent configurations

Now, let us to proceed to study the variables involved in (9) and how they are derived from an encoder configuration.

Local differences, $d_{z-i}(t)$, are bounded by $\pm 4(2^D - 1)$, as per Table 3-1 from CCSDS 120.2-G-1 [10]. Hence,

$$\left| 2^{-\left(\rho(t)+\zeta_z^{(i)}\right)} \cdot 4 \cdot (2^D - 1) \right| < 1. \tag{10}$$

Given that

$$4 \cdot (2^D - 1) = 2^{2+D} - 4 < 2^{2+D}, \tag{11}$$

this worst bound is employed for $d_{z-i}(t)$ to obtain that

$$\left| 2^{-\rho(t)-\zeta_z^{(i)}+2+D} \right| < 1, \tag{12}$$

or equivalently

$$-\rho(t) - \zeta_z^{(i)} + 2 + D < 0. \tag{13}$$

Weight exponent offsets $\zeta_z^{(i)}$ can be arbitrarily set in the interval $-6 \leq \zeta_z^{(i)} \leq 5$, and we set them to $\zeta_z^{(i)} = 5$ for our convenience. I.e.,

$$-\rho(t) + D < 3. \tag{14}$$

The value $\rho(t)$ is defined as

$$\rho(t) \overset{\text{def}}{=} \text{clip}\left(\nu_{\text{min}} + \frac{t - N_{\text{X}}}{t_{\text{inc}}}, \{\nu_{\text{min}}, \nu_{\text{max}}\}\right) + D - \Omega, \tag{15}$$

which substituted in (14) yields

$$\Omega < 3 + \text{clip}\left(\nu_{\text{min}} + \frac{t - N_{\text{X}}}{t_{\text{inc}}}, \{\nu_{\text{min}}, \nu_{\text{max}}\}\right). \tag{16}$$

Given that $-6 \leq \nu_{\text{min}} \leq \nu_{\text{max}} \leq 9$, if $\nu_{\text{min}} = \nu_{\text{max}} = 9$ weights remain constant when

$$\Omega \leq 11, \tag{17}$$

regardless of the original image dimensions or bit depth.

Table 1: Image Corpus

Sensor	Scenes	Rows	Entropy
Hyperion	5	3170 3187 3242	9.57
Aviris	4	512	10.64
Airs	7	135	11.31
Modis	8	1354	8.55

To summarize, users can force a CCSDS 123.0-B-2 encoder to operate under constant weights by employing the following settings: $\zeta_z^{(i)} = \zeta_z^* = 5$, $\nu_{\text{min}} = \nu_{\text{max}} = 9$, and $\Omega \leq 11$.

While other values of $\zeta_z^{(i)}$, ζ_z^*, ν_{min}, or ν_{max} may still achieve the same effect, it is not necessary to consider them. They do not have any other effect on compression performance, and the current selection allows for larger Ω values.

Weights have a resolution of $\Omega + 3$ bits in signed integer representation. Hence, 14-bit weights can be employed under the weight update bypass scheme and still produce compliant bitstreams. Using this result in combination with narrow local sums might produce implementations where critical data dependencies within a single image line are removed.

It is important to note that, this encoder configuration necessarily relies on a well-crafted set of initial weights. There may be some some encoder performance penalty derived from using constant weights, which is analyzed in Section3.

3. EXPERIMENTAL RESULTS

This section presents a set of experiments to evaluate the coding performance impact when the weight updating of the CCSDS 123.0-B-2 predictor stage is bypassed. Results are provided for lossless and near-lossless coding. The results are presented employing different strategies to obtain the initial weights $\omega_z^i(t)$ to compress the image.

The coding performance in terms of bit per sample (bps) is used as a metric. It is defined as

$$\text{bps} = \frac{\text{Compressed since in bits}}{\text{Bands} \times \text{Rows} \times \text{Columns}} \tag{18}$$

All results presented are generated employing the free available implementation of CCSDS 123.0-B-2 [11] of the French space agency (CNES) developed by the Group of Interactive Coding of Images [12] at the Universitat Autònoma de Barcelona [13].

3.1. Test Corpora

Experiments are conducted on four different sensors of a subset of the test corpora defined by the CCSDS Data Compression working group [14]. The corpus used in this proceeding is formed by a set of scenes of four different sensors: Hyperion, Airs, Aviris, and Modis. The sensor name, number of scenes, number of rows in scenes, average entropy in bits per sample are summarized in Table 1. Number of bands and columns do not have impact on this contribution, thus they are not indicated.

3.2. Overhead Evaluation

This section shows the coding performance impact when the weight updating is bypassed and when it is not bypassed. To facilitate the readability, we distinct between bypass and not bypass the weight updating as two different strategies. “Fast Mode”, when the weight updating is bypassed, whereas, when the weights are updated in the prediction stage, we named as “Regular Mode”. For the Regular Mode, the parameters are full prediction mode, number of prediction bands equal to 3, Ω equal to 19. Whereas for the Fast Mode the parameters $\zeta_z^{(i)}$ and ζ_z^* are equal to 5, ν_{min} and ν_{max} are 9, and Ω is 11.

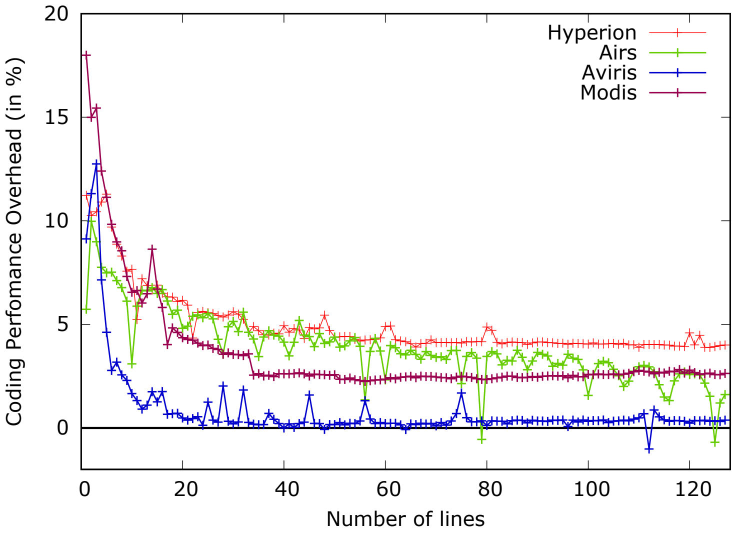

Figure 1: Overhead averaged evaluation for different sensors. The overhead is provided in function of the number of lines compressed in regular mode.

It is important to note that, in Fast Mode the initial weights must be previously set. These weights can be obtained employing different exogenous strategies. Aimed to evaluated the coding performance impact of the Fast Mode, three experiments are presented. Each experiment employs a concrete exogenous strategy to define the initial weights employed for the Fast Mode and compared with the Regular Mode.

- Exogenous Strategy 1 is aimed to know how many lines are needed to stabilize the coding performance penalty. The strategy considers Y the total lines to be processed of an image, then the first Y' lines are processed in Regular Mode; the weights after coding line Y' are saved and used to compress the rest of the lines, i.e. $Y - Y'$, in Fast Mode.
- Exogenous Strategy 2 assesses the impact of employing preconfigured weights. First the whole scene is encoded in Regular Mode, the obtained weights after encoding are saved and employed to encoded again the same scene but in Fast Mode. This assesses the minimum impact when an image encoded bypassing the weight updating. The obtained weights are produced for lossless and near-lossless (at different PAEs). The weights are used to encode the data with the same quantization step in which the weights are obtained.
- Exogenous Strategy 3 evaluates the impact of having preconfigured weights for the different sensors and use Fast Mode for coding the acquired scenes. Weights are obtained encoding previously a whole scene in lossless mode, then the obtained weights are employed to encode different scenes of the same sensor in lossless or near-lossless mode.

The first experiment evaluates the lossless coding performance overhead when Exogenous Strategy 1 is used. The overhead of this strategy is depicted in Fig. 1. The vertical axis provides the overhead in % between coding all Y lines in Regular Mode and coding Y' lines (showed in the horizontal axis) in Regular Mode and the rest of the lines in Fast Mode. Results are reported in average for all scenes of our corpus and for Hyperion, Airs, Aviris and Modis sensors. Results are showed only for the firsts 128 lines, for $Y' > 128$ results do not vary. From this experiment can be appreciated that the coding overhead is stabilized after the first 40 lines are compressed in Regular mode, the coding overheads are 5% for Hyperion, 3% for Airs, 4% for Modis, and less than 1% for Aviris .

Table 2: Coding performance analysis for Exogenous Strategy 2. Preconfigured weights are obtained encoding the same image in lossless.

		Regular Mode	Fast Mode	Overhead
Hyperion	ErtaAle	5.20	5.43	4.42%
	MtStHelens	5.40	5.65	4.62%
	LakeMonona	5.21	5.54	6.33%
	Average	5.27	5.54	5.12%
Airs	gran9	7.36	7.41	0.67%
	gran16	7.13	7.25	1.68%
	gran60	7.91	7.99	1.01%
	gran82	6.73	6.89	2.38%
	gran120	7.36	7.49	1.76%
	gran126	7.95	8.05	1.25%
	gran129	6.61	6.62	0.15%
	gran151	7.97	8.03	0.75%
	gran182	7.85	8.05	2.54%
	Average	7.43	7.53	1.36%
Aviris	hawaii	4.75	4.78	0.63%
	maine	5.03	5.16	2.58%
	yellowstone_sc00	9.87	9.66	-2.12%
	yellowstone_sc03	9.78	9.58	-2.04%
	Average	7.35	7.29	-0.75%
Modis	A2001123.0000day	6.49	6.63	2.15%
	A2001123.0000night	5.53	5.99	8.31%
	A2001123.1630day	8.12	8.24	1.47%
	A2001123.1630nigh	6.39	7.00	9.54%
	A2001222.0835day	9.04	9.13	0.99%
	A2001222.0840day	8.39	8.45	0.71%
	A2001222.1200day	8.82	8.85	0.34%
	A2001222.1200night	5.38	5.97	10.97%
	Average	7.27	7.53	3.61%

Table 3: Lossless and Near-Lossless coding performance analysis for Strategy 2. Results are provided at different PAEs for Regular, Fast Mode and Fast Mode'.

	Regular Mode	Fast Mode	Fast Mode'
Hyperion			
PAE = 0	5.27	5.54	5.54
PAE = 1	3.64	3.96	3.95
PAE = 3	2.52	2.81	2.79
PAE = 7	1.62	1.86	1.89
PAE = 15	0.97	1.12	1.16
PAE = 31	0.54	0.62	0.68
Airs			
PAE = 0	7.43	7.53	7.53
PAE = 1	5.87	5.97	5.97
PAE = 3	4.79	4.84	4.84
PAE = 7	3.77	3.83	3.83
PAE = 15	2.79	2.83	2.83
PAE = 31	1.88	1.89	1.91
Aviris			
PAE = 0	7.36	7.30	7.30
PAE = 1	5.83	5.77	5.78
PAE = 3	4.69	4.61	4.62
PAE = 7	3.76	3.67	3.67
PAE = 15	2.96	2.86	2.89
PAE = 31	2.28	2.18	2.28
Modis			
PAE = 0	7.27	7.53	7.53
PAE = 1	5.75	6.00	6.01
PAE = 3	4.63	4.88	4.89
PAE = 7	3.69	3.89	3.93
PAE = 15	2.87	3.02	3.04
PAE = 31	2.14	2.25	2.27

The second experiment evaluates the coding performance impact when Exogenous Strategy 2 is used for lossless and near-lossless coding. Results for lossless coding are provided in Table 2. This table shows the coding performance (in bps) for Regular and Fast Mode and, it also includes the overhead of Fast Mode with respect of Regular Mode (in %). From these results can be observed that the overhead is, in average each sensor, at most near 5%. For those scenes that have a low number of lines, such for Airs and Aviris sensors, the coding performance is almost the same for Regular and Fast Mode. This is because of the weight updating does not have enough data to adapt the weights properly. On the other hand, Table 3 shows the coding performance when different quantization steps are applied. Results are provided for Regular Mode, Fast Mode, and Fast Mode'. In Fast Mode the weights are obtained encoding the whole scene previously in lossless mode and employ that weights for encoding the final data (in lossless or near-lossless). For the Fast Mode', the methodology is the same but the weights are produced encoding the scene with the same quantization step employed fir coding the final image. Values showed in this table indicate that for near-lossless coding, the best performance is achieved by Fast Mode, when weights are trained through the lossless path.

The third, and last, experiment utilizes the Strategy 3 for different sensors. For sensors Hyperion, Airs, Aviris and Modis, the employed scenes during the training process are ErtaAle, Airs120, Hawaii and A2001123.0000day, respectively. Table 4 shows the average coding performance results at different quantization steps for Regular and Fast Mode, and the overhead in % with respect of the Regular Mode. The average is computed employing all the scenes of the corpus described in 1 discarding the one of the training procedure. The weights are obtained encoding the training image losslessly, since as is showed in Table 3 it provides the best results for lossless and near-lossless coding, indistinctly. From results of this table can be appreciated that the overhead, in general, is increased according to the PAE's value. For the Airs, Aviris and Modis sensors the the bit-rate supplement is not higher than 3.6%, 7.3% and 2.6%, respectively. However, for the Hyperion sensor our strategy penalizes considerably when the quantization step is increased.

Table 4: Lossless and near-lossless coding performance for Strategy 3.

	Regular Mode	Fast Mode	Overhead
Hyperion			
PAE = 0	5.27	5.53	5.00%
PAE = 1	3.70	3.95	6.71%
PAE = 3	2.58	2.81	8.90%
PAE = 7	1.67	1.91	13.91%
PAE = 15	0.99	1.15	15.80%
PAE = 31	0.55	0.69	25.78%
Airs			
PAE = 0	7.43	7.58	2.12%
PAE = 1	5.87	6.02	2.59%
PAE = 3	4.79	4.88	1.88%
PAE = 7	3.77	3.88	3.08%
PAE = 15	2.79	2.88	3.61%
PAE = 31	1.88	1.94	3.45%
Aviris			
PAE = 0	7.36	7.38	0.91%
PAE = 1	5.87	5.86	0.31%
PAE = 3	4.75	4.68	-1.31%
PAE = 7	3.82	3.70	-3.30%
PAE = 15	3.02	2.99	-0.17%
PAE = 31	2.33	2.40	7.29%
Modis			
PAE = 0	8.17	8.30	1.58%
PAE = 1	6.66	6.78	1.92%
PAE = 3	5.53	5.67	2.56%
PAE = 7	4.57	4.68	2.52%
PAE = 15	3.71	3.79	2.18%
PAE = 31	2.86	2.94	2.95%

4. CONCLUSIONS

In this paper the Fast Mode strategy for the CCSDS 123.0-B-2 predictor and its coding performance analysis are presented. The strategy is based on the fact that tuning some parameters of the coding process the prediction weights are never updated. This fact allows to speed the coding process at expenses of coding performance penalization. Results indicate that, in general, coding the first 128 lines updating the weights and the rest without updating the weights, produce a penalization from 1% to 5%. In addition, this contribution shows that, competitive coding performance are obtained even the weights are built with a training image, and the trained weights are used to compress another scene of the same sensor using the Fast Mode, producing overheads between 1% and 5% for lossless. This penalty augments as the quantization step increases, reaching overheads about of 25% and 3% when PAE is 31 for the Hyperion and Modis sensor, respectively.

ACKNOWLEDGMENTS

This work was supported in part by the Centre National d'Études Spatiales, and by the Spanish Ministry of Economy and Competitiveness and the European Regional Development Fund under Grants RTI2018-095287-B-I00 and PID2021-125258OB-I00 (MINECO/FEDER, UE), and by the Catalan Government under grants Beatriu de Pinós BP2018-00008 and 2017SGR-463. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776151 (Hi-SIDE project).

REFERENCES

1. Consultative Committee for Space Data Systems (CCSDS), *Lossless Multispectral & Hyperspectral Image Compression. Recommendation for Space Data System Standards, CCSDS 123.0-B-1*. CCSDS, May 2012. [Online]. Available: https://public.ccsds.org/Pubs/123x0b1ec1.pdf
2. ——, *Lossless Multispectral & Hyperspectral Image Compression. Recommendation for Space Data System Standards, CCSDS 123.0-B-2*. CCSDS, 2019.
3. J. Bartrina-Rapesta, I. Blanes, F. Aulí-Llinàs, J. Serra-Sagristà, V. Sanchez, and M. W. Marcellin, "A lightweight contextual arithmetic coder for on-board remote sensing data compression," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 55, no. 8, pp. 4825–4835, 2017.
4. S. Álvarez Cortés, J. Bartrina-Rapesta, and J. Serra-Sagristà, "Multilevel split regression wavelet analysis for lossless compression of remote sensing data," *IEEE Geoscience and Remote Sensing Letters*, vol. 15, no. 10, pp. 1540–1544, 2018.
5. I. Blanes, A. Kiely, M. Hernández-Cabronero, and J. Serra-Sagristà, "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 Sensing*, vol. 11, no. 11, 2019. [Online]. Available: https://www.mdpi.com/2072-4292/11/11/1390
6. M. Hernández-Cabronero, J. Portell, I. Blanes, and J. Serra-Sagristà, "High-performance lossless compression of hyperspectral remote sensing scenes based on spectral decorrelation," *Remote Sensing*, vol. 12, no. 18, 2020. [Online]. Available: https://www.mdpi.com/2072-4292/12/18/2955
7. M. M. Torres, M. Hernández-Cabronero, I. Blanes, and J. Serra-Sagristà, "High-throughput variable-to-fixed entropy codec using selective, stochastic code forests," *IEEE Access*, vol. 8, pp. 81 283–81 297, 2020.
8. M. Hernández-Cabronero, A. B. Kiely, M. Klimesh, I. Blanes, J. Ligo, E. Magli, and J. Serra-Sagristà, "The ccsds 123.0-b-2 "low-complexity lossless and near-lossless multispectral and hyperspectral image compression" standard: A comprehensive review," *IEEE Geoscience and Remote Sensing Magazine*, vol. 9, no. 4, pp. 102–119, 2021.
9. J. Bartrina-Rapesta and F. Aulí-Llinàs, "Dual link image coding based on ccsds-123," *IEEE Geoscience and Remote Sensing Letters*, vol. 19, pp. 1–5, 2022.
10. Consultative Committee for Space Data Systems (CCSDS), *Spectral Pre-Processing Transform for Multispectral & Hyperspectral Image Compression*. CCSDS, Dec. 2015. [Online]. Available: https://public.ccsds.org/Pubs/120x2g1.pdf
11. (2022, May) Low-Complexity Near-Lossles. [Online]. Available: https://logiciels.cnes.fr/en/license/173/728
12. (2022, May) Group on Interactive Coding of Images. [Online]. Available: https://gici.uab.cat
13. (2022, May) Universitat Autònoma de Barcelona. [Online]. Available: https://www.uab.cat
14. (2022, May) Test Corpora defined by the CCSDS Data Compression Working Group. [Online]. Available: https://cwe.ccsds.org/sls/docs/SLS-DC/123.0-B-Info/TestData/