Review and implementation of the emerging CCSDS Recommended Standard for multispectral and hyperspectral lossless image coding

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***Abstract*—A new standard for image coding is being developed by the MHDC working group of the CCSDS, targeting onboard compression of multi- and hyper-spectral imagery captured by aircraft and satellites. The proposed standard is based on the "Fast Lossless" adaptive linear predictive compressor, and is adapted to better overcome issues of onboard scenarios.**

In this paper, we present a review of the state of the art in this field, and provide an experimental comparison of the coding performance of the emerging standard in relation to other state-of-the-art coding techniques. Our own independent implementation of the MHDC Recommended Standard, as well as of some of the other techniques, has been used to provide extensive results over the vast corpus of test images from the CCSDS-MHDC.

***Keywords*-lossless image coding, multi- and hyper-spectral imagery, CCSDS-MHDC-123 standard.**

I. Introduction

Current remote-sensing sensors collect large amounts of information that are to be readily transmitted to the ground, since they have a limited memory capacity. However, these sensors usually have also a limited data transmission capability, so that a compression process may help reduce the transmission time and better exploit the channel bandwidth. In addition, as these sensors are often used in environments with limited computing capability, only low complexity algorithms are suitable for such a scenario.

At the same time, due to the economical cost and difficulty in collecting this information, it is customarily more convenient to perform a lossless compression process as opposed to a lossy compression process. In the case of satellite-borne sensors this need is further exacerbated, as captured images are commonly required at high fidelity for a posteriori processing tasks such as crop classification or target recognition.

In state-of-the-art image coding two different approaches are feasible to encode multi-/hyper-/ultra-spectral data, either 2D coding, benefiting from the spatial redundancy among neighboring pixels in a given component or band (also known as intra-component coding), or 3D coding, exploiting also inter-component redundancy.

Examples of 2D coding approaches are LOCO-I [1] and 2D-CALIC [2]. The first approach is the basis of the JPEG-LS standard [3], while the second approach provides a better coding performance at a higher computational complexity.

Since most remote-sensing images have a large number of spectral components, taking into account this third dimension may prove fruitful. In this sense, and exploiting both intra-component and inter-component correlation, LCL-3D [4], an extension of LOCO-I algorithm, 3D-CALIC [5], which is able to switch between intra-band and inter-band compression mode depending on the similarity of two consecutive bands, and M-CALIC [6], a modification of 3D-CALIC using only inter-band compression mode, have been proposed.

Conceptually simpler examples of 3D coding approaches belonging to the family of look-up tables (LUT) algorithms are LUT [7] (using a single LUT), Locally Averaged Interband Scaling (LAIS)-LUT [8] and LAIS-Quantized-LUT (LAIS-QLUT) [9] (LAIS-LUT and LAIS-QLUT using two LUTs). Coding results of these algorithms seem to be good for calibrated images, but possibly not as suitable for uncalibrated images, since uncalibrated images do not show the same kind of regularity. It was demonstrated [10] that LUT-based compression approaches exploit artifacts that are sometimes introduced by the calibration process, making them less appealing for onboard use, where such artifacts are not likely to occur.

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Fast Lossless (FL) [11] is another 3D coding algorithm that consists of predicting a pixel using only causal information (i.e., that part of the image that has already been processed). FL provides better results for uncalibrated images, and similar coding performance to LUT and its variants for calibrated images.

Other lossless coding techniques include SLSQ [12], with a version based on heuristics, SLSQ-HEU, and an optimal version, SLSQ-OPT; CCAP [13], a compressor based on a conditional average prediction; and ACAP [14], an adaptive combination of adaptive predictors.

In view of the growing demand for remote sensing image compression, the Multispectral and Hyperspectral Data Compression (MHDC) Working Group of the Consultative Committee for Space Data Systems (CCSDS) has lately been working on the proposal and approval of a Recommended Standard for lossless compression. This proposal is based on the FL coding technique, and will be outlined in Section II. Section III introduces our open-source implementations of LUT, LAIS-LUT, LAIS-QLUT, FL coding techniques, and, most importantly, of the emerging CCSDS MHDC Standard. Experimental results comparing the performance of all these techniques as well as of some other reference techniques are also reported in this Section. Conclusions are drawn in Section IV.

II. CCSDS MHDC Recommended Standard for on-board lossless data compression

The CCSDS is composed of the world's major space agencies: NASA, ESA, CNES, JAXA, CSA, FSA, etc. Since 1982, the CCSDS has been working towards the development of space data handling standards. To date, more than 500 space missions have elected to fly with CCSDS protocols and realized the benefits: reduced cost, risk and development time, as well as enhanced interoperability and cross-support [15].

The CCSDS has developed two Recommended Standards for data compression: CCSDS 121.0-B-1 [16] and CCSDS 122.0-B-1 [17]. The latter is a standard for both lossy and progressive lossy-to-lossless compression of two-dimensional grayscale images based on the wavelet transform; the former is a standard for lossless entropy coding, specifically, it is a formalization of the Rice coding algorithm. Realizing the need for more effective compression approaches for spacecraft imaging sensors capturing multiple spectral bands, the MHDC Working Group (WG) [18] has been developing a new Recommended Standard for lossless compression of multi- and hyperspectral images. The standard is based on the FL algorithm which has low computational complexity and memory requirements, and provides good compression performance on a variety of multispectral and hyperspectral images.

As of this writing, the proposed standard is a draft "Red Book" [19] under review by CCSDS member agencies and thus is subject to revision. Once it has been finalized, the standard will become a "Blue Book" that will be freely available on the CCSDS web site [15] as document CCSDS 123.0-B-1, "Lossless Multispectral and Hyperspectral Image Compression."

In the remainder of this section, we briefly outline the FL compression algorithm on which the standard is based. This simplified description provides an indication of the steps involved in compression, but for the sake of brevity and clarity we omit some of the details of the standard. For example, the standard only makes use of integer quantities while the algorithm we describe here effectively uses real-valued quantities; we ignore some practical concerns addressed by the standard, like register overflow and limiting the length of output codewords; and we omit any discussion of handling prediction at image boundaries. For a more thorough description of the FL algorithm, see reference [20], and for details of the standard itself, refer to the Blue Book.

The FL algorithm predicts the value of each sample considering the values of previously encoded samples in a small three-dimensional neighborhood. This calculation makes use of sample values in the current and P preceding spectral bands; a typical value is $P = 3$. Prediction is accomplished using adaptive linear prediction with prediction weights updated using the sign algorithm. An entropy coding stage then losslessly encodes the differences between original and predicted sample values. Compression is performed in a single pass through the image, and the standard supports the common band-interleaved-by-pixel (BIP), band-interleaved-by-line (BIL) and band-sequential (BSQ) scan orders.

Let $s_{z,y,x}$ denote a sample at horizontal position x, vertical position y, and spectral band z. The "local mean" value, $\mu_{z,y,x}$, is computed from previously compressed nearby samples in spectral band z. A user may chose to use the "neighbor-oriented" local mean, in which case

$$\mu_{z,y,x} = \frac{1}{4}\left(s_{z,y,x-1} + s_{z,y-1,x-1} + s_{z,y-1,x} + s_{z,y-1,x+1}\right)$$

or the "column-oriented" local mean, in which case

$$\mu_{z,y,x} = s_{z,y-1,x}.$$

We can think of the local mean $\mu_{z,y,x}$ as a preliminary estimate of the value of $s_{z,y,x}$. For many types of multi-band imagers, the neighbor-oriented local mean provides a better preliminary estimate than the column-oriented local mean. However, pushbroom hyperspectral imagers may have significant variations in responsiveness between adjacent detector elements. In this case, compression performance generally improves by simply using the previous sample in the same spectral band z and column x, (that is, the column-

oriented local mean) for the preliminary estimate.

Differences between local mean values and previously encoded sample values are arranged in a "local difference vector," $\mathbf{U}_{z,y,x}$. Under "full" prediction mode, the local difference vector is defined as

$$\mathbf{U}_{z,y,x} = \begin{pmatrix} s_{z,y-1,x} - \mu_{z,y,x}, \\ s_{z,y,x-1} - \mu_{z,y,x}, \\ s_{z,y-1,x} - \mu_{z,y,x}, \\ s_{z-1,y,x} - \mu_{z-1,y,x}, \\ s_{z-2,y,x} - \mu_{z-2,y,x}, \\ \vdots \\ s_{z-P,y,x} - \mu_{z-P,y,x} \end{pmatrix}.$$

These first three components are eliminated from $\mathbf{U}_{z,y,x}$ under "reduced" prediction mode.

Note that these first three components of $\mathbf{U}_{z,y,x}$, which are called "directional local differences," are each equal to the difference between the local mean $\mu_{z,y,x}$ and a previously compressed sample in the same spectral band z. The remaining components of $\mathbf{U}_{z,y,x}$, called "central local differences," are each equal to the difference between the sample at the same x and y position in a previous spectral band $z-i$ and the central local difference $\mu_{z-i,y,x}$ in that previous spectral band.

The use of reduced prediction mode (in combination with column-oriented local means) is intended for raw data from pushbroom hyperspectral imagers. Full prediction mode (combined with neighbor-oriented local means) generally provides better performance for multispectral imagers, whisk-broom imagers, and calibrated imagery.

The predicted sample value is computed as

$$\hat{s}_{z,y,x} = \mu_{z,y,x} + \mathbf{W}_z^{\mathrm{T}}(t)\mathbf{U}_{z,y,x} \tag{1}$$

where $\mathbf{W}_z(t)$ is a weight vector having the same dimensions as $\mathbf{U}_{z,y,x}$, the index t is defined as $t = y \cdot N_x + x$, and here N_x is the image width. We remark that t amounts to the index of a sample within its spectral band when samples in the band are arranged in raster-scan order.

In equation (1), in effect, the predicted sample value is computed by adjusting the preliminary estimate $\mu_{z,y,x}$ by an offset $\mathbf{W}_z^{\mathrm{T}}(t)\mathbf{U}_{z,y,x}$. Thus, the quantity $\mathbf{W}_z^{\mathrm{T}}(t)\mathbf{U}_{z,y,x}$ serves as a prediction of the amount by which the sample $s_{z,y,x}$ differs from the preliminary estimate.

The prediction error

$$e_{z,y,x} = s_{z,y,x} - \hat{s}_{z,y,x}$$

is used to update the weight vector via the sign algorithm as follows:

$$\mathbf{W}_z(t+1) = \mathbf{W}_z(t) + \mathbf{U}_{z,y,x} \cdot \mathrm{sgn}(e_{z,y,x}) \cdot 2^{-\rho(t)}.$$

Here the parameter $\rho(t)$ controls the adaptation rate; $\rho(t)$ begins at some user-specified initial value, then at regular intervals $\rho(t)$ is increased by one until it reaches some final value.

The prediction error $e_{z,y,x}$ is used to calculate an integer "mapped prediction residual" $\delta_{z,y,x}$ from which the original sample value can be recovered. Let f denote the following mapping from integers onto nonnegative integers:

$$f(n) = \begin{cases} |n| + \theta_{z,y,x}, & \text{if } |n| > \theta_{z,y,x} \\ 2n, & \text{if } 0 \le n \le \theta_{z,y,x} \\ -2n-1, & \text{if } -\theta_{z,y,x} \le n < 0 \end{cases}$$

where $\theta_{z,y,x} = \min\{\mathrm{round}(\hat{s}_{z,y,x}), 2^D - 1 - \mathrm{round}(\hat{s}_{z,y,x})\}$ and D denotes the dynamic range (i.e., bit depth) of the image samples. Then $\delta_{z,y,x}$ is equal to $f(e_{z,y,x})$ or $f(-e_{z,y,x})$, depending on whether $\hat{s}_{z,y,x}$ is less than or greater than $\mathrm{round}(\hat{s}_{z,y,x})$.

The mapped prediction residuals $\{\delta_{z,y,x}\}$ serve as the output of the prediction stage and are losslessly compressed using an entropy coding stage. The original FL algorithm uses an adaptive coding approach using Golomb-Power-of-2 (GPO2) codes, similar to the approach used in JPEG-LS [1]. The standard allows either this approach, referred to as the "sample-adaptive" entropy coder in the standard, or a "block-adaptive" entropy coder. The block-adaptive coder, which also makes use of GPO2 codes, is the Rice coding algorithm as formalized in the CCSDS 121.0-B standard.

The sample-adaptive entropy coder maintains separate entropy coding statistics for each spectral band. Consequently, it produces the same compressed image size regardless of the order in which samples are encoded. It also tends to provide slightly more effective compression than the block-adaptive coder. The block-adaptive encoding approach was included as an option in the standard so that implementers could take advantage of existing space-qualified hardware implementations of this encoder.

III. Implementations and Experimental Results

A. Evaluated coding techniques and developed implementations

Experimental results are reported for the following techniques: LUT [7], LAIS-LUT [8], LAIS-QLUT [9], FL [11], JPEG-LS [3], and for the MHDC Lossless Recommended Standard [19] of the CCSDS MHDC WG.

LUT, LAIS-LUT, LAIS-QLUT, FL, and MHDC Standard results have been obtained with our open-source implementations, while JPEG-LS results have been produced with HP implementation [21]. Results are also reported for a differential JPEG-LS approach, where JPEG-LS is applied to the differences between spectral bands.

We have developed three different open-source implementations [22]: one for the family of LUT-related coding techniques [7]–[9], a second implementation was programmed to execute Fast Lossless [11] algorithm, to pave the way for

the implementation of the CCSDS MHDC Standard [19] for lossless compression. This third implementation is named Emporda (FL-Emporda in the tables with results).

The motivation for publicizing our open-source implementations is to help adopt the emerging MHDC Standard for lossless compression by most remote-sensing agencies worldwide, and help them assess its suitability with regard to their needs.

As for practical matters, in all five of our implementations, a band of the image must be compressed in its entirety before starting to compress the next band. Full frame mode is used to ease comparison among implementations.

For our implementation of LUT, LAIS-LUT and LAIS-QLUT, only images stored in Band Sequential Format (BSQ) can be compressed, look-up tables are initialized only once for each band, at the beginning of the compression process, and specifically for LAIS-QLUT, only integer quantization factors not larger than 50 are allowed. The entropy coder used in order to encode the residual samples is the arithmetic coder by Alistair Moffat [23].

For our implementation of FL, only images stored in Band Sequential Format (BSQ) can be compressed, a band is compressed in "regions" of 32 lines, and the weights are initialized once for every band, before starting the encoding of that band. The "step size parameter" is 0.00008, and is updated once for every region, in row 10, multiplying it by 0.75; the default values for the other optional parameters are those recommended by the author in the original article [11]. The entropy coder used to encode the residual samples is again the arithmetic coder by Moffat [23], which is different from the GPO2 entropy coder used for MHDC implementations of FL. In fact, given the same settings, FL plus arithmetic coding should produce better coding results.

For our Emporda implementation of the CCSDS MHDC Recommended Standard for Lossless Compression, images can be loaded in BIP, BIL, and BSQ formats, but then all images are encoded with the same compression algorithm. The values of the parameters and the specifics of the algorithm that have been used for producing the results for this implementation are reported in Table I.

Unless otherwise stated in Table I, all parameter values are those recommended.

Table I
PARAMETERS USED IN THE EXPERIMENTS FOR FL-EMPORDA

Parameter	Value
Previous bands	15
Dynamic range	16
Output word size	4
Predictor meta-data flag	false
Coder meta-data flag	false
Local mean	neighbor oriented mode
Prediction mode	full prediction mode
Register size	32
Weight initialization method	default
Weight initialization table flag	false
Weight component resolution	13
Weight update scaling exponent change interval	64
Weight update scaling exponent initial parameter	-1
Weight update scaling exponent	3
Adaptive encoder	sample adaptive encoder
Unary length limit	16
Rescaling counter size	6
Initial count exponent	1
Initialization accumulator table flag	false
Accumulator initialization constant	5

Table II
IMAGE INFORMATION

Instrument	Image Type	Bit Depth	Number of Bands	Width	Height
AIRS	raw	12-14	1501	90	135
CASI	raw	12	72	405	{2852, 1225}
SFSI	raw	12	240	496	140
AVIRIS	raw	16	224	680	512
AVIRIS	raw	12	224	{614,680}	512
Hyperion	raw	12	242	256	{1024, 3187, 3176, 3242}
IASI	calibrated	12	8461	66	60
MODIS	night, raw	12	17	1354	2030
MODIS	day, raw	12	14	1354	2030
MODIS	500m, raw	12	5	2708	4060
MODIS	250m, raw	12	2	5416	8120
Landsat	raw	8	6	1024	1024
Vegetation	raw	10	4	1728	{10080, 10193}
MSG	calibrated	10	11	3712	3712
Pleiades	HR, Simulated	12	4	224	{2456, 3928, 2448}
SPOT5	HRG, processed	8	3	1024	1024

B. Coding performance evaluation

The experiments have been conducted on a subset of 3D remote sensing images collected by the CCSDS MHDC WG. The name and characteristics of the images are provided in Table II, an excerpt from the recent paper [20].

Results have been classified in four different groups, according to calibrated versus uncalibrated, and to either multi-spectral or hyper-spectral. For all groups, a final average row is provided to better seize the performance of each technique.

Table III reports results for multi-spectral uncalibrated images. For multi-spectral uncalibrated images, several different behaviors can be appreciated. For MODIS images, qLUT provides the best results for MODIS-1km_day; for MODIS-1km_night, FL-Emporda achieves the highest coding performance; JPEG-LS Diff. yields the best outcome for the other two images. For Landsat images, techniques based on the FL coding technique yield the best performance, closely followed by JPEG-LS Diff.. For Vegetation images, JPEG-LS has the best achievement, with our implementations of the CCSDS MHDC Recommended Standard following behind. In general, LUT-based coding techniques do not provide an adequate accomplishment for multi-spectral uncalibrated images.

Table III
MULTI-SPECTRAL UNCALIBRATED IMAGES IN THE CCSDS TEST SET. LOSSLESS COMPRESSION RESULTS (BITS PER PIXEL PER BAND, BPPPB).

Image	LUT	LLUT	qLUT	FL (Arith.)	FL-Emporda	JPEG-LS	JPEG-LS Diff.
MODIS-1km_day	5.42	5.24	5.04	5.95	6.44	5.13	5.67
MODIS-1km_night	7.81	7.82	6.56	5.93	5.51	6.10	6.59
MODIS-250m	9.59	9.38	9.04	7.57	7.38	7.45	7.22
MODIS-500m	9.61	9.45	9.14	7.77	7.52	8.06	7.23
Landsat-Agriculture	4.97	4.74	4.40	3.58	3.69	4.14	3.91
Landsat-Coast	3.95	3.75	3.59	2.85	2.85	3.11	3.06
Landsat-Mountain	4.70	4.44	4.29	3.75	3.83	4.28	4.17
VEGETATION-1-1b	7.70	7.37	6.84	5.40	5.20	5.35	5.09
VEGETATION-2-1b	7.79	7.44	6.89	5.46	5.24	5.38	5.12
Average	6.84	6.63	6.20	5.36	5.30	5.44	5.34

Table IV
OTHER MULTI-SPECTRAL IMAGES IN THE CCSDS TEST SET. LOSSLESS COMPRESSION RESULTS (BITS PER PIXEL PER BAND).

Image	LUT	LLUT	qLUT	FL (Arith.)	FL-Emporda	JPEG-LS	JPEG-LS Diff.
MSG-RC15	5.66	5.43	4.69	3.86	3.60	3.79	4.02
MSG-RC31	5.35	5.12	4.47	3.61	3.37	3.47	3.81
MSG-RC3	5.44	5.20	4.52	3.65	3.40	3.53	3.87
Pleiades-Montpellier	9.15	8.77	8.65	7.56	7.43	8.00	7.41
Pleiades-Perpignan	9.11	8.71	8.53	7.36	7.22	7.70	7.23
SPOT5-Toulouse-1	6.22	5.98	5.79	5.13	5.15	5.51	5.47
SPOT5-Toulouse-2	5.99	5.77	5.38	4.26	4.30	4.56	4.54
SPOT5-Toulouse-3	6.01	5.79	5.35	4.14	4.22	4.48	4.47
Average	6.62	6.35	5.92	4.95	4.84	5.13	5.10

Table IV reports results for other multi-spectral images. In spite of the different nature of these multi-spectral remote sensing images, a common trend is that FL and FL-Emporda implementations yield a very similar behavior, better than other coding approaches. Again, LUT-based techniques produce the worst results, although it is interesting to note that each LUT-variant improves with respect to its former basis.

Table V reports results for hyper-spectral uncalibrated images. Yellowstone images are captured from an AVIRIS sensor. Again, the family of algorithms based on FL coding technique yields superior coding performance as compared to the other techniques, including JPEG-LS Diff. For these images, there is a significant gap between JPEG-LS and JPEG-LS Diff., of more than 1 bpppb. The performance of LUT-related techniques is now closer to the best performing techniques, although still between 1 and 0.5 bpppb behind.

Table VI reports results for hyper-spectral calibrated images. For IASI images, with so many spectral components and relatively small spatial sizes, it is interesting to note that FL-Emporda implementation clearly provides the most competitive coding performance. For these images, with small spatial sizes (66×60), our implementation of the FL coding technique does not work well due to the extra per-band symbol dictionary required by the arithmetic coder.

In general, it can be observed that, although LUT-based techniques are significantly improving the performance of its predecessor, these algorithms obtain quite worse results than the other coding techniques. A convincing explanation was suggested in [10], where it was hypothesized that LUT-based techniques are able to exploit calibration-induced artifacts specific to 1997 AVIRIS calibrated images.

JPEG-LS Diff. provides somehow better coding performance than LUT-based techniques, but not as competitive as FL-related coding techniques. Our implementation of FL coding technique works reasonably well for most image corpus but for hyper-spectral calibrated images.

In conclusion, FL-related coding techniques, including CCSDS MHDC Standard, provide very competitive coding performance at a very acceptable computational cost, which makes them suitable for on-board use.

IV. CONCLUSION

The Multispectral and Hyperspectral Data Compression Working Group of the Consultative Committee for Space Data Systems has been developing a new Recommended Standard for Lossless Compression. The draft standard is currently under review by CCSDS member agencies and final approval is anticipated for Fall, 2011.

With the aim of helping to spread the knowledge and use of this emerging Standard, we have developed an open-source implementation that is currently available for assessing its benefits and performance as compared to previous CCSDS Recommended Standards or to other lossless coding techniques and standards.

We encourage space agencies to deploy this implementation and provide feedback to the CCSDS MHDC Working Group.

Table V
HYPER-SPECTRAL UNCALIBRATED IMAGES IN THE CCSDS TEST SET. LOSSLESS COMPRESSION RESULTS (BITS PER PIXEL PER BAND).

Image	LUT	LLUT	qLUT	FL (Arith.)	FL-Emporda	JPEG-LS	JPEG-LS Diff.
AIRS-Granule-120	5.60	5.07	4.91	4.39	4.30	6.79	5.20
AIRS-Granule-126	5.81	5.21	5.08	4.53	4.40	7.19	5.41
AIRS-Granule-129	5.32	4.79	4.71	4.12	4.17	6.08	4.90
AIRS-Granule-151	5.94	5.30	5.11	4.60	4.42	6.95	5.37
AIRS-Granule-16	5.40	4.89	4.81	4.18	4.22	6.71	5.06
AIRS-Granule-182	6.15	5.33	5.20	4.56	4.42	7.02	5.40
AIRS-Granule-193	5.84	5.26	5.09	4.60	4.41	7.11	5.39
AIRS-Granule-60	5.84	5.18	5.07	4.50	4.37	7.33	5.39
AIRS-Granule-82	5.16	4.67	4.59	4.09	4.17	6.39	4.94
AIRS-Granule-9	5.47	4.91	4.81	4.29	4.24	6.87	5.19
CASI-t0180f07-raw	5.51	5.22	5.19	4.80	4.78	5.23	4.93
CASI-t0477f06-raw	5.81	5.47	5.42	4.96	4.97	5.44	5.20
SFSI-Mantar_Raw	5.23	5.00	4.99	4.58	4.76	4.89	5.12
Yellowstone-Sc00-Uncalibrated-680	7.16	6.79	6.75	6.48	6.41	9.18	6.98
Yellowstone-Sc03-Uncalibrated-680	6.93	6.61	6.58	6.34	6.27	8.87	6.86
Yellowstone-Sc10-Uncalibrated-680	6.28	6.01	5.98	5.77	5.67	7.32	6.19
Yellowstone-Sc11-Uncalibrated-680	6.72	6.31	6.28	6.00	5.97	8.50	6.51
Yellowstone-Sc18-Uncalibrated-680	7.24	6.83	6.79	6.50	6.52	9.30	6.96
Maine-Uncalibrated-680	3.45	3.19	3.18	2.70	2.78	4.53	3.39
Hawaii-Uncalibrated-614	3.26	3.05	3.03	2.59	2.71	4.61	3.30
Hyperion GeoSample	5.82	5.58	5.57	4.53	4.64	5.03	4.57
Hyperion GeoSample Flat-Fielded	4.46	4.26	4.22	3.91	4.09	4.83	4.36
Average	5.65	5.22	5.15	4.68	4.67	6.64	5.30

Table VI
HYPER-SPECTRAL CALIBRATED IMAGES IN THE CCSDS TEST SET. LOSSLESS COMPRESSION RESULTS (BITS PER PIXEL PER BAND).

Image	LUT	LLUT	qLUT	FL (Arith.)	FL-Emporda	JPEG-LS	JPEG-LS Diff.
IASI-Desert	5.93	5.38	5.30	5.23	4.73	7.26	5.94
IASI-Ecosse	5.86	5.36	5.31	5.56	4.80	8.20	6.16
IASI-Pole_nord	5.41	5.07	5.02	5.23	4.62	7.40	5.87
IASI-Trop_ocean	6.17	5.54	5.48	5.30	4.79	7.54	6.10
Average	5.84	5.34	5.28	5.33	4.74	7.60	6.02

Extensive coding experiments have been conducted over a large corpus gathered by the MHDC Working Group.

From a practical point of view, FL-related techniques, the emerging MHDC Standard among them, seem to provide the best trade-off between coding performance and computational complexity.

Results reported for the open-source implementation of the MHDC Standard are very similar to those produced by the MHDC Working Group, suggesting that FL-Emporda implementation might be considered a useful reference implementation.

Open-source implementation of other remote sensing lossless coding techniques, namely LUT, LAIS-LUT, LAIS-QLUT and FL, has also taken place.

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