The CCSDS Data Compression Recommendations : Development and Status

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ABSTRACT

The Consultative Committee for Space Data Systems (CCSDS) has been engaging in recommending data compression standards for space applications. The first effort focused on a lossless scheme that was adopted in 1997. Since then, space missions benefiting from this recommendation range from deep space probes to near Earth observatories. The cost savings result not only from reduced onboard storage and reduced bandwidth, but also in ground archive of mission data. In many instances, this recommendation also enables more science data to be collected for added scientific value. Since 1998, the compression sub-panel of CCSDS has been investigating lossy image compression schemes and is currently working towards a common solution for a single recommendation. The recommendation will fulfill the requirements for remote sensing conducted on space platforms.

Keywords: Lossless data compression, lossy image compression, CCSDS, standards, space missions.

1. INTRODUCTION

1.1 CCSDS objectives and achievements

The Consultative Committee for Space Data Systems (CCSDS) [1] was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of 10 member agencies, 23 observer agencies and over 100 industrial associates. The main objectives of this committee is to define international standards that enable a better interoperability of on-board and ground systems of the various space agencies, thus reducing cost by eliminating project-unique design and by using shared facilities. The standardization work is led by 3 panels, panel 1 being in charge of space communication protocols development. In the frame of panel 1, a wide range of recommendations have been established and approved as ISO international standards, covering all the aspects of a space link from the physical layer (RF & modulation) to the application layer (source coding, file transfer, …) of the OSI model of ISO [2].

1.2 CCSDS space link protocols overview [3]

A space link is a communication link between a spacecraft and its associated ground system or between two spacecrafts. A space link protocol is a communication protocol designed to be used over a space link, or in a network that contains one or multiple space links. CCSDS has developed over the years a set of communication protocols, specifically tuned to the space links characteristics and to the operations of spacecrafts, covering : the physical, data link, network, transport and application layers. CCSDS layered approach to protocol development allows also usage of internet suite of protocols (IP, TCP, UDP, FTP) over the CCSDS data link protocols, for those missions requiring strict direct compatibility with the ground commercial infrastructure. The CCSDS space link protocols stack is depicted in figure 1-1 together with the internet stack.

Telemetry Space Data Link Protocol (TM-SDLP) is capable of sending processed telemetry efficiently using a variable length data unit called the source packet. Source packet generated by various instruments and subsystems on a spacecraft are transmitted to the ground in a stream of continuous, fixed length transfer frames. This standard has been used by over

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100 space projects enabling them to share on-board and ground data processing equipment. Based on similar concepts, Tele-command (TC) Space Data Link protocol enables sending commands to a spacecraft with a data unit known as the TC packet. TC packets destined for various instruments and subsystems on a spacecraft are transmitted from the ground in a stream of sporadic, variable length transfer frames. The AOS (Advanced Orbiting Systems) Space Data Link Protocol is an extension of TM-SDLP enabling the bi-directional transfer of both TM/TC and various types of on-line data (such as audio and video data). It is used on the International Space Station.

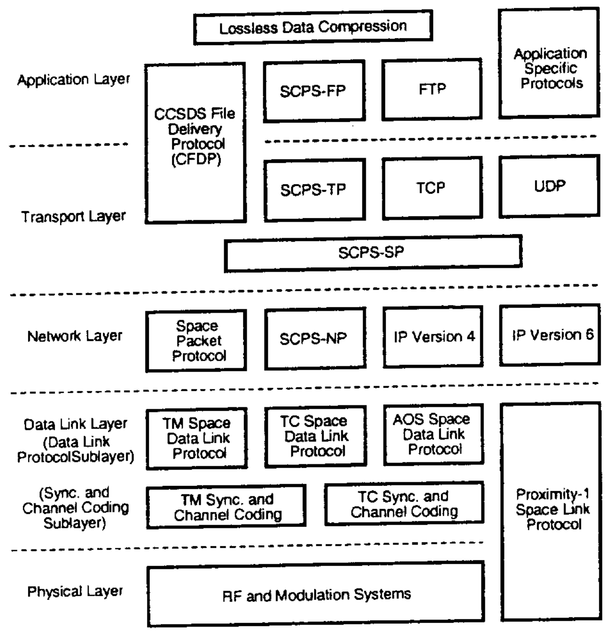


Fig. 1-1: CCSDS Space Link protocols

In the following, we will develop further the characteristics of the CCSDS compression recommendations.

1.3 CCSDS source coding recommendations

Sub-panel 1C of CCSDS is responsible for the development of source coding recommendations. From 1995 to 97, this group has developed a universal lossless data compression standard [4][5] either to increase the science return or to reduce the requirement for on-board memory, station contact time, and data archival volume. This standard has been widely used since then and is described in section 2. Since 1998, the compression sub-panel of CCSDS has been investigating lossy image compression schemes and is currently working towards a common solution for a single recommendation. The recommendation will fulfill the requirements for remote sensing conducted on space platforms. Requirements, solutions under review and performances are discussed in section 3.

2. LOSSLESS DATA COMPRESSION RECOMMENDATION

2.1 Requirements

Implementation of a recommendation for space applications differs from implementation for ground use in several aspects. These include the computation resource for software implementation, power consumption for hardware implementation, and the interface to packet data structure which provides data protection in the communication link. The requirements for the lossless compression thus were formulated:

a. The algorithm has to adapt to the changes in data statistics to maximize compression performance.
b. The algorithm must be compatible with a real time implementation while minimizing memory and power budgets.

c. The algorithm must interface with a packet data system such that each packet can be independently decoded without requiring information from other packets.

The Lossless Data Compression algorithm can be applied at the application data source or performed as a function of the on-board data system (see Figure 2-1). The performance of the data compression algorithm is independent of where it is applied. However, if the data compression algorithm is part of the on-board data system, the on-board data system will, in general, have to capture the data in a buffer. In both cases, it may be necessary to rearrange the data into appropriate sequence before applying the data compression algorithm. The purpose of rearranging data is to improve the compression ratio.

After compression has been performed, the resulting variable-length data structure is then packetized as specified in references [6] and [7]. The packets containing compressed data should be transported through a space-to-ground communication link from the source on-board a space vehicle to a data sink on the ground using a packet data system as shown in Figure 2-1.

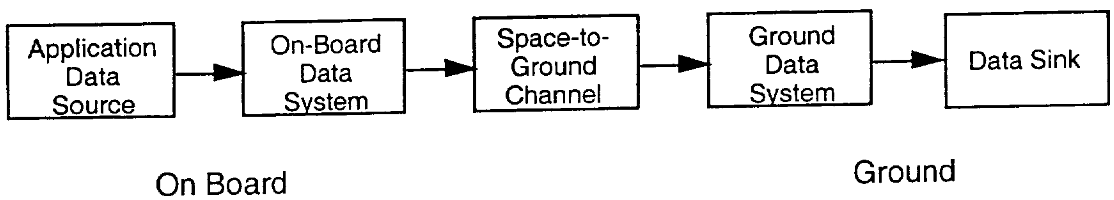


Fig. 2-1: Packet Telemetry Data System

2.2 General description

The recommendation is based on the Rice algorithm [8] with added low entropy options. The algorithm exploits a set of variable-length codes to achieve compression. Each code is nearly optimal for a particular geometrically distributed source. By using several different codes and transmitting the code identifier, the algorithm can adapt to many sources from low entropy (more compressible) to high entropy (less compressible). Because blocks of source samples are encoded independently, side information does not need to be carried across packet boundaries if de-correlation of source samples are only executed among these blocks, then the performance of the algorithm is independent of packet size.

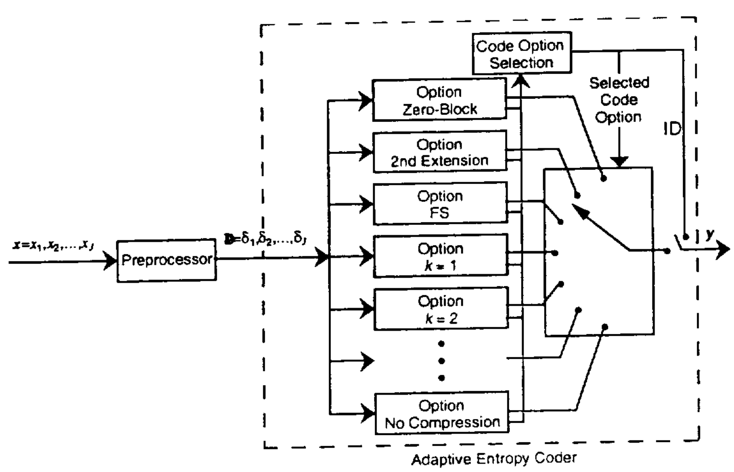


Fig. 2-2: The Encoder Architecture

A block diagram of the algorithm is shown in Figure 2-2. It consists of a preprocessor to de-correlate a block of J-sample data and subsequently map them into symbols suitable for the entropy coding stage. The entropy coding module is a collection of variable-length codes operating in parallel on blocks of J preprocessed samples. The coding option achieving the highest compression is selected for transmission, along with an ID bit pattern used to identify the option to the decoder. Because a new compression option can be selected for each block, the algorithm can adapt to changing source statistics. Although the CCSDS Recommendation specifies that the parameter J be either 8 or 16 samples per block, the preferred value is 16. The value of 16 samples per block is the result of experiments performed on several classes of science data, both imaging and non-imaging. These studies monitored the achievable compression ratio as a function of the parameter J, which was set to 8, 16, 32, and 64 samples/block for the various classes of science data. Values of J less than 16 result in a higher percentage of overhead, which yields a lower compression ratio, whereas values of J higher than 16 yield low overhead but have less adaptability to variations in source data statistics.

2.2.1 The fundamental sequence encoding

The most basic code construct in the algorithm is the *Fundamental Sequence* code which is also known as the "comma code". In this code, the codeword contains a string of "0" digits equal to the decimal value of the symbol to be coded. It then uses digit "1" to signal the end of a current codeword. This simple procedure allows FS codewords to be decoded without the use of lookup tables.

Table 2-1 illustrates the FS codewords for preprocessed sample values with n-bit dynamic range.

Preprocessed Sample Values, δ_i	FS Codeword
0	1
1	01
2	001
.	.
.	.
.	.
2^n-1	0000 . . . 00001 (2^n-1 zeros)

Table 2-1: Fundamental Sequence Codewords As a Function of the Preprocessed Samples

2.2.2 The split-sample option

Most of the options in the entropy coder are called 'split-sample options'. The k^{th} split-sample option takes a block of J preprocessed data samples, splits off the k least significant bits (LSB) from each sample and encodes the remaining higher order bits with a simple FS codeword before appending the split bits to the encoded FS data stream. This is illustrated in Table 2-2 for the case of k split bit being 0 (no split-bit), 1 or 2 on a sequence of 4-bit samples. From Table 2-2 either $k = 1$ or 2 will achieve data reduction from the original 32 bits to 29 bits. As a convention, when a tie exists, the option with smaller k value is chosen. In this case, $k = 1$ will be selected. When a block of J samples are coded with one split-sample option, the k split bits from each sample are concatenated.

Each split-sample option in the algorithm is designed to produce compressed data with an increment in the code word length of about 1 bit/sample (approximately k + 1.5 to k + 2.5 bits/sample) [5]; the code option yielding the fewest encoded bits will be chosen for each block by the option-select logic. This option selection process assures that the block will be coded with the best available code option on the same block of data, but this does not necessarily imply that the source entropy lies in that range. The actual source entropy value could be lower; the source statistics and the effectiveness of the preprocessing stage determine how closely entropy can be approached.

Sample Values	4-bit Binary Representation	FS Code, $k = 0$	$k = 1$ 1 LSB + FS Code	$k = 2$ 2 LSB + FS Code
8	1000	000000001	0 00001	00 001
7	0111	00000001	1 0001	11 01
1	0001	01	1 1	01 1
4	0100	00001	0 001	00 01
2	0010	001	0 01	10 1
5	0101	000001	1 001	01 01
0	0000	1	0 1	00 1
3	0011	0001	1 01	11 1
Total Bits	32	38	29	29

Table 2-2: Examples of Split-Sample Options Using Fundamental Sequence Codes

2.3 Performance comparison

Performance comparison between the CCSDS recommendation and other available lossless compression schemes can be rather straightforward if implementation constraints are not taken into account. In the CCSDS packet data architecture, potential error propagation is minimized by compressing either a scan line of data or a trace of sensor data and then insert the compressed bit string in an independent packet. In Table 2-3, the coded bits-per-pixel (bpp) obtained at different condition is listed for several data files by using the current recommendation, the well-known LZW algorithm [9] and the new JPEG-LS [10] algorithm.

Four types of sample data are used. The first spot-panchromatic data represents high entropy, high-resolution (10m panchromatic) ground observation imaging data from the SPOT satellite. The second example represents very low entropy star field data taken from the wide-field-planetary-camera (WFPC) on the Hubble Space Telescope (HST). These two images are shown later in Figure 3-4 as part of the test set for lossy image compression work. The third example is from the acousto-optical spectrometer on the Submillimeter Wave Astronomy Satellite (SWAS). The spectrometer waveforms are shown in Figure 2-3. The fourth example is from a lidar instrument to be flown on the Geoscience Laser Altimeter System (GLAS), only 10 traces are used in the test. Two are depicted in Figure 2-4.

In the comparison, the *unix compress* (based on LZW algorithm) is applied to the whole data set or to each line to simulate independent compression for error containment by using packet data structure for each line. The current JPEG-LS requires 2D data, thus for the last two examples, the data are treated as though they were 2D. The CCSDS compression is applied using either a 1D or 2D predictor.

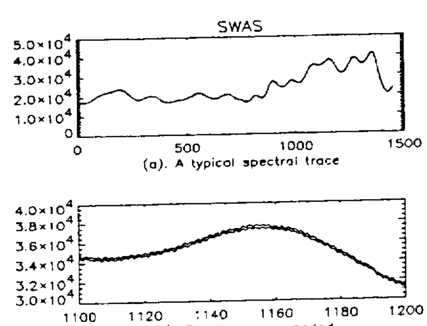


Figure 2-3: AOS traces

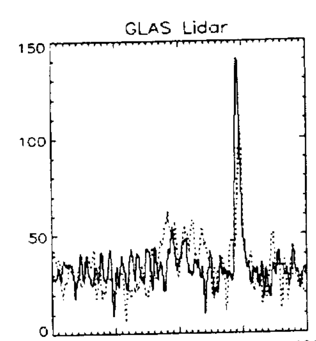


Figure 2-4: Two traces from the Lidar instrument

Test File	LZW bpp (line-based/ file-based)	JPEG-LS bpp	CCSDS bpp (1D/2D predictor)
Spot_panchr (1000x1000, 8-bit)	9.09/7.24	4.00	4.85/4.43
Wfpc (800x800, 12-bit)	5.38/3.63	3.63	4.05/3.78
AOS traces (1450x2, 16-bit)	16/16.00	9.08	10.10/6.90
Laser altimeter traces (352x10, 8-bit)	7.34/6.10	4.23	4.16/4.99

Table 2-3: Coded bpp obtained at different conditions

2.5 Implementation and applications

Both software implementation and hardware implementation exist today. Software implementation is normally applied when the processing throughput requirement is relatively low and when onboard processor can afford the processing load, and such are typical for a range of deep space probes. Near Earth missions are usually characterized by high speed requirement in excess of 10 Msamples/sec, for which implementations in radiation tolerant application specific integrated circuit (ASIC) or field programmable gate arrays are much more suitable. Table 2-4 contains a list of known space applications that have or will have benefited from this recommendation.

Mission	Launch	Lead Agency	Implementation
SERTS-97 (Sounding Rocket)	11/97	NASA/GSFC	HW
COBRA	/97	DOE/USA	HW
LEWIS/SSTI	0/97	NASA	HW
CASSINI CDA	10/97	NASA/JPL	SW upload after launch
SWAS/SMEX-3	01/99	NASA/GSFC	SW
KOMPSAT-1	/99	KARI	HW
IMAGE/MIDEX-1	02/00	NASA/JPL	SW
THEMIS/Mars Odyssey	04/01	NASA/JPL	HW
MAP/MIDEX-2	07/01	NASA/GSFC	SW
EOS-CHEM/AURA	/02	NASA/GSFC	HW
VCL/ESSP-01		NASA/GSFC	HW
ROSETTA	01/03	ESA	HW
SBIRS	Multiple	DOD/USA	HW
INTEGRAL SPI	/03	CNES	SW
MESSENGER MLA	/03	NASA/GSFC	SW
GIFTS/EO-3	/04	NASA/LaRC	HW
PICARD	/05	CNES	SW/DSP
NPP	/	NOAA/NASA	HW
NGST	/	NASA/GSFC	HW
ESDIS/HDF --archive	/03	NASA/GSFC	SW

Table 2-4 CCSDS Lossless Data Compression Applications

3. LOSSY IMAGE COMPRESSION DEVELOPMENT

3.1 Requirements

In 1998, the CCSDS sub-panel 1C initiated a new work item to investigate the feasibility of establishing a recommendation for lossy data compression for future space sensors. To limit the scope of the work, the compression was first considered only for 2D image data, with the understanding that the recommendation could be applicable to higher dimensional sensor data, like multi or hyper-spectral data. Subsequently a set of requirements for the algorithm was agreed upon and is listed in Table 3-1.

1	Offer royalty free license to all CCSDS space agencies if any patent is included in the algorithm	Optional
2	Process both frame and non-frame (push-broom) data	Mandatory
3	Offer adjustable coded data rate or image quality (up to a lossless mode)	Mandatory
4	Work over large quantization range (4 to16-bit input pixels)	Mandatory
5	Offer real-time processing with space qualified electronics (over 20 Msamples/sec, less than 1 watt/Msamples/sec)	Mandatory
6	Provide progressive transmission (either resolution or PSNR progressive)	Optional
7	Require minimum ground operation	Mandatory
8	Allow for error containment within a small image area, in case of an uncorrected channel error	Mandatory

Table 3-1: Lossy Image Compression Requirements

The real-time processing requirement in item 5 is based on currently (year 2000, 2001) available radiation tolerant circuit fabrication technology. As space science technology advances with time, the quoted processing speed and power consumption need to be adjusted.

A set of test images was also collected. This test set contains a wide range of space-borne imagery ranging from very low activity scene collected from the faint-object-camera on the Hubble Space Telescope, to some extreme high entropy data from the SPOT or synthetic aperture radar (SAR). Two of them are shown in Figure 3-4.

3.2 Candidate algorithms

Candidate algorithms were submitted from the three space agencies, CNES, ESA and NASA. After several iterations of test on the image data set, currently two categories of algorithm remain. The first employs a transform (wavelet or lapped transform) followed by a bit plane encoder; and the second uses a wavelet transform followed by a rate controlled quantizer and an entropy coder. Top level description for each is provided in the following sections.

3.2.1 Transform with Bit Plane Encoder

Figure 3-1 depicts the architecture of this scheme. The de-correlator can be a Discrete Wavelet Transform (DWT) or a lapped transform. The bit plane encoder provides progressive transmission and its construct is similar to SPHIT coder [11], but utilizes inter-band correlation for coding. The entropy coder utilizes the CCSDS lossless recommendation.

ESA has proposed a so-called Local Wavelet Transform, LWT as the de-correlator. In brief, it performs a normal DWT on a whole image, but instead of processing one level of resolution at a time, it starts the processing of the next resolution level as soon as sufficient data is available. After the processing of the first 15 lines a set of 8 x 8 blocks of de-composed samples coming from the first 8 image lines become available for further processing by the next stage of the coder, being the Bit Plane Encoder, BPE. This method of processing allows also strip processing for push-broom imaging instruments and it also provides ways to limit error propagation.

Alternatively, NASA has proposed a Modulated Lapped Transform (MLT) [12] as the de-correlator for its potential for fast processing. The MLT proposed is a size 8 transform with a window size of 16 (overlapping 4 pixels to the right and 4 pixels to the left of the 8-size block). The output of each block will be a size 8x8 transform coefficient block.

The bit plane encoder takes the 8 x 8 transform domain components grouped into three family trees, each has one parent, four children and sixteen grand children as shown in Figure 3-2. The magnitudes of components are scanned for any most significant bit (MSB) on the scanned bit plane. This bit plane scanning proceeds from the top most bit plane downward, thus inherently accomplishes a quantization by a factor of 2 in succession. The positional information of those identified components is represented by a family tree structure and may be further coded for efficiency. This information along with their sign information are shifted to the output bit string from higher bit planes to lower bit planes.

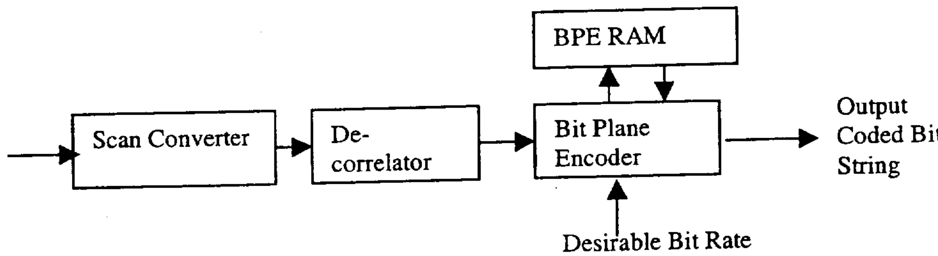


Figure 3-1 Functional Diagram of the Coder

The output bit string constitutes an embedded data format that allows progressive transmission and decoding to start at lower bpp rate, and proceed to higher bpp. The bit string can be terminated at any desirable rate for precise control of output data rate. With this scheme, lossless compression can be achieved if the LWT is an integer wavelet.

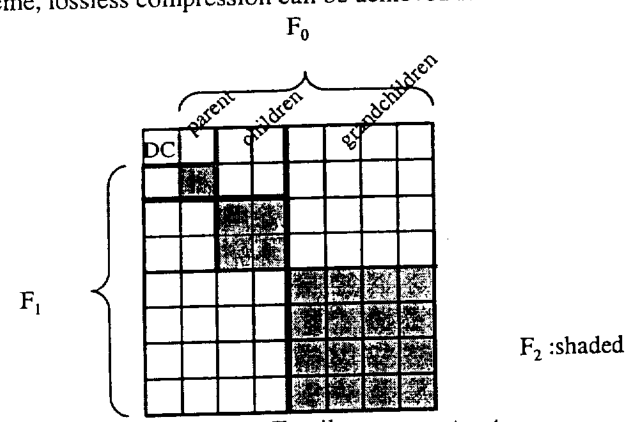


Figure 3-2: Family tree construct

3.2.2 DWT with rate-controlled quantizer

Fig 3-3 depicts the architecture of this scheme. This algorithm has been developed by CNES in collaboration with I3S/CNRS laboratory [13]. It will be used on the PLEIADES-HR mission which is a very high resolution (0.7 m) earth observation system. It is composed of a decorrelator, a quantizer. an entropy coder and a rate regulation providing a fixed rate output according to a compression ratio (CR) directive given by the user. The main characteristics of those 4 modules are the following :

Decorrelator : decorrelation is performed by a scan-based wavelet transform. The wavelet base used is the bi-orthogonal (9,7) with 3 level of decomposition giving a total of 10 subbands at the output. The advantage of wavelet based compression is that the entire image can be filtered without being broken into sub-blocks as required in DCT compression schemes. This full image filtering eliminates the block artifacts seen in DCT compression and offers more graceful image degradation at high compression ratio. The rate-distortion performance of wavelet based schemes is also superior to DCT based ones. Wavelet representations differ in their choice of wavelet. Bi-orthogonal wavelets have been chosen for their symmetry, perfect reconstruction and linear phase. We have compared some bi-orthogonal wavelet filters on some representative images and concluded that (9-7) Daubechies bi-orthogonal filters are the best ones [14].
To facilitate the real time implementation of the DWT at the very high rates (typical of high resolution earth remote sensing missions), the lifting scheme is used to reduce the complexity of the transform in terms of number of operations

per pixel. This leads to a speed-up of 1.9, compared to the standard implementation of the wavelet filters by convolution. Further information on the lifting scheme may be found in [15].
A scan-based (or line-based) implementation of the wavelet transform is being used. This line-based approach avoids the complete buffering of the image before the wavelet transform can be performed, this complete buffering being incompatible with on-board memory limitation. The basic idea is to perform part of the transformation after each line is received. Filtering along lines is performed on the fly when a line is read at the input. Filtering along columns is performed as soon as n transformed lines are available, with n=9 in the case of the 9-7 filters. The size of the buffer required for the decomposition on one resolution level is n=9 lines. This principle can be generalized for more than one resolution level by introducing a buffer at each resolution level. Due to subsampling, its size is half the size of the buffer at the previous resolution. Since we have chosen 3 decomposition levels, the steady state output of such an implementation is composed of sequence of "8 lines of wavelet coefficients", named a Line Of Blocks (LOB). This scan -based implementation provides the same transformed coefficients as the traditional wavelet transform.

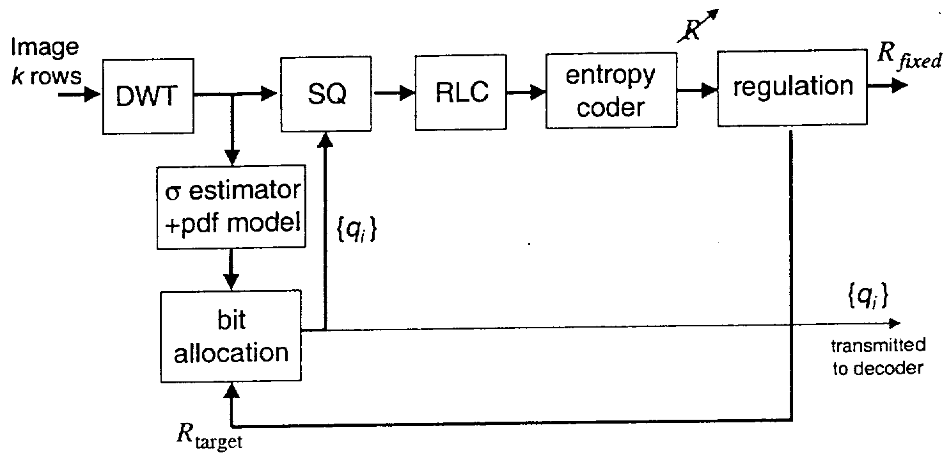


Fig. 3-3: Block diagram of the DWT CNES algorithm

Quantizer : the quantization is scalar and uniform, since a variable-length coder is being used. The quantization step q(i,n) to be used for each sub-band(i) of the 10 sub-bands of a LOB(n), is computed for each LOB by the bit allocation procedure (see fig.3-3) which performs optimal bit allocation (i.e. : minimal distortion under overall rate constraint) between the 10 sub-bands.

Entropy coder : the entropy coder is two-stage : first a Run-Length Coding (RLC) is performed on each sub-band of a LOB, followed by a Huffman coding of the run-length symbols. Therefore, each sub-band is coded separately with a very simple and efficient technique. Scanning order of each sub-band is directional, i.e. : vertical contours are scan vertically, resp. horizontal and diagonal, to favor long runs of zeros. This coding technique provides an output rate almost equal to the entropy of the quantized coefficients. Huffman tables of the Run-Length symbols are stable and therefore well suited for on-board compression.

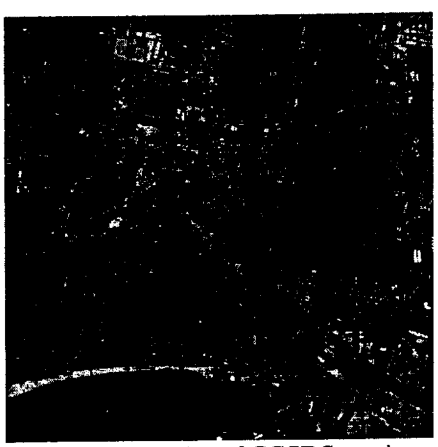
Rate regulation : in most space-borne and high rate applications, a fixed output bit rate from the compression unit is desirable since transmission to ground is fixed rate. To achieve that, a rate regulation has to be performed since variable length coding is being used. Rate regulation is composed of two parts : a small rate regulation buffer (typically 10 image lines in size) combined with a simple rate control loop, and a bit allocation procedure. The rate control loop will derive, for each LOB(n), from the filling level of the regulation buffer, a target rate ($R_{target}(n)$). The rate control loop can be a classical Proportional Integral (PI) with appropriate parameters. The bit allocation is the one of EBWIC [16]. It allocates the target rate $R_{target}(n)$ among the ten sub-bands of LOB(n) according to the variance of each sub-band, in such a way that minimal distortion (rmse) for the overall LOB is achieved. Sub-bands probability density functions (pdf's) are modeled by Genaralized-Gaussian Densities (GGD) : $p(x) = a.e^{-|b.x|^{\alpha}}$ where a, b, α are computed from the variance and the kurtosis of the sub-band. This GGD model provides a rate and a distortion model for each sub-band. Therefore, the rate constrained problem of bit allocation can be written in the form of Lagrangian operators. Solving this Langragian gives the set of quantization steps (q(i,n)) to be used for each sub-band(i) of LOB(n). This efficient bit allocation is central to the performance of the overall compression scheme.

3.3 Performance comparison

These two candidate algorithms have been compared both quantitatively (in terms of rmse and maximum absolute error), visually (to search for specific artifacts) and w.r.t. specific applications of remote sensing images (e.g. : content classification from multispectral images). They also have been compared to JPEG2000 which is a reference in terms of rate-distortion performance. The algorithms are designated by : "DWT+BPE" for the "Wavelet Transform with Bit Plane Encoder", "DWT CNES" for the "Wavelet Transform with rate-controlled quantizer". The "MLT+BPE" (Modulated Lapped Transform with Bit Plane Encoder) gives very similar results to the "DWT+BPE" scheme. It is therefore not mentioned in the comparative table 3-2.

These comparisons have been performed in the following conditions :

- We have used a set of 20 reference images. These images are representative of the various types of images that can be acquired by a space-borne instrument (high resolution earth observation, solar, stellar, meteorological, synthetic aperture radar, planetary, ...). Dynamic ranges from 8-bit to 16-bit per pixel images. Two examples are given in fig. 3-4.
- We have used 4 pre-defined rates which cover the complete range of compression ratio potentially usable by a space-borne compression : 2.0, 1.0, 0.5 and 0.25 bpp.
- The algorithms have been compared in a scan-based mode which is typical of missions where push-broom and high rate instruments are being used. The two CCSDS candidate algorithms are inherently scan-based (also they can operate in frame-based mode). For JPEG2000, we are using the scan-based mode which has been introduced in the standard by SAIC and CNES. The size of the scan element is 8 lines across swath for the 2 CCSDS candidates. Each scan element is compressed independently from the others. For JPEG2000, we used for the comparison 8-line precincts, precincts being the area of the image on which rate-distortion optimization is being done.



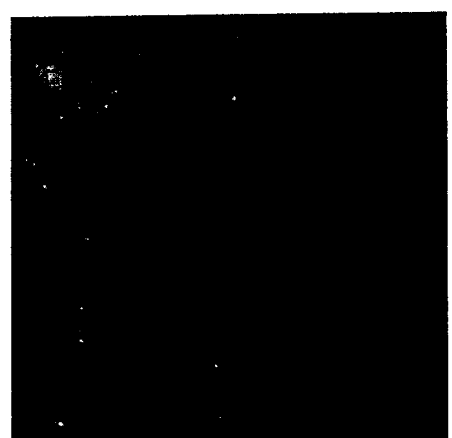


Figure 3-4 : Examples of CCSDS test images : SPOT panchromatic image and Wide Field Planetary Camera image

Table 3-2 gives the average PSNR and Max Absolute Error for the 3 algorithms over the CCSDS test image set. It shows that the 3 algorithms are very close in terms of performances over the full range of rates, image dynamics and contents. Visually also, it is very hard to distinguish between the three, since they are all three based on wavelet transform and tends to create the same type of artifacts. Overall, the performances evaluation (quantitative, visual and applicative) did not enable CCSDS group to decide between the three. Implementation complexity was a more decisive criteria. In particular, ASIC implementation analysis showed that JPEG2000 EBCOT coder was at least a factor two more complex than the two coders of the CCSDS candidate algorithms. Therefore, JPEG2000 algorithm compliance with requirement 5 of table 3-1 (real-time processing with space electronics) was considered questionable.

Rate (bpp)	Average PSNR (dB)			Average Max Absolute Error		
	DWT CNES	DWT+BPE	JPEG2000	DWT CNES	DWT+BPE	JPEG2000
8-bit images						
2.0	42.35	41.03	41.47	11.60	15.40	13.20
1.0	36.49	35.63	35.52	26.60	29.80	32.20
0.5	32.53	32.30	32.06	52.60	51.80	52.80
0.25	30.40	29.83	29.48	74.40	80.00	89.20
10-bit images						
2.0	54.87	54.47	54.92	18.40	24.20	18.30
1.0	48.10	47.69	47.80	49.10	58.50	53.90
0.5	43.42	42.98	42.90	107.20	96.60	113.20
0.25	40.01	39.36	39.32	210.00	187.60	195.30
12-bit images						
2.0	66.90	65.75	66.49	24.00	28.70	22.70
1.0	61.79	61.19	61.20	50.00	50.00	46.30
0.5	58.92	58.58	58.48	87.00	79.00	83.70
0.25	56.92	56.60	56.29	159.00	146.30	139.30

Table 3-2 : Quantitative comparison of CCSDS candidate algorithms and JPEG2000 in scan-based mode

3.4 Complexity comparison

Implementation complexity is a major issue for space applications due to the requirement for processing speed and power consumption, in addition to the limitations imposed by radiation tolerance on space electronics. Traditional complexity analysis based on the number of multiplications, additions and conditional *if* –statement for software implementation usually does not apply well when ASIC is contemplated. In ASIC design, often it is more important to maintain pipeline processing than to reduce number crunching. Parallelism is a common practice in ASIC design, but is detrimental to conventional sequential computing. Thus it becomes difficult to assess complexity for the proposed algorithms without embarking on realistic implementation development. Instead, we provide the following facts and development status on the major functional blocks:

(1) De-correlator

LWT (ESA) : The LWT has been the subject of a detailed design in view of its implementation in an ASIC. Constraints related to memory budget minimisation while keeping a high throughput have been fully respected in this exercise. A complete compressor embedding the LWT has been produced and mapped on a high end configurable FPGA. This allowed to derive a throughput figure better than 14 Msamples/s at a conservative clock rate of 50 MHz. An ASIC called "FlexWave" will now be produced on this basis.

MLT (NASA) : a radiation tolerant ASIC to perform up to 16-bit hybrid 2D transform (1D in MLT, 1D in DCT) was fabricated in 2000. The chip will process over 27 Msamples/sec at 0.12watts/Msamples/sec.

DWT (CNES) : a radiation tolerant ASIC to perform a (9-7) DWT at 20 Msamples/s on up to 16-bit precision pixels is entering design for the PLEIADES-HR mission, after a feasibility study has shown the possibility to integrate the complete DWT CNES algorithm (apart from the rate regulation and bit allocation functions) on a single 1 Mgates ASIC. Power consumption of this ASIC is estimated at 0.15 watt/Msample/sec.

(2) Entropy Coder

BPE (NASA) : the bit plane encoder is well under design (70% design complete) and is expected to process at 20 Msamples/sec at lower than 0.15watts/Msamples/sec. The throughput speed is limited by the currently available rad-hard BPE external RAM with access time of 20 Msamples/sec.

Quantizer/Entropy Coder (CNES) : quantizer is very simple since it is a scalar uniform quantizer. Entropy coder is composed of a Run-Length Coder (RLC) followed by a Huffman coder. Those two are very similar to the classical JPEG encoder. A radiation tolerant ASIC has been developed for SPOT5 satellite to perform "RLC+Huffman" coding. This ASIC (called EQCF) is now in flight. Its characteristics are the following (1997 technology) : 12 Msamples/s, less than 0.1 watt/Msample/sec.

3.5 Status

Currently, details of the above algorithms have been documented in a White Book. The CCSDS compression panel is working towards making a decision to either select a single algorithm for space agencies or to adopt the 2 candidate algorithms described. Software exchange has been initiated to cross-validate performance for each algorithm. The 2002 Fall meeting in Houston, Texas will hopefully accomplish the objective.

4. CONCLUSION

The lossless data compression algorithm recommended by CCSDS has benefited many space missions by either reducing bandwidth, onboard storage requirement, or by increasing science data return. The percentage data reduction may not be the best achievable considering all other available techniques; however, its simplicity and adaptivity does allow high-speed space implementation and applicability to not only image data, but data emanating from the vast diversity of instruments including interferometer, altimeter and spectrometer.

The lossy image data compression effort is currently in the last stage of development for a final selection. The candidates can be applied to high-speed push-broom data or framed image data. They provide a very good "complexity-performance" compromise which is of specific importance for space-borne implementations. The selection will enable future cross-support between agencies and reduce the overhead associated with each space mission having to develop its own compression scheme.

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