The New CCSDS Image Compression Recommendation

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Abstract— The Consultative Committee for Space Data Systems (CCSDS) data compression working group has recently adopted a recommendation for image data compression, with a final release expected in 2005. The algorithm adopted in the recommendation consists of a two-dimensional discrete wavelet transform of the image, followed by progressive bit-plane coding of the transformed data. The algorithm can provide both lossless and lossy compression, and allows a user to directly control the compressed data volume or the fidelity with which the wavelet-transformed data can be reconstructed. The algorithm is suitable for both frame-based image data and scan-based sensor data, and has applications for near-Earth and deep-space missions. The standard will be accompanied by free software sources on a future web site. An Application-Specific Integrated Circuit (ASIC) implementation of the compressor is currently under development. This paper describes the compression algorithm along with the requirements that drove the selection of the algorithm. Performance results and comparisons with other compressors are given for a test set of space images.

1. INTRODUCTION

The benefits of data compression to space missions include increasing the ability to collect science data, and reductions in onboard storage and telemetry bandwidth requirements. Because of these benefits, the Consultative Committee for Space Data Systems (CCSDS) has been engaged in recommending data compression standards for space applications.

The first CCSDS data compression recommendation, adopted in 1997, standardized a version of the lossless Rice compression algorithm [1]. Space missions benefiting from this recommendation range from deep space probes to near Earth observatories.

In 1998, the CCSDS data compression working group began to assess the feasibility of establishing an image compression recommendation suitable for spaceborne applications. The working group agreed that a suitable compressor must meet the requirements listed in Table 1, which were intended to reflect the envisioned application for real-time hardware compression onboard a spacecraft.

Table 1. CCSDS Image Data Compression Requirements

1	Process both frame and non-frame (push-broom) data
2	Offer adjustable coded data rate or image quality (up to a lossless mode)
3	Accommodate from 4-bit up to 16-bit input pixels
4	Provide real-time processing with space qualified electronics (≥20 Msamples/sec, ≤1 watt/Msamples/sec, based on year 2000 space electronics technology)
5	Require minimum ground operation
6	Limit the effects of a packet loss to a small region of the image.

Apart from the requirements listed in Table 1, perhaps the biggest consideration in the algorithm selection process was to optimize rate-distortion performance. The ability to perform progressive compression was viewed as a highly desirable feature, but not mandatory. It was the hope of the working group that if any patents were included in the recommendation, a royalty-free license could be offered to all CCSDS member agencies.

The working group also assembled a set of 20 test images ranging from Earth observations to star field, galaxies and solar images. The dynamic ranges of the test images include 8-bit, 10-bit, 12-bit and a 16-bit radar image.

Candidate algorithms were proposed, and performance evaluations were conducted based on both quantitative rate-distortion evaluations and subjective assessments of image quality. In addition, implementation architecture studies were performed to assess the real-time processing capabilities of the proposed algorithms. A consensus was reached in 2003, and a wavelet-based compression algorithm was selected. The selected algorithm combined

[1]Research performed by Yeh for this paper was conducted for the U. S. Government. Portions of the research described in this paper were carried out by Kiely at Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronatuics and Space Administration.

elements from different algorithms that were initially proposed, along with modifications to reduce complexity.

In Section 2, we describe the compression algorithm. Compression performance results of the algorithm on the test images are given in Section 3. Section 4 describes the current status of the recommendation.

2. ALGORITHM DESCRIPTION

The recommended algorithm consists of two functional modules as depicted in Figure 1: a Discrete Wavelet Transform (DWT) module that performs decorrelation, and a Bit-Plane-Encoder (BPE) that encodes the decorrelated data. This general image compression approach is widely used, see, for example, references [2, 3, 4].

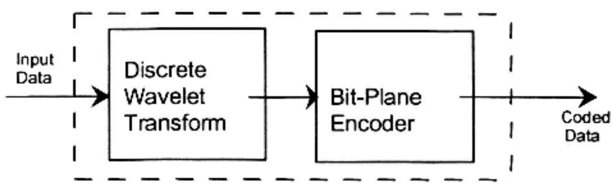


Figure 1 - The Two Functional Modules of the Algorithm

2.1 Discrete Wavelet Transform

The recommendation specifies two DWTs that may be used. When applied to one-dimensional data, both transforms effectively use 9 filter taps to compute low-pass output, and 7 filter taps to compute high-pass output. Each filter is thus referred to as a "9/7" DWT under the usual naming convention. The two filters differ in the need for floating-point arithmetic. The floating-point filter [4] requires floating-point calculations and gives improved performance at low bit rates, while the integer filter [5] permits lossless compression and requires no floating-point operations. There are many variations in methods for computing integer and floating point 9/7 DWTs, and the reader is encouraged to refer to [6] for exact specifications of the forward and inverse transforms that are to be used with this recommendation.

A single-stage two-dimensional DWT is computed by first applying the one-dimensional DWT to the rows of the image, and then to the columns of the transformed image, as illustrated in Figure 2. Subsequent stages of decomposition are applied to the low-pass horizontal / low-pass vertical subband output from the previous stage, producing the pyramidal decomposition described in [7]. The standard calls for 3 stages of DWT decomposition, decomposing an image into 10 subbands, as illustrated in Figure 3. Fewer than three levels of DWT decomposition would yield smaller blocks with less intra-block correlation to exploit with the applied entropy coding. More than three levels would be expensive to implement in hardware, due to the larger dimensions of each block and the more extensive code tables required.

The BPE described in Section 2.2 is used to encode the subbands produced by the two-dimensional DWT decomposition. For effective operation, the BPE relies on the same bit plane in each of the subbands having the same relative priority in terms of contribution to overall image distortion. For the integer transform, this requires the subbands to be scaled. The scaling factors are chosen to be powers of two so that scaling can be performed using bit-

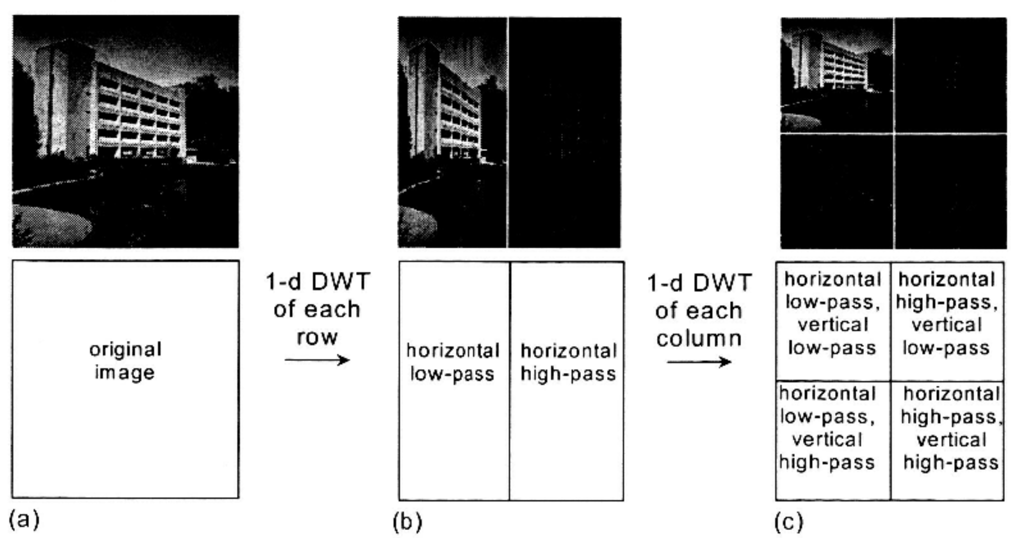


Figure 2 - Single Level Two-Dimensional DWT Decomposition of an Image

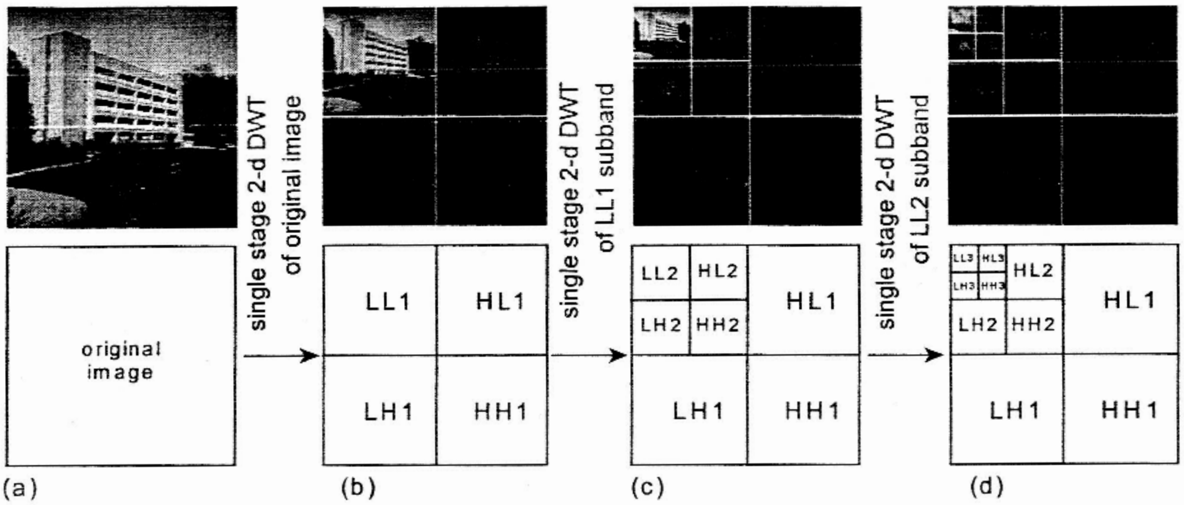


Figure 3 – Example of 3-Level Two-Dimensional DWT Decomposition of an Image

shift operations. Under the floating-point DWT, no scaling is performed, but DWT coefficients are rounded to the nearest integer.

2.2 Bit Plane Encoder

The Bit Plane Encoder (BPE) processes wavelet coefficients in groups of 64 coefficients referred to as a *block*. A block loosely corresponds to a localized region in the original image. A block consists of a single coefficient from the lowest spatial frequency subband, referred to as the *DC coefficient*, and 63 *AC coefficients*, as illustrated in Figure 4. Blocks are processed in raster scan order, i.e., rows of blocks are processed from top to bottom, and proceeding from left to right horizontally within a row.

This structure is used to jointly encode information pertaining to groups of coefficients within the block because they exhibit significant statistical correlation. Corresponding parent, children and grandchild coefficients are correlated in that their absolute values usually decrease in that order. They are further correlated in the sense that the binary words that describe updates to sets of coefficients are not distributed uniformly.

A *segment* is defined as a group of consecutive blocks. Coding of DWT coefficients proceeds segment-by-segment and each segment is coded independently of the others. The number of blocks in a segment can be assigned by the user to any value between 16 and 2^{20} inclusive; the value might be chosen based on the memory available to store the segment. Segments with many blocks have the desirable property of producing a code stream which is embedded globally. This means that the distortion of the decompressed image will be uniform on a global scale despite the inevitable presence of locally variable compressibility. Segments with few blocks on the other hand are convenient to implement by requiring small code buffer sizes.

Within a segment, the BPE first encodes a quantized version of the DC coefficients for the segment by applying the Rice coding algorithm to differences between successive quantized coefficients. Bits providing further DC coefficient resolution are included as part of the subsequent bit-plane coding process.

Next, the BPE successively encodes bit planes of coefficient magnitudes in a segment, proceeding from most-significant to least-significant bit plane, inserting AC coefficient sign bit values at appropriate points in the encoded data stream. The resulting encoded bitstream constitutes an embedded data format that provides progressive transmission within a segment; DWT coefficient resolution effectively improves by a factor of 2 as encoding proceeds from one bit plane to the next.

Coefficients within a block are arranged in groups, each with at most 4 coefficients. Conceptually, at a given bit plane, a binary word can be used to describe an update to each coefficient in the group for which all more significant magnitude bits are zero. These words are entropy coded using one of a handful of variable-length binary codes; the specific code is selected adaptively. The entropy coded data are arranged so that all parent coefficients in the segment are updated first, followed by children, and then grandchildren coefficients. Finally, the segment includes (uncompressed) update bits for the coefficients in the segment for which more significant magnitude bits are not all zero.

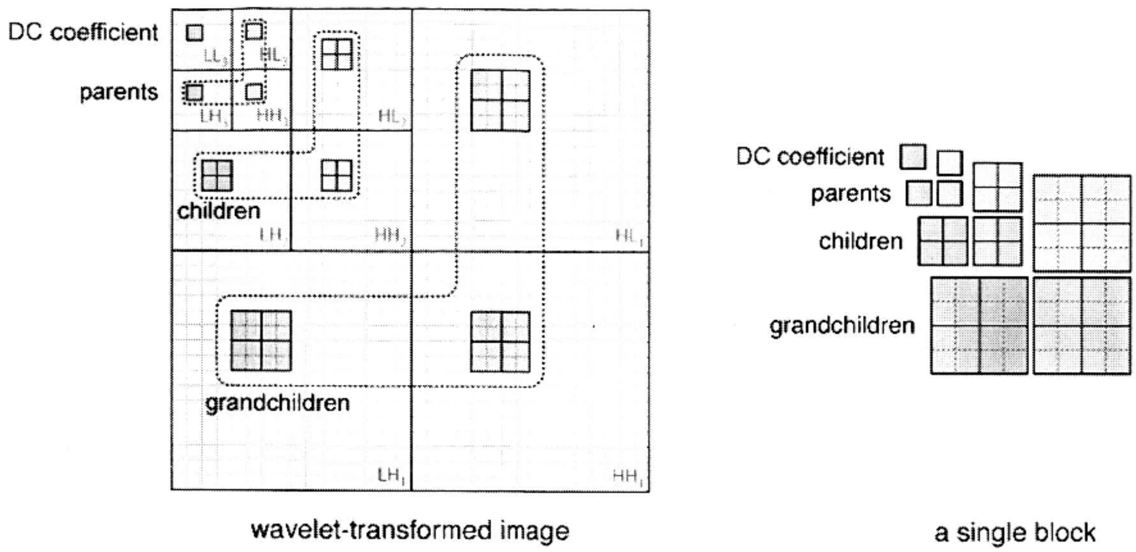


Figure 4 - In this schematic of a wavelet-transformed image, the 64 shaded pixels comprise a single block.

The tradeoff between reconstructed image quality and compressed data volume for each segment can be controlled by specifying the maximum number of bytes in each compressed segment, and a "quality" limit that constrains the amount of DWT coefficient information to be encoded. Compressed output for a segment is produced until the byte limit or quality limit is reached, whichever comes first. The encoded bitstream for a segment can be further truncated (or, equivalently, coding can be terminated early) at any point to further reduce the data rate, at the price of reduced image quality for the corresponding segment.

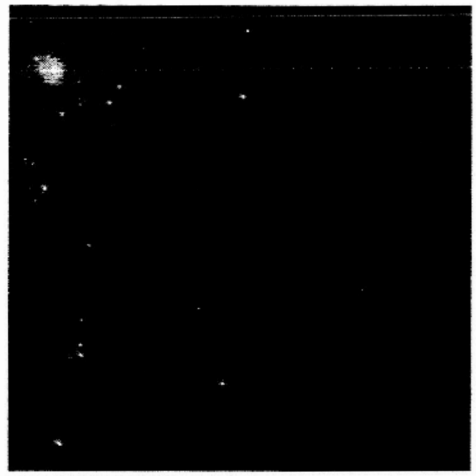
3. PERFORMANCE

The quantitative performance of the new recommendation has been evaluated on the test image available at http://www.ccsds.org/docu/dscgi/ds.py/View/Collection-613 with image size and depth information summarized in Table 2. The set of images has widely varying statistics as can be seen from two examples given in Figure 5.

Table 2. List of Test Images

Image	Source	Size	Bits/ pixel
Mars	Mars Pathfinder: Sojourner	512x512	8
Spot_band1/band2 /band3	SPOT Imaging	500x500	8
Spot_panchromatic band	SPOT Imaging	1000x1000	8
Forest band1/band4	NOAA Polar Orbiter	2048x2048	10
Ice band1/band4	NOAA Polar Orbiter	2048x2048	10
India band1/band4	NOAA Polar Orbiter	2048x2048	10
North Atlantic Band1/band4	NOAA Polar Orbiter	1024x1024	10
Ocean band1/band4	NOAA Polar Orbiter	2048x2048	10
Solar	Big Bear Solar Observatory	1024x1024	12
Sunspot	Big Bear Solar Observatory	512x512	12
WFPC	Hubble Space Telescope	800x800	12
FOC	Hubble Space Telescope	1024x512	12
SAR	ERS-1	512x512	16

(a)



(b)

Figure 5 - Examples of Test Images: (a) SPOT Panchromatic Image and (b) Wide Field Planetary Camera Image

As an indication of compression performance, we compare the two DWT options of the recommendation with the JPEG2000 standard when used with the 9/7 floating-point DWT. For this comparison, we simulate performance for "push-broom" spacecraft compression applications. In the case of the CCSDS recommendation, this means defining a segment of blocks to correspond to the image width, and imposing a fixed rate constraint on each compressed segment. Similar constraints are imposed on the JPEG2000 coder by using the scan-based mode introduced by SAIC and CNES with 8-line precincts [8]. We evaluated the performance at bit rates ranging from 1/4 up to 2 bits/pixel.

Table 3 shows the Peak-Signal-To-Noise Ratio (PSNR) in dB and the maximum absolute error averaged over images with the same dynamic range. It is seen from these results that the new CCSDS recommendation has performance similar to that of the JPEG2000 standard when both methods use the floating point 9/7 DWT under the "push-broom" constraints described above. As one might expect, use of the integer 9/7 DWT results in more than 1 dB loss in performance at higher bit rates.

Implementation complexity played a significant role in the final algorithm selection. In particular, an early analysis of ASIC implementation complexity suggested that the JPEG2000 coder was at least a factor of two more complex than other coding options being considered. For spacecraft applications, this could have a significant impact on the achievable processing rate.

4. STATUS

A first version draft of the new image compression recommendation (known as a *red book* in CCSDS parlance) has been approved for agency review.[2] The data compression working group will issue a second draft after taking into account review comments from different agencies. Following agency review of the second red book, it is expected that a formal recommendation, (a *blue book*), will be released in 2005.

The compression working group is also producing a *green book* which is not part of the recommendation, but will serve as an user's guide for implementers. The green book will cover subjects such as system issues relating to error propagation and rate control, implementation schemes for wavelet transform using localized transform, and detailed study results.

Several implementations are being pursued concurrently both for the purpose of validating the recommendation, and also to provide a technology demonstration for space implementation. Software implementations have been produced at JPL and GSFC. Additional software implementations are under development at the University of Idaho, in an effort led by Prof. Gary Maki, and the

[2] The CCSDS web site, www.ccsds.org, describes the meaning of the different books and includes downloadable versions of CCSDS recommendations.

Table 3. Performance Comparison for Push-Broom Mode

Rate (bits/pixel)	PSNR (dB)			Maximum Absolute Error		
	Floating -point DWT	Integer DWT	JPEG2000	Floating-point DWT	Integer DWT	JPEG2000
Average for 8-bit images						
2.00	41.37	40.22	41.47	18.00	15.20	13.20
1.00	35.76	35.18	35.52	34.40	29.00	32.20
0.50	32.37	31.95	32.06	60.60	52.20	52.80
0.25	29.89	29.50	29.48	93.40	81.80	89.20
Average for 10-bit images						
2.00	54.70	53.26	54.92	26.00	23.50	18.30
1.00	47.76	47.10	47.80	63.20	53.40	53.90
0.50	42.97	42.60	42.90	115.50	95.10	113.20
0.25	39.36	39.12	39.32	204.80	188.30	195.30
Average for 12-bit images						
2.00	65.93	64.30	66.49	33.33	28.00	22.70
1.00	61.18	60.17	61.20	59.00	50.67	46.30
0.50	58.57	57.87	58.48	88.67	78.67	83.70
0.25	56.62	56.12	56.29	142.00	141.33	139.30

University of Nebraska in an effort led by Prof. Khalid Sayood. These codecs are written in C and are in the process of cross-verification. A JAVA implementation based on earlier documentation was developed at the University of Barcelona under the direction of Prof. Joan Serra. This version did not include the full BPE specification for pattern coding, but could be used to estimate performance. A hardware ASIC implementation is being developed at the University of Idaho's Center for Advanced Microelectronics and Biomolecular Research (CAMBR) facility[3] where the Radiation-Hardness-By-Design (RHBD) technique [9] has been developed and is being applied to the algorithm to produce high-speed space-qualified circuits. The projected throughput is over 20 Msamples/sec. This implementation separates the DWT and BPE into two ASICs.

The software development and verification is expected to be completed before the publication of the green book, which will then include an open-source website for users to download and execute the codes. The ASIC flight hardware will be available commercially.

5. CONCLUSION

The CCSDS data compression working group has finalized an algorithm for image data compression, intended for onboard compression. The algorithm yields nearly the demanding rate-distortion performance of the commercial JPEG2000 standard but significantly alleviates on-board implementation complexity. On-board operation has been eased by relieving the user of selecting data-dependent encoding tables for optimum compression performance.

The recommendation makes use of 9/7 DWTs. An integer DWT can be used for applications requiring lossless compression, good performance at high rates, or to avoid floating point operations in the DWT calculation. A floating-point DWT can be used for improved performance at low bit rates.

The DWT is followed by a bit-plane encoder that produces an encoded bitstream providing progressive transmission within a coded segment.

The algorithm is applicable to a variety of imaging instruments, and is suitable for push-broom sensors requiring immediate processing of data.

The final recommendation is expected to be released in 2005. An open source C software implementation is

[3] www.cambr.uidaho.edu

expected to be available soon, and an ASIC hardware implementation is currently under development.

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