Testing JPEG 2000 Compression for Earth Science Data

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Abstract- **The scan-based implementation of JPEG 2000 Parts 1 and 2, which has been developed by SAIC for use with Earth Science data, is being tested on a variety of images from NASA satellites and similar instruments. Electro-optical, thermal, radar, multispectral, and hyperspectral data sets are included. The test script computes statistical quality criteria, such as mean-squared-error (MSE), maximum absolute error (MAXAE), and peak signal-to-noise ratio (PSNR) over a range of compression ratios. Subjective tests, such as visual image quality assessment and task-oriented testing, are also planned. In this paper, we summarize the first results and present some image quality examples.**

I. BACKGROUND

JPEG 2000 is the new international standard for image data compression, recently defined by the International Standards Organization (ISO). Part 1 of the standard, ISO/IEC 15444-1, is the Core Coding System containing the features that all decoders must support, in order to be called JPEG 2000 compliant. JPEG 2000 Part 2, ISO/IEC 15444-2, includes many optional features that are useful for special applications, including the downlink and archiving of Earth Science data.

Fig. 1 is a flow diagram of the JPEG 2000 algorithm. The component transform is used for three-color or for multi-spectral/hyperspectral data, to perform decorrelation in the wavelength dimension. The wavelet transform performs de-correlation in the two spatial dimensions. The quantizer is the principal source of "lossiness" in compression, while the entropy coder is lossless. Finally, the rate controller ensures that the desired compression ratio is reached.

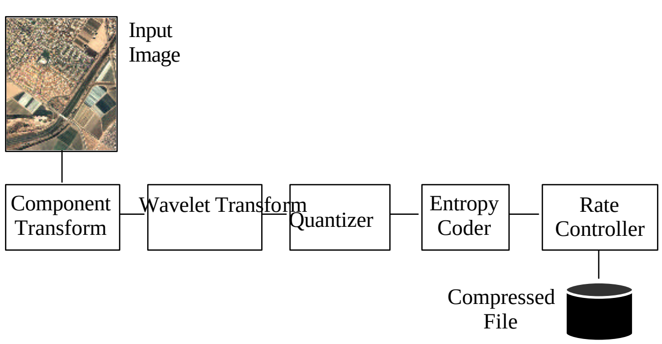

Fig. 1. Flow diagram of the JPEG 2000 encoder.

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Under a contract with the Earth Science Technology Office (ESTO), Science Applications International Corporation (SAIC) is developing a low-memory version of JPEG 2000, including both Part 1 and Part 2 features, for use in future Earth Science Enterprise (ESE) missions. The software, based on the JPEG 2000 Verification Model (VM), was completed in the first year of this project. It compresses the image on a tile-by-tile or precinct-by-precinct basis (a precinct is an area in the wavelet domain that corresponds to a location in the image domain), where a tile or precinct may contain as few as eight image lines. The Part 2 features activated in this implementation (also known as the scan-based mode or the Skylark VM) include arbitrary wavelet filters and decomposition structures, single sample overlap wavelet transforms, wavelet or linear transforms in the wavelength dimension, and trellis-coded quantization. These features and their importance for remote sensing applications are described in detail in our contribution to ESTC 2001 [1].

II. THE TEST PLAN

The goals of this testing program are:

- To verify that the scan-based implementation of JPEG 2000 (including Part 2 features) will operate in a satisfactory manner on all types of Earth Science data – panchromatic (EO), thermal infrared (IR), multispectral (MSI), hyperspectral (HSI), and synthetic aperture radar (SAR).
- To determine the maximum compression ratio that can be applied to various data sets while retaining the information required for scientific investigations.
- To compare the performance of scan-based JPEG 2000 with that of other compression algorithms, including frame-based JPEG 2000, baseline JPEG, SPIHT, and others being used or considered for NASA missions.

The environment is a Linux-based PC running at 1.2 GHz, and similar UNIX-based workstations. Each image is compressed losslessly by scan-based JPEG 2000, using the 5x3 reversible wavelet filter. The compressed file size and compression ratio are measured, for comparison with other algorithms capable of lossless compression.

Lossy compression is performed using the irreversible 9x7 wavelet filter and the Mallat decomposition; however, for SAR data the 10x18 wavelet filter and the packet decomposition are used. For MSI, no component transform is used because the optimum transform would be sensor-specific. For HSI, the component transform is either a wavelet or a linear predictor. Both scalar quantization (SQ) and trellis-coded quantization (TCQ) are being tested. The number of quality layers is one, six, and generic. Each image is compressed to bit rates of 2.0, 1.0, 0.50, 0.25, 0,125, and 0.0625 bits per pixel (bpp), corresponding to compression ratios of 4-128 for 8-bit data, or 8-256 for 16-bit data. The following parameters are computed: mean-squared error, root-mean-squared error, mean absolute error, maximum absolute error, mean error, and peak signal-to-noise ratio.

The scan-based mode of JPEG 2000 is used with a range of precinct heights from 8 to 64 lines. One case using tiles will also be computed, with and without single-sample overlap (SSO). Comparisons will be made with frame-based JPEG 2000 and, where feasible, with baseline JPEG, SPIHT, and other algorithms proposed by NASA. Visual quality evaluations and task-oriented evaluations are also planned.

Table 1 lists the images that have been included in the test set up to this time. They are taken from the JPEG 2000 test set, the test images of the Consultative Committee on Space Data Systems (CCSDS), and various high-quality multispectral images that we have on hand or were able to obtain from the relevant Web sites. We plan to add some SAR images from the JERS-1 Global Rain Forest Mapping Project, and some hyperspectral data obtained by AVIRIS and Hyperion, in the near future.

TABLE 1
TEST IMAGE SET

Name	Instru-ment	# Bands	Resolu-tion	Size	Bit Depth	Date
Panchromatic						
Aerial 1	Airborne		?	14565x14680	8	?
Aerial 2	Airborne		?	2048x2048	8	?
Spot LA	SPOT		10m	1000x1000	8	?
Hungary	Landsat 7		15m	10000x10000	8	26/9/99
Camp Lejeune	Landsat 7		15m	9400x10400	8	4/5/00
Kamchatka	Ikonos		1m	5500x10028	12	6/9/00
Russia	Ikonos		1m	5000x5000	12	12/6/00
Thermal IR						
Camp Lejeune	Landsat 7		60m	2350x2600	8	4/5/00
Hungary	Landsat 7		60m	2500x2500	8	26/9/99
SAR						
Pentagon	Airborne		?	1024x1024	16	?
Stadium	Airborne		?	800x800	12	?
MSI						
New So. Wales	MODIS	7	500m	2708x4080	12	26/4/01
Cape York	MODIS	7	500m	2708x4060	12	21/8/00
Florida	MODIS	7	500m	2708x4060	12	19/2/01
Boston	MODIS	7	500m	2708x4060	12	2/5/01
Hungary	Landsat 7	6	30m	5000x5000	8	26/9/99
Camp Lejeune	Landsat 7	6	30m	4700x5200	8	4/5/01
Phoenix	Ikonos	4	4m	4100x4300	12	21/12/00
Yuma	Ikonos	4	4m	5600x4800	12	13/4/01
Spot LA	SPOT	3	20m	500x500	8	?
Forest	AVHRR	2	1.1km	2048x2048	10	?
Ice	AVHRR	2	1.1km	2048x2048	10	?
India	AVHRR	2	1.1km	2048x2048	10	?
No. Atlantic	AVHRR	2	1.1km	1024x1024	10	?

III. TEST RESULTS

In this section we present a sample of the results obtained with the test program as of this writing (1 May 2002). Additional results may be available at the time of the conference.

A. Lossless Compression

One of the principal advantages of JPEG 2000 over previous compression methods is the ability to perform both lossless and lossy compression with a single algorithm. Lossless compression is obtained by using a reversible integer 5x3 wavelet filter, followed by the entropy coder. No explicit quantization is used, but lossy compression can be obtained from a losslessly encoded file by truncating the bitstream at the appropriate point. This unique capability is important for data base management, where the archive is lossless but a client may require only a lower quality image.

Table 2 gives the lossless compression ratios for all the images that have been tested to date. In accordance with our previous experience, the highest compression ratios are obtained with thermal infrared data (in this case, Band 6 on Landsat 7), and the lowest compression ratios occur in SAR imagery, where the clutter is extremely difficult to compress. We plan to compare our results with those from JPEG-LS, an algorithm designed specifically for lossless compression and not capable of lossy compression.

TABLE 2
LOSSLESS COMPRESSION RATIOS

Name	Ratio
Panchromatic	
Aerial 1	2.21
Aerial 2	1.45
Spot LA	1.88
Hungary	2.44
Camp Lejeune	2.55
Kamchatka	1.73
Russia	2.07
Thermal IR	
Camp Lejeune	3.92
Hungary	3.63
SAR	
Pentagon	1.20
Stadium	1.50
MSI	
New South Wales	1.56
Cape York	1.70
Florida	1.52
Boston	1.64
Hungary	2.18
Camp Lejeune	2.49
Phoenix	1.68
Yuma	1.66
Spot LA	1.59
Forest	2.45
Ice	2.45
India	2.23
North Atlantic	1.90
Ocean	2.27

B. Lossy Compression

As described in the test plan, all the images currently in the test set (except for the SAR images) have been compressed using the irreversible 9x7 wavelet filter and the Mallat decomposition tree. The size of the scan elements (in image lines) and the number of quality layers were varied. TCQ was used for all image types, and SQ was also used on the panchromatic images, for comparison. The multispectral images were compressed using the multiple component feature of JPEG 2000, which performs rate control across all bands, but no component transform was used. The hyperspectral data sets have not yet been tested. The statistical parameters listed in the test plan were computed as a function of compressed bit rate. To date, we have examined only the PSNR statistic as a function of various parameters. This quantity is defined as:

$$PSNR = 10 \log_{10} \frac{\left(2^B - 1\right)^2}{MSE} , \qquad (1)$$

where B is the bit depth of the image pixels and MSE is the mean-squared-error, that is, the average of the squared difference between pixel values in the original image and the decompressed image. Fig. 2 shows the variation of PSNR as a function of bit rate (or compression ratio) for the four MODIS images in the test set. Each curve represents the average of seven wavelength bands in a single image, since we observed very little band-to-band difference. These results represent the case of 8-line scan elements and a single quality layer, which we take as the baseline.

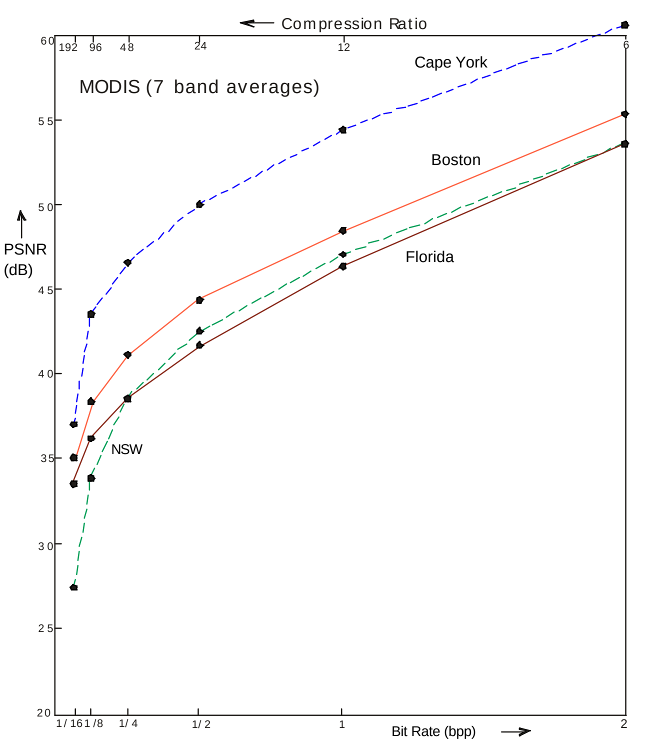


Fig. 2. PSNR as a function of bit rate (or compression ratio) for four MODIS images.

According to Taubman and Marcellin [2], well reconstructed images typically have PSNR values of 30 dB or more. Taking a more conservative threshold of 40 dB, we would expect the MODIS images to be well reconstructed above bit rates of 0.25 to 0.5 bits per pixel (bpp), corresponding to compression ratios of 24 to 48.

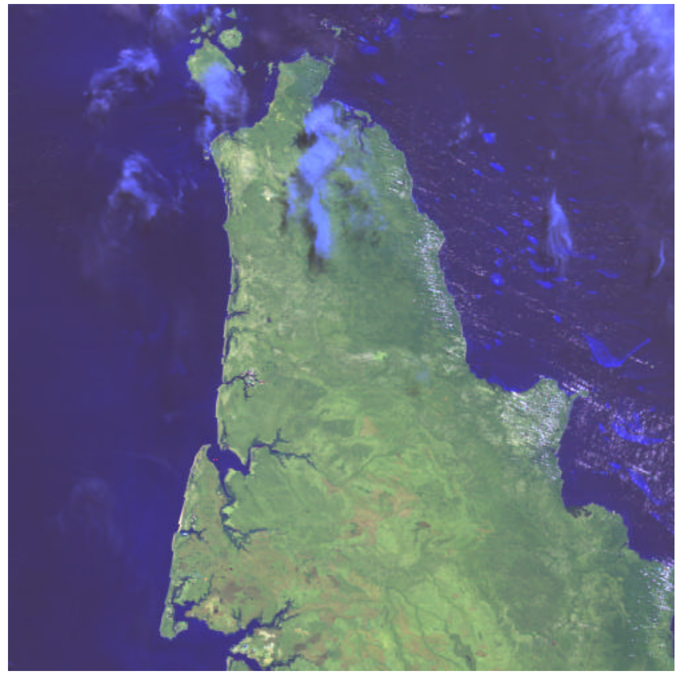
In Fig. 3, we can see how visual image quality varies as a function of bit rate or compression ratio. This montage of four renderings of a 512 x 512 chip from the MODIS Cape York image presents (a) the uncompressed image; (b) decompressed from 2.0 bpp; (c) decompressed from 0.5 bpp; and (d) decompressed from 0.125 bpp. The 2.0 bpp image (compression ratio 6) is virtually indistinguishable from the original, as is the 1.0 bpp image (not shown, compression ratio 12). The 0.5 bpp image (compression ratio 24) is a little smoother than the original but is free from artifacts. The 0.25 bpp image (not shown; compression ratio 48) is even smoother and exhibits some artifacts. The 0.125 bpp (compression ratio 96) contains examples of strong wavelet artifacts.

C. Variations in the Test Procedure

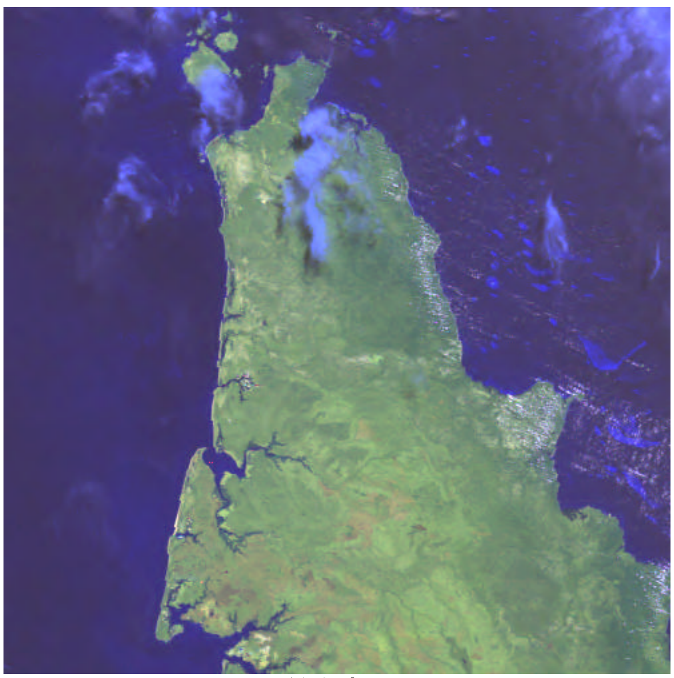
As indicated in the test plan, several factors were varied during the testing in order to determine their effect on image quality. The first of these was scan element (precinct) size. Scan elements corresponding to 8, 16, 32, and 64 image lines were tested for all images. The 8-line scan element corresponds to the lowest memory usage, while the 64-line scan element is the largest to show any difference from the full-frame version of JPEG 2000. An examination of the results for the seven panchromatic images reveals that the loss in PSNR between 64-line scan elements and 8-line scan elements is typically less than 0.5 dB from 2.0 bpp down to 0.25 bpp; but at 0.125 and 0.0625 bpp, the difference can be 1 dB or even more. This loss at very low bit rates is due to the increased overhead required to signal large numbers of small scan elements — overhead which requires a disproportionate fraction of the file size at very low bit rates.

A second feature to be varied was the number of quality layers used in compression. One of the most valuable features of JPEG 2000 is the possibility of re-ordering the compressed file so as to change the progression of the data for transmission. JPEG 2000 supports four progression orders: progression by resolution, by quality, by location, and by component. The scan-based mode compresses the image data in location order. In order to have the capability of re-ordering the codestream for future transmission in quality progression order, a number of quality layers must be signaled during compression. This additional signaling produces a small loss in compression efficiency, again due to the increased overhead. In our test procedure, we used a single layer (i.e., no progression by quality), six layers (a practical intermediate stage), and the “generic” mode of 50 layers. Again, an examination of the results for the seven

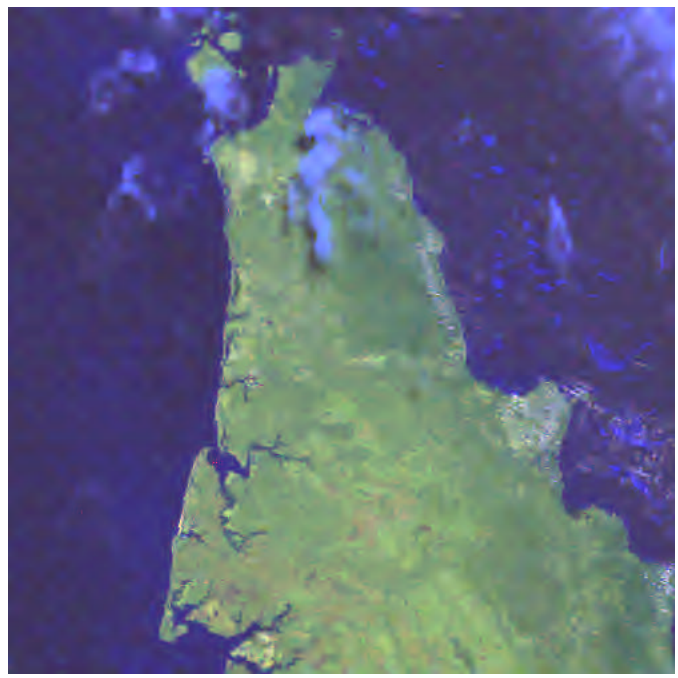
(a) Original (12 bpp)



(b) 2.0 bpp



(c) 0.5 bpp



(d) 0.125 bpp

Fig. 3. Original and three compressed/decompressed versions of a chip from the MODIS Cape York image. MODIS bands 7, 6, 4 were used to create the false color pictures.

panchromatic images indicates that the cost of adding the extra layers is generally less than 0.5 dB, although there are some exceptions. There is no clear trend with bit rate or scan element size.

Finally, we compressed the panchromatic images using SQ instead of TCQ, keeping all other parameters the same. Fig. 4 shows the comparison for two images: Russia, a 12-bit Ikonos image, and Camp Lejeune, an 8-bit image from the Landsat 7 panchromatic sensor. The baseline configuration of 8-line scan elements, single layer was used. We see that SQ gives very slightly better results at low bit rates, due to the overhead required to signal the TCQ step sizes. But TCQ is better at 1.0 bpp and above, reaching an advantage of about 1 dB at 2.0 bpp. This result is in line with our previous experience, and should produce a noticeable difference in image quality between the two quantizers.

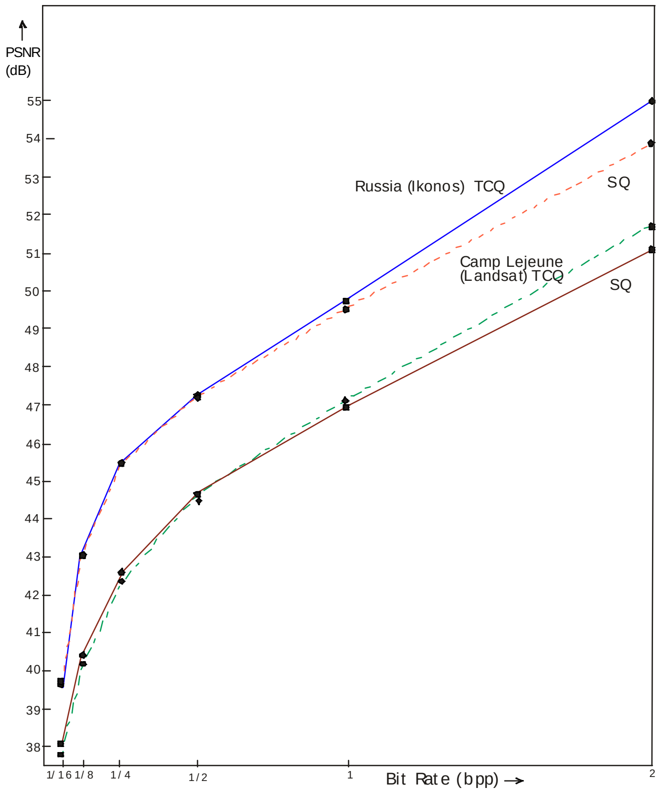


Fig. 4. Comparison between TCQ and SQ for two panchromatic images.

IV. CONCLUSIONS AND FUTURE PLANS

We are in the process of running an extensive test program on the scan-based implementation of JPEG 2000, Parts 1 and 2, which we have developed under contract to ESTO. A preliminary analysis of the statistical results indicates that this algorithm is useful for many types of Earth Science imagery, including panchromatic, thermal IR, SAR, multispectral and hyperspectral data. Good image quality should be obtained at bit rates of 0.5 to 2.0 bpp (compression ratios of 4 to 32), and usable image quality at even higher compression ratios. Lossless compression is also possible.

The next step is to port the scan-based JPEG 2000 software from the laboratory environment to a flight simulation environment, and to repeat the tests under more realistic conditions. Our goal is to raise the Technology Readiness Level (TRL) of this implementation from TRL 3 to TRL 5.

REFERENCES

[1] J. Rountree, B. Webb, T. Flohr, M. Marcellin, "Optimized compression for earth science data using JPEG 2000," *Proc. Earth Science Technology Conference 2001*, NP-2001-8-338-GSFC, Greenbelt, MD, August 2001.

[2] D. Taubman, M. Marcellin, *JPEG 2000: Image Compression Fundamentals, Standards and Practice*, Boston: Kluwer, 2002, p. 6.