JPEG2000 Encoding of Remote Sensing Multispectral Images with No-Data Regions

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***Abstract*—Most sensors used for Remote Sensing (RS) purposes capture more than one component to seize different features from the earth surface. Usually, multispectral images acquired for RS applications are either corrected, or the user/application determines valid regions within the image. Consequently, regions without information may emerge (*no-data* regions). This letter proposes to encode multispectral images with no-data regions through the JPEG2000 framework taking into account the lack of importance of these irrelevant regions. Experimental results, performed on data from real scenarios, suggest that the best approach analyzed is a Shape-Adaptive (SA) KLT to decorrelate the spectral redundancy, and then shape-adaptive multi-component JPEG2000. The coding performance improvement over other coding systems considered (BISK, SA WDR, and SA TARP) is from 5dB to 20dB in SNR Energy.**

***Index Terms*—No-data region coding, shape-adaptive, JPEG2000, decorrelation transform, KLT, remote sensing**

I. Introduction

Nowadays, digital images are an important source of data to enhance the abilities of devices and applications for Remote Sensing (RS). Consequently, storage capability, manipulation, and transmission of these images have become an important issue [1]. Most sensors capture images containing multiple components. In some cases, images contain regions without useful data, here named as *no-data* regions. In RS there are three main situations where no-data regions arise: 1) geometric and radiometric corrections are devised to improve the accuracy of the images acquired; 2) atmospheric events can cover large regions of the earth surface (*e.g.* clouds); and 3) regions of interest are determined by the user/application. Shape-Adaptive (SA) coding systems are able to encode only certain regions of any arbitrary shape within the image (see [2]), making them suitable to deal with no-data regions.

In the literature, several coding approaches for multispectral images containing no-data regions have been presented. On one hand, there are SA two-dimensional (2D) coding systems extended to its three-dimensional (3D) generalization. In [3]–[5] three different SA 3D coding systems are introduced: 3D-OB-SPIHT, 3D-OB-SPECK, and 3D-BISK, the latter yielding the best coding performance, because BISK [6] is a coding system specifically devised to handle no-data regions. Also, TARP [7] and WDR [8] can be generalized to a 3D SA version. Nevertheless, 3D coding systems entail some shortcomings: the Bitplane Encoder (BPE) does not allow component scalability and the whole image must be encoded at a time, causing a high computational resources requirement. On the other hand, as a second approach for encoding no-data multispectral images, in [9] and [10] each component is encoded independently from the others through a SA 2D coding system, and then a rate-control step is performed. This strategy allows quality and component scalability, a more efficient use of the resources (encoding one single component at a time in memory constrained systems), and, finally, the encoding of all components could be parallelised in hardware schemes.

JPEG2000 [11] is one of the latest standards developed by the Joint Photographic Experts Group (JPEG), structured in 13 different parts, addressing the encoding, transmission, security, and manipulation of images and video. Part 1 [12] of the standard is the basis of the other parts. JPEG2000 is a wavelet-based coding scheme composed of a two-tiered coding system built on the Embedded Block Coding with Optimized Truncation (EBCOT) [13] paradigm. JPEG2000 benefits from the Post Compression Rate Distortion (PCRD), defined in EBCOT, that combines the bit-streams from code-blocks minimizing the overall error. Among other features, the JPEG2000 core coding system provides scalability by quality, spatial location, resolution, and component. These types of scalability fulfill most of the requirements of remote sensing applications; nevertheless, approaches to eliminate the cost of coding no-data regions are not considered in JPEG2000 standard. In order to add support for shape-adaptive coding to JPEG2000 for mono-component images containing no-data regions, in [14] we proposed several pre-processing techniques and modifications to JPEG2000 coding stages. Results suggested that the use of a shape-adaptive approach clearly outperforms the other evaluated approaches. Later, in [15], a shape-adaptive version of JPEG2000 was compared to BISK [6] and to SA-SPIHT [16], again with SA-JPEG2000 yielding the best coding performance.

The main idea of this letter is to develop a 2D encoding scheme followed by a rate-control method for multispectral images containing no-data regions through

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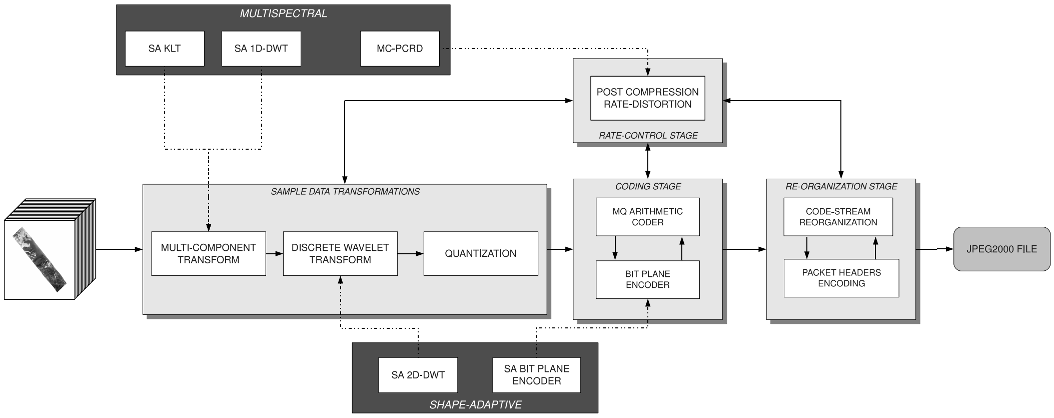

Figure 1. Main stages of the JPEG2000 core coding system in light gray: Sample Data Transformations Stage, Coding Stage, Re-organization Stage, and Rate-Control Stage. Dark gray boxes indicate our approaches and modifications introduced to allow the SA encoding of multispectral images.

the JPEG2000 framework, named as shape-adaptive multi-component JPEG2000 (SA-MC-JPEG2000). The scheme may apply two different decorrelation approaches to take advantage of the similarity among components, and avoids the cost of coding no-data regions, extending the modifications applied to the JPEG2000 in [14] and [15] to the multi-component scenario, thus achieving high coding performance results.

This letter is structured as follows: Section II introduces the decorrelations and modifications carried out over JPEG2000 encoding scheme to encode multispectral images containing no-data regions; Section III presents the data set, and assesses the coding performance reporting several experimental results performed on data from real applications; and in Section IV we draw some conclusions.

II. Shape-Adaptive Multi-Component JPEG2000

JPEG2000 core coding system consists of four main stages depicted in Figure 1 (in light gray). The *Sample Data Transformations* Stage is devised to compact the image energy, decorrelating the image through the Multi-Component transform and the Discrete Wavelet Transform (DWT). The *Coding* Stage encodes the coefficients from the Most Significant Bitplane (MSB) to the Least Significant Bitplane (LSB) using a fractional Bitplane Encoder (BPE) based on EBCOT. The main function of the *Rate-Control* Stage is to manage the bit-rate and/or the distortion of the final code-stream produced by the coding system; the PCRD is the most popular method to conduct this optimization process, using the bit-rate and the distortion to pose the optimization problem. Finally, the *Re-organization* Stage organizes the final code-stream in containers that encapsulate and sort the bit-stream segments using one or several progression orders.

Figure 1 presents our proposal, depicting in dark gray the decorrelation approaches and modifications carried out over the JPEG2000 main stages. On one hand, two modifications to JPEG2000 are needed to avoid completely the cost of coding no-data regions: a shape-adaptive version of the Discrete Wavelet Transform (SA 2D-DWT) is implemented, and a SA BPE is performed to encode only the coefficients that correspond to the data regions. These modifications are detailed in Section II-A. On the other hand, in Section II-B, two different transformations are considered in the Multi-Component Transform step to decorrelate the spectral redundancy of multispectral images: one-dimensional DWT (1D-DWT), and the Karhunen-Loêve Transform (KLT). Also, in the Rate-Control stage, a Multi-Component PCRD (MC-PCRD) is considered to combine the bit-stream from each component, minimizing the overall distortion.

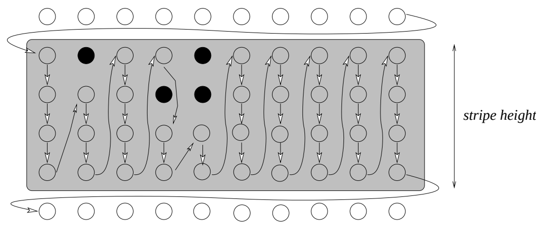

Figure 2. Scanning order skipping no-data coefficients. Coefficients corresponding to the no-data regions are depicted in black.

A. Shape-Adaptive Encoding of No-Data Regions

An issue that comes up when applying the DWT to an image is what happens at the image boundaries, i.e. how to deal with the non-existent samples –those samples outside the image– needed for the application of the filter-bank. This is commonly addressed carrying out a mirror effect that virtually extends the image boundaries. The main idea behind the SA DWT technique is to apply a mirror effect at the boundaries of the data region [17]. In addition to the SA 2D-DWT, the BPE is also modified to avoid the coding of no-data coefficients by skipping them in the fractional bitplane encoder of the Coding Stage; this modification is straightforward (see Figure 2).

B. Encoding of Multispectral Images

Two different approaches to exploit the spectral redundancy are considered: a SA one-dimensional DWT [1] approach; and a SA version of the KLT (SA KLT), because

KLT is the transform known to produce the best results for most situations [18], in particular it is optimal for Gaussian sources. The first approach is named as SA 1D-DWT; the second approach is named as SA 1D-KLT. For both approaches, a SA 2D-DWT may be applied in the spatial domain. In [18], several approaches to decorrelate the spatial and spectral domains in RS images are studied to improve the coding efficiency.

To allow scalability by quality, we must organize the information in the code-stream in decreasing order of importance. After the application of a 2D coding system, a Rate-Control stage is needed to combine all components' bit-streams. The PCRD optimization procedure of EBCOT produces a rate-distortion optimal code-stream for a single component image. However, there are several ways that this single component truncation procedure can be extended to the multispectral case. In [1] three different strategies have been evaluated: 1) Band Independent Fixed-Rate (BIFR) encodes each band independently and assigns identical rate to all bands; 2) Band Independent Rate Allocation (BIRA) also codes each component independently, however, rates are allocated explicitly so that more important components are encoded with higher rate; 3) MC-PCRD performs the PCRD optimization across multiple components simultaneously, performing to the maximum of its potential and yielding the best coding performance. The MC-PCRD rate-control method is thus selected for the experiments.

III. Experimental Results

A. Data Set

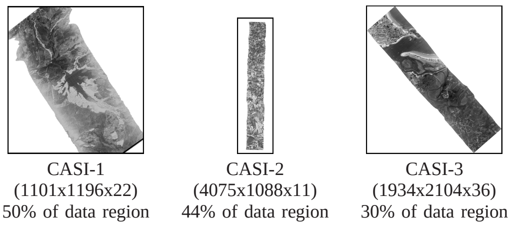

Figure 3. Image set obtained with the CASI sensor. White areas depict no-data regions. Percentage of data region is provided.

The proposed scheme has been tested using an image set devised for RS real scenario, provided by ICC [19], and acquired through the Compact Airborne Spectrographic Imager (CASI) sensor that can be programmed to obtain a maximum of 288 bands from red to near infrared. All images are from Spain. The set is composed of three images (CASI-1, CASI-2, CASI-3) with a bit-depth of 16 bits per sample per component (bpspc). The lines captured by the sensor are affected by the movement of the airplane; therefore, it is necessary to geometrically correct the image and, as a consequence, no-data regions arise. First image used is CASI-1, a flight over Toledo, devised to capture the main spectral features of water. Second image, CASI-2, is a flight over Lleida, devised to capture the features of vegetation and farming for agriculture purposes. The third image, CASI-3, is a flight over Cantabria, devised to capture distinct features from the earth surface. Names, dimensions, and percentage of data region of each image are given in Figure 3.

B. Coding Performance

The SA-MC-JPEG2000 has been implemented in our JPEG2000 Part 1 and Part 2 implementation BOI [20]. These tests have been carried out using either SA 1D-DWT or SA 1D-KLT as a spectral decorrelation approach. For all the experiments, in the spatial domain, 5 levels of DWT have been applied; in the spectral domain, the DWT number of levels depends on the total number of components: up to 5 levels have been applied. To evaluate the coding performance results over different images, *Signal-to-Noise Ratio (SNR) Energy* has been computed, only for data regions, at different bit-rates equivalently spaced. It is defined as: SNR Energy $= 10 * log_{10} \frac{E^2}{MSE}$, where $E = \sum_{i=1}^{\#samples} x_i^2$ is the energy of the image (with x_i an image sample) and MSE is the *Mean Squared Error*.

The first experiment pretends to evaluate the coding performance, in SNR Energy, achieved by our MC-JPEG2000 software when decorrelation transforms (1D-DWT and 1D-KLT) are applied to an image composed of 11 components. Figure 4 shows a comparison between applying a spectral decorrelation followed by MC-JPEG2000 against the application of a plain MC-JPEG2000 without spectral decorrelation, the former providing a superior coding performance. We can also see in Figure 4 that the choice of the spectral decorrelation has an important effect in the final coding performance, 1D-KLT providing superior results than 1D-DWT.

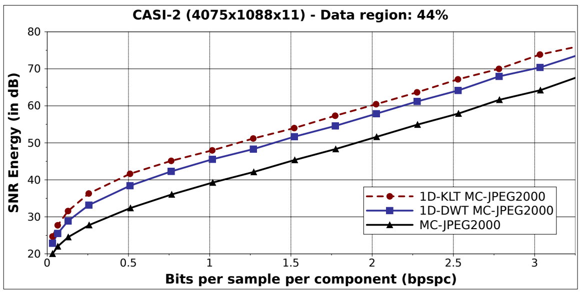

Figure 4. CASI-2 image (see more details in Section III-A) rate-distortion curves for MC-JPEG2000 with and without spectral decorrelation.

Most of the available implementations of the 2D coding systems that are able to encode multispectral images with no-data regions do not consider a rate-control method. A feasible approximation is to emulate 2D coding systems from its 3D extension: the main idea is to replace the rate-control method by the BPE of a 3D coding system, because, since the BPE is an embedded process, the rate-control is implicit when a 3D BPE is applied to the whole image. To decorrelate the spectral and spatial redundancies in 3D coding systems, a generalization of the SA 2D-DWT is performed, named as *SA 3D Squared* [1]. The SA 3D Squared transform generates prismal subbands, where the dimensions are determined by the number of components of the image and the number of levels applied in the spectral domain; however, when the number of levels applied to the spectral domain are set to 0, a SA 2D-DWT is performed to each component. Consequently, if a 3D BPE is used, each subband will be composed of n planes with a depth of 1, instead of 1 prism of depth n. This increases substantially the coefficient sets to be evaluated. With this strategy, no decorrelation in the spectral domain would be performed, so, the SA 1D-KLT approach is carried out before the 3D encoding process.

The second experiment evaluates the coding performance provided by 2D coding systems followed by a rate-control method against that of 3D coding systems. Table I shows the results obtained with the QccPack software [21] for the SA versions of 3D-WDR, 3D-TARP, and 3D-BISK. Results suggest that the SA 1D-KLT decorrelation applied to a 2D coding system obtains better results than SA 3D Squared for all bit-rates. Among the compared coding techniques, the differences are meaningless when the same decorrelation approach is considered.

Image: CASI-1. Data region: 50%					
	0.0625	0.25	0.5	1.0	1.5
Decorrelation	3D-WDR				
SA 3D Squared	9.73	23.29	30.14	37.56	43.33
SA 1D-KLT	**19.81**	**29.62**	**36.49**	**43.47**	**50.57**
Decorrelation	3D-TARP				
SA 3D Squared	9.82	23.30	30.18	37.55	43.29
SA 1D-KLT	**19.58**	**28.73**	**35.67**	**43.13**	**49.88**
Decorrelation	3D-BISK				
SA 3D Squared	10.53	22.84	30.55	37.86	42.99
SA 1D-KLT	**19.61**	**28.91**	**36.67**	**43.09**	**48.73**

Table I
CODING PERFORMANCE FOR IMAGE CASI-1. RESULTS REPORT THE SNR ENERGY IN DB FOR DIFFERENT BIT-RATES.

Next coding performance evaluation is carried out between two different rate-control methods: the 3D-BISK from the QccPack software, and our 2D implementation of BISK (2D-BISK), where BISK is applied to each component independently and then an interleaving process is performed to produce the final bit-stream. To decorrelate the spectral domain, the SA 1D-KLT approach is used for both rate-control methods. Figure 5 shows the rate-distortion curves for the image CASI-2. Results suggest that 3D-BISK is outperformed by a 2D-BISK followed by an interleaving process.

The 3D coding systems are devised to encode the whole image at a time. Thus, one MSB encoding is performed for all the components, and it does not take into account the different amount of energy provided by each component, consequently, the BPE execution has to mark the insignificance of many samples within low energy components for several bitplanes. Moreover, when the BPE from a 3D coding system is used as an implicit rate-control method, the number of coefficient sets to consider is increased. Thus, extra bits are needed to mark the insignificance of these sets, penalizing the final coding performance.

Our last coding performance evaluation is carried out among our proposal SA-MC-JPEG2000, MC-JPEG2000, and 2D-BISK (all of them implementing a decorrelating spectral transform). Table II shows the coding performance

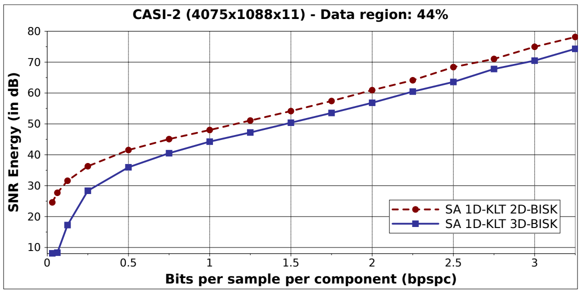

Figure 5. CASI-2 image rate-distortion curves for 3D-BISK using the BPE as a rate-control method, and 2D-BISK implementing a multi-component interleaving process.

results for different bit-rates. Three important points are worth noting from these results. The first point is that 2D coding systems that implement a rate-control method (SA-MC-JPEG2000, MC-JPEG2000, and 2D-BISK) obtain superior coding performance than the SA 3D coding systems reported in Table I, for which the rate-control is emulated by the 3D BPE (3D-WDR, 3D-TARP, and 3D-BISK). The second point is that the SA 1D-KLT decorrelation approach obtains better results than other considered approaches (see Table I and Table II). The last point is that the SA-MC-JPEG2000 obtains the best coding performance among the coding systems evaluated, nevertheless, it does not provide a JPEG2000 compliant bit-stream. On the other hand, MC-JPEG2000 generates a JPEG2000 compliant bit-stream and still achieves very competitive results compared to other shape-adaptive coding techniques (BISK, SA TARP, and SA WDR).

IV. CONCLUSIONS

Images devised to Remote Sensing (RS) applications may contain regions without information, here named as *no-data* regions. In this letter, we propose a shape-adaptive coding scheme for multispectral images containing no-data regions for the JPEG2000 framework (SA-MC-JPEG2000). In our approach, to properly exploit the spectral redundancy of multispectral images, two different decorrelations are proposed for the Sample Data Transformations stage (SA 1D-DWT and SA 1D-KLT), and a Multi-Component Post Compression Rate Distortion (MC-PCRD) is performed in the Rate-Control Stage. Moreover, to avoid completely the cost of encoding no-data regions, two modifications to JPEG2000 standard coding pipeline are introduced: a Shape Adaptive (SA) version of the Discrete Wavelet Transform (DWT) and of the Bitplane Encoder (BPE).

Experimental results suggest that the best technique is SA-MC-JPEG2000, which employs a SA 1D-KLT to decorrelate the spectral domain, and then a shape-adaptive multi-component JPEG2000. Nevertheless, SA 1D-KLT does not provide component scalability since all components are required to invert the transform, in contrast with SA 1D-DWT. Results also suggest that, for all images considered, the coding performance of compliant MC-JPEG2000 is similar to that 2D-BISK –followed by a rate-control process–, and superior to other shape-adaptive

	Image: CASI-1. Data region: 50%					Image: CASI-2. Data region: 44%					Image: CASI-3. Data region: 30%				
	0.0625	0.25	0.5	1.0	1.5	0.0625	0.25	0.5	1.0	1.5	0.0625	0.25	0.5	1.0	1.5
Decorrelation	SA-MC-JPEG2000					SA-MC-JPEG2000					SA-MC-JPEG2000				
SA 1D-DWT	24.64	32.25	38.01	44.44	49.86	25.92	33.49	38.77	45.91	52.09	31.00	35.79	40.81	46.69	56.11
SA 1D-KLT	**27.36**	**36.37**	**41.60**	**48.15**	**53.36**	**28.54**	**36.90**	**42.13**	**48.41**	**54.58**	**34.69**	**39.21**	**43.60**	**48.78**	**57.64**
Decorrelation	MC-JPEG2000					MC-JPEG2000					MC-JPEG2000				
1D-DWT	24.31	31.81	37.62	44.05	49.36	25.52	33.17	38.41	45.54	51.66	30.58	35.42	40.52	46.32	55.64
SA 1D-KLT	26.91	36.00	41.27	47.81	52.90	27.93	36.53	41.77	48.03	54.06	34.32	38.94	43.36	48.52	57.30
Decorrelation	2D-BISK					2D-BISK					2D-BISK				
SA 1D-DWT	23.91	31.91	37.62	44.20	49.55	25.33	32.82	38.09	45.41	51.35	30.42	35.22	40.48	46.32	55.54
SA 1D-KLT	27.01	35.97	41.33	47.84	53.00	27.70	36.30	41.55	48.03	54.15	34.24	38.99	43.31	48.40	57.29

Table II

CODING PERFORMANCE FOR CASI DATA SET. RESULTS REPORT THE SNR ENERGY IN dB FOR DIFFERENT BIT-RATES.

coding techniques (SA TARP, and SA WDR). Moreover, JPEG2000 framework considers many features and capabilities that are not available in those other coding techniques. Finally, the use of several SA 3D coding systems like 3D-WDR, 3D-TARP, and 3D-BISK, does not seem to work properly for the data set considered.

REFERENCES

[1] J. E. Fowler and J. T. Rucker, *Hyperspectral Data Exploitation: Theory and Applications*. Hoboken, NJ, USA: John Wiley & Sons Inc., 2007, ch. “3D wavelet-Based Compression of Hyperspectral Imager”, pp. 379–407.

[2] M. Cagnazzo, S. Parrilli, G. Poggi, and L. Verdoliva, “Costs and Advantages of Object-Based Image Coding with Shape-Adaptive Wavelet Transform,” *EURASIP Journal on Image and Video Processing*, pp. Article ID 78 323, 13 pages, 2007.

[3] J. T. Rucker and J. E. Fowler, “Shape-adaptive embedded coding of ocean-temperature imagery,” in *IEEE Proceedings of the Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, California, November 2006, pp. 1887–1891.

[4] G. Minami, Z. Xiong, A. Wang, and S. Mehrotra, “3-D wavelet coding of video with arbitrary regions of support,” *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 11, no. 9, pp. 1063 – 1068, September 2001.

[5] X. Tang, W. A. Pearlman, and J. W. Modestino, “Hyperespectral image compression using three-dimensional wavelet coding,” in *Proceedings of SPIE*, Santa Clara, California, January 2003, pp. 1037–1047.

[6] J. Fowler, “Shape-Adaptive Coding Using Binary Set Splitting with K-D Trees,” in *IEEE International Conference on Image Processing*, vol. 2, October 2004, pp. 1301–1304.

[7] Y. Wang, J. T. Rucker, and J. E. Fowler, “Embedded Wavelet-Based Compression of Hyperspectral Imagery Using Tarp Coding,” in *Proceedings of the International Geoscience and Remote Sensing Symposium*, vol. 3, July 2003, pp. 2027–2029.

[8] J. Tian and R. O. Wells, “Embedded image coding using wavelet difference reduction,” *Wavelet Image and Video Compression*, vol. 450, pp. 289–301, 2002.

[9] M. Cagnazzo, G. Poggi, and L. Verdoliva, “Region-Based Transform Coding of Multispectral Images,” *IEEE Transactions on Image Processing*, vol. 16, no. 12, pp. 2916–2926, December 2007.

[10] M. Cagnazzo, S. Parrilli, G. Poggi, and L. Verdoliva, “Improved Class-Based Coding of Multispectral Images With Shape-Adaptive Wavelet Transform,” *IEEE Geoscience and Remote Sensing Letters*, vol. 4, no. 4, pp. 566–570, October 2007.

[11] D. Taubman and M. Marcellin, *JPEG2000: Image Compression Fundamentals, Standards, and Practice*. Kluwer International Series in Engineering and Computer Science, 2002, vol. 642.

[12] ISO/IEC 15444-1, “JPEG2000 image coding system. Part 1: Core coding system,” December 2000.

[13] D. Taubman, “High performance scalable image compression with EBCOT,” *IEEE Transactions on Image Processing*, vol. 7, no. 7, pp. 1158–1170, July 2000.

[14] J. Gonzalez-Conejero, F. Auli-Llinas, J. Bartrina-Rapesta, and J. Serra-Sagristà, “JPEG2000 Coding Techniques Addressed to Images Containing No-Data Regions,” *Lecture Notes in Computer Science*, vol. 4678/2007, no. Advanced Concepts for Intelligent Vision Systems (ACIVS), pp. 1024–1036, August 2007.

[15] J. Gonzalez-Conejero, J. Serra-Sagristà, C. Rubies-Feijoo, and L. Donoso-Bach, “Encoding of images containing no-data regions within JPEG2000 framework,” in *IEEE International Conference on Image Processing*, October 2008, pp. 1057–1060.

[16] M. Cagnazzo, G. Poggi, L. Verdoliva, and A. Zinicola, “Region Oriented compression of multispectral images by shape-adaptive wavelet transform and SPIHT,” in *IEEE International Conference on Image Processing*, vol. 4, October 2004, pp. 2459–2462.

[17] S. Li and W. Li, “Shape Adaptive Discrete Wavelet Transforms for Arbitrarily Shaped Visual Object Coding,” *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 10, no. 5, pp. 725–743, August 2000.

[18] B. Penna, T. Tillo, E. Magli, and G. Olmo, “Transform coding techniques for lossy hyperspectral data compression,” *IEEE Trans. Geoscience Remote Sensing*, vol. 45, no. 5, pp. 1408–1421, May 2007.

[19] Cartographic Institute of Catalonia, ICC, “ICC Website,” Available: http://www.icc.cat, July 2009.

[20] Group on Interactive Coding of Images, Dep. of Information and Communications Engineering, Universitat Autonoma de Barcelona, “BOI software,” Available: http://www.gici.uab.es/BOI, July 2009.

[21] J. Fowler, “QccPack: An open-source software library for quantization, compression, and coding,” in *Applications of Digital Image Processing XXIII*, vol. 4115, August 2000, pp. 294–301.