

# Interactive transmission of spectrally wavelet-transformed hyperspectral images

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## ABSTRACT

The size of images used in remote sensing scenarios has constantly increased in the last years. Remote sensing images are not only stored, but also processed and transmitted, raising the need for more resources and bandwidth. On another side, hyperspectral remote sensing images have a large number of components with a significant inter-component redundancy, which is usually taken into account by many image coding systems to improve the coding performance. The main approaches used to decorrelate the spectral dimension are the Karhunen Loève-Transform and the Discrete Wavelet Transform (DWT).

This paper is focused on DWT decorrelators because they have a lower computational complexity, and because they provide interesting features such as component and resolution scalability and progressive transmission. Influence of the spectral transform is investigated, considering the DWT kernel applied and the number of decomposition levels.

In addition, a JPIP compliant application, CADI, is introduced. It may be useful to test new protocols, techniques, or coding systems, without requiring significant changes on the application. CADI can be run in most computer platforms and devices thanks to the use of JAVA and the configuration of a light-version, suitable for devices with constrained resources.

**Keywords:** Hyperspectral data coding, interactive hyperspectral data transmission, JPEG2000, JPIP, Quality Scalability.

## 1. INTRODUCTION

Images play a significant role in many fields of our society, notably in remote sensing applications like environmental monitoring, geographical information systems, disaster assessment and management, or land use classification in agriculture.<sup>1</sup> In the last years, advances of imaging sensors and satellites have implied larger amounts of captured data, which are then transmitted back to the earth for dissemination. New technology of imaging sensors captures images at very narrow wavelength, achieving hundreds of contiguous spectral bands, with high spatial and spectral resolutions. These images are subsequently processed, transmitted, and analyzed to retrieve important information. An example of this kind of sensor is the AVIRIS,<sup>2</sup> an airborne hyperspectral sensor that records 224 contiguous bands, from 400nm to 2500nm, of size 2048 rows  $\times$  614 columns  $\times$  2 bytes/sample per band (over 537 Megabytes per image).

Image compression has become increasingly of interest in both data storage and data transmission from remote acquisition platforms (satellites or airbornes) because, after compression, storage space and transmission time are reduced. Thus, several approaches have been employed for compression of hyperspectral images: vector-quantization-based techniques,<sup>3,4</sup> Karhunen-Loève-Transform (KLT) applied to spectral pixel vectors,<sup>5,6</sup> extensions of the common 2-dimensional image-compression methods to 3-dimensional methods,<sup>7</sup> or wavelet-based compression systems (JPEG2000,<sup>8,9</sup> SPIHT,<sup>10,11</sup> SPIHT-3D,<sup>12</sup> SPECK-3D,<sup>10</sup> ICER,<sup>13</sup> ICER-3D,<sup>14</sup> etc.).

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It is worth noting that our society trends towards remote displaying of images, that is, a scenario where images are stored in remote servers and clients browse on such images. Consequently, achieving acceptable response times when displaying remote images demands for communication networks with high bandwidth and also for image compression techniques. Several approaches have been developed to achieve an efficient image transmission. The first applications focused on interactive image transmission appeared in the 90s, and they were based on the JPEG<sup>15</sup> and GIF<sup>16</sup> standards. But the main drawback of these applications were that image region transmission compelled to deliver the whole image and cropping it at the client side. These weak points were overcome by means of 1) compression of images at different resolutions and qualities, and 2) the use of specific protocols to deliver images. Despite that some weak points were overcome, the server was forced to have images stored in several resolutions and qualities. Consequently, it was an overload for the server and the interactivity was restricted to off-line-defined image regions. In 1996, a consortium of several companies developed both an image format, FlashPix,<sup>17</sup> and a transmission protocol, Internet Imaging Protocol(IIP).<sup>18</sup> FlashPix is based on a hierarchical structure of the image at different resolutions, which allows to transmit regions of the image, and the IIP protocol defines a protocol to interactively transmit FlashPix images. The main disadvantage is also that images must be stored at different resolutions. On the other hand, MrSID, developed by Lizardtech,<sup>19</sup> and ECW, from ER Mapper,<sup>20</sup> are raster compression formats based on wavelet technology which offer multi-resolution, progressive transmission, and interactive zooming, but their main drawback is that they are not open standards.

The JPEG2000 standard, developed by the Joint Photographic Experts Group, is composed by 12 parts including image coding (Part-1<sup>21</sup> and Part-2<sup>22</sup>), transmission (Part-9<sup>23</sup>), security and video. JPEG2000 is a powerful standard which supports multi-component, variable bit depth per component, flexible canvas coordinate system, different progression orders, regions of interest coding, etc., which make JPEG2000 an image coding system with many degrees of flexibility. The core coding system of JPEG2000 is constituted by four main stages: sample data transformations, sample data coding, rate-distortion optimization, and code-stream re-organization. The *sample data transformations* stage tiles the input images data, shifts unsigned image values to make them zero mean, compacts the energy of the image through the application of several decomposition levels of Discrete Wavelet Transform (DWT), and quantizes transformed coefficients. Then, the image is logically partitioned in code-blocks that are independently coded by the *sample data coding* stage, called Tier-1. Tier-1 generates one quality embedded code-stream for each code-block, hence the need of *rate-distortion optimization* techniques to select the best code-stream segments of code-blocks to construct the final code-stream for a given target bit-rate. The last stage of the core coding system is the *code-stream re-organization*, which allows the creation of successive layers of quality and, through the Tier-2, encodes the auxiliary data needed to identify layers' contents.

Part-9 of the JPEG2000 standard, JPEG2000 Interactive Protocol (JPIP), is a client-server architecture for interactive image transmission. It defines a request-response syntax that allows clients to select portions of an image, called Windows of Interest (WOI), which are delivered from the server to clients eliminating redundant representation of the image and redundant transmissions. This efficient transmission is achieved because the delivered data are segments of the code-stream. The aforementioned request syntax allows clients to include query fields describing many possibilities, for instance, image name, component, frame size, region, layers, session, status of client cache, etc.

This work has a twofold purpose. On the one hand, it is focused on evaluating transmission of spectrally transformed images against transmission of images without transformation across the spectral components. This evaluation is conducted within the framework of JPEG2000 standard. On the other hand, the development of a JPIP implementation is presented. It provides a good framework to test new protocols, algorithms, coding techniques, and even whole coding systems, because of its high and modular flexibility.

This paper is structured as follows. Section 2 contains an overview of hyperspectral image coding, mainly on image compression exploiting the spectral dimension by means of the wavelet technology, within JPEG2000. Different rate-allocation strategies to generate JPEG2000 compliant files from the compressed hyperspectral images are also explained in this section. Interactive image transmission is reviewed in section 3, centered on the JPIP protocol. It also tackles transmission of hyperspectral images with and without transform across the spectral domain. In addition, a JPIP compliant application, CADI, used to carry out the experiments is introduced. Then, section 4 presents some experimental results. The last section contains a summary and draws some conclusions.

## 2. REVIEW OF HYPERSPECTRAL IMAGE CODING

Hyperspectral images usually have a similar global structure across components. However, different pixel intensities could exist among nearby spectral components or in the same component due to different absorption properties of the atmosphere

or the material surface being imaged. This means that two kinds of correlations may be found in hyperspectral images: intraband correlation among nearby pixels in the same component, and interband correlation among pixels across adjacent components. Interband correlation should be taken into account because it allows a more compact representation of the image by packing the energy into fewer number of bands, enabling a higher compression performance.

There are many technologies which could be applied to remove correlation across the spectral dimension, but two of them are the main approaches for hyperspectral images: the KLT and the DWT. (The Karhunen-Loève-Transform is also known as Principal Components Analysis). Although the KLT achieves the best results,<sup>24,25</sup> it is not always an attractive decorrelator due to its high computational complexity. Conversely, the DWT provides a reasonable computational complexity as well as some interesting features like component and resolution scalability and support for progressive transmission.

## 2.1 Compression of spectrally wavelet-transformed images with JPEG2000

As have been previously explained, the JPEG2000 standard is a powerful image coding system that allows many degrees of flexibility for compressing images. Although JPEG2000 was designed to allow compression of images with up to 16385 spectral components in a single code-stream, it does not indicate how spectral components should be encoded to achieve the best compression performance. While the Part-1 of the standard does not allow decorrelation across the spectral dimension (except for decorrelation of color components for RGB images), the Part-2 allows that any decorrelation might be applied across the spectral components, including both the KLT and the DWT.

As said, hyperspectral image compression performance is improved when interband correlation is taken into account.<sup>8,26</sup> In this case, and considering only wavelet-based spectral decorrelators, two possibilities appear, depending on how the hyperspectral image is considered, either the whole image as a cube, or considering separately the spectral and the spatial dimensions. The first possibility could be understood as a direct extension of the 2-D transform to 3-D. Table 1 below summarizes three kinds of wavelet-based decorrelators which could be applied to hyperspectral images, which are graphically presented in figure 1.

3D square transform	3D rectangular transform	3D hybrid
It is obtained by performing one decomposition level of a one-dimensional transform in each dimension. Then, this process is successively applied on the low-frequency cube. The resulting decomposition is a 3-D Mallat decomposition.	It is obtained by performing all decomposition levels of the wavelet transform along one dimension, then successively along the other desired dimensions.	It is obtained by performing all decomposition levels of the wavelet transform across the spectral dimension, and then a 2-D square transform is carried out independently for each spectrally transformed component.

Table 1: Types of three-dimensional DWT.

Penna *et al.*,<sup>27</sup> Fowler *et al.*<sup>8</sup> and Serra *et al.*<sup>26</sup> have shown that the 3D hybrid rectangular / square transform outperforms the 3D square for hyperspectral images. Consequently, the 3D hybrid square has been selected here.

## 2.2 JPEG2000 rate-allocation strategies for multi-component images

As have been previously explained, JPEG2000 is divided in four parts. In the second stage, *sample data coding*, quantized coefficients are logically grouped into rectangular blocks, called code-blocks, following the scheme proposed in EBCOT,<sup>28</sup> and each code-block is independently coded by an entropy encoder obtaining one code-stream for each. A rate-distortion technique is needed to truncate and select the best code-stream segments for each code-block. In the last stage, *code-stream re-organization*, code-streams are merged and arranged to form the final code-stream. It is worth noting that the JPEG2000 standard does not specify how each code-stream must be truncated and arranged. However, the EBCOT algorithm produces the rate-distortion optimal segments of code-streams by means of optimal truncation points for each independent code-stream. Then segments of code-streams are concatenated to form the final code-stream following the order set by, for instance, the Post-Compression Rate-Distortion Optimization (PCRD-Opt) algorithm.

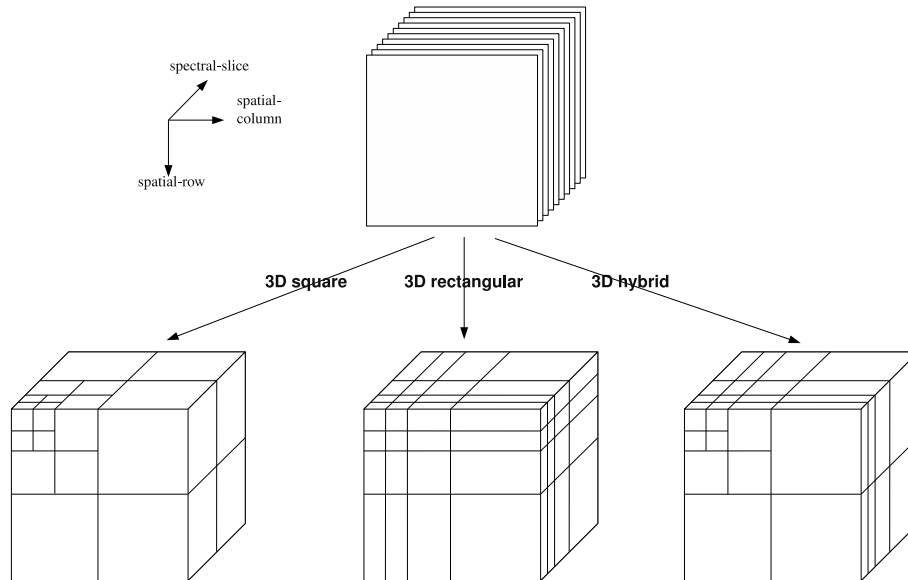


Figure 1: Types of three-dimensional DWT, with a 3 level spectral decomposition and a 3 level spatial decomposition.

An important issue that must be considered when a multi-component image is coded with JPEG2000 is the rate-allocation strategy. The PCRD-Opt achieves optimal rate-distortion code-streams for a single-component image, but its extension to multi-component images may be done according to three different strategies<sup>8</sup> (in all three cases, the generated final code-stream is JPEG2000-compliant):

**Band-Independent Fixed-Rate (BIFR).** This method is a band-independent rate-allocation strategy which assigns a fixed rate for each component. See figure 2a.

**Band-Independent Rate Allocation (BIRA).** This method is also a band-independent rate-allocation strategy which assigns a variable rate for each component. Different criteria could be used to allocate the rate for each component, such as energy, variance, or entropy. See figure 2b.

**Multi Component (MC).** This method performs the PCRD-Opt across the image components. The PCRD-Opt is applied simultaneously to all code-streams of the whole image, computing the truncation points in both spatial and spectral dimensions. This method achieves the best results.<sup>8</sup> See figure 2c.

### 3. JPEG2000 INTERACTIVE TRANSMISSION OF IMAGES

The first approach to interactively transmit JPEG2000 images was proposed in 2001 by Deshpande and Zeng<sup>29</sup>. The main idea behind this first approach is to use the byte-range transmission capability of the HyperText Transfer Protocol (HTTP)<sup>30</sup> to transmit segments of JPEG2000 code-streams. Before the transmission of the code-stream segments, clients must download an index file containing a list of the code-stream byte ranges containing different image resolutions and spatial locations and, once this index file is downloaded, the client requests byte-ranges of the JPEG2000 code-stream through the HTTP protocol. The main advantage of this approach is that any HTTP server can be used and that it does not require the definition of any specific transmission protocol. However, the drawbacks are that the transmission of the index file widely increases the initial response time, and that the computational load is completely unbalanced against the client, which is precisely the one that might have constrained resources.

The second approach proposed for the transmission of JPEG2000 code-streams was introduced by Li and Sun.<sup>31</sup> Basically, this approach creates a virtual representation of the image at the client side that is accessed by applications through the so-called virtual media access protocol (Vmedia). This approach allows both the use of a HTTP server or a Vmedia server that improves the transmission performance. To enhance the transmission over the network, the Vmedia protocol may also use an index file similar to the previous approach. The drawbacks of this approach are similar to the drawbacks

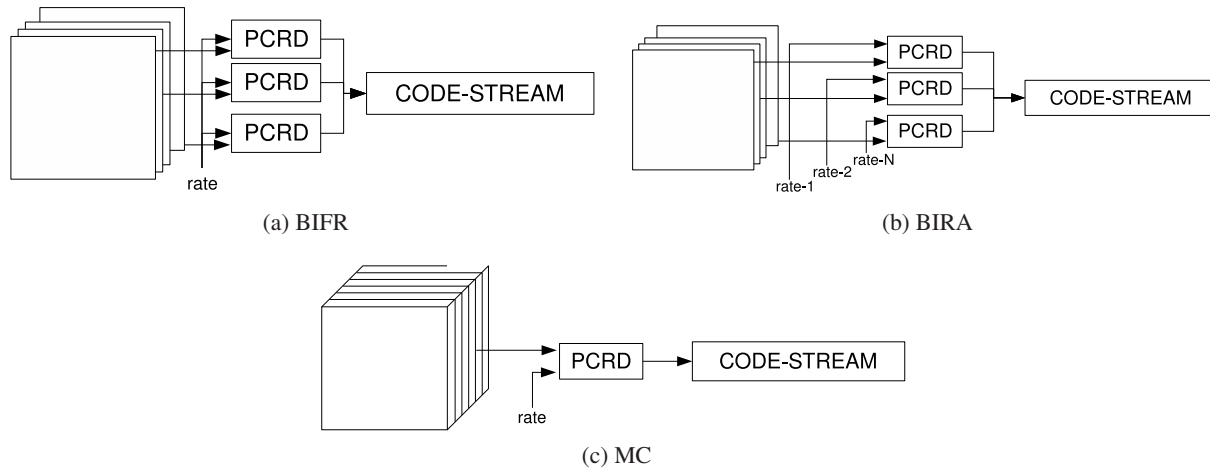


Figure 2: Rate-allocation strategies for hyperspectral images.

of the previous approach, because clients must also request specific chunks of the compressed image, and because the decoding takes place at the client-side.

The unfavourable points arising from these first approaches have been overcome by the JPIP protocol.<sup>23</sup> JPIP defines a simple syntax and several techniques to efficiently transmit JPEG2000 code-streams using very low computational resources. A key-feature of JPIP is that it gives several degrees of freedom to both client and server sides, allowing applications to decide whether to use stateful or stateless connections, cache or non-cache management, etc. This freedom is achieved by the definition of the data-bin container, which is the self-contained structure containing the actual data transmitted over the network. The negotiation between client and server allows the delivery of code-stream segments in different ways depending on the image, the network state, and the server load.

The tremendous flexibility of JPIP allows applications to fulfill a wide range of requirements and necessities. Recently, some studies have been proposed to improve the quality of the transmitted images through smart transcoding techniques<sup>32,33</sup> and a slight extension of the JPIP protocol has been also proposed in<sup>34</sup> to exploit the redundancy between requests of different clients through web proxy cache. An XML based model for the cache management is introduced in<sup>35</sup> aimed to improve the efficiency of applications.

### 3.1 Transmission of hyperspectral images without spectral transform

When hyperspectral images are compressed considering that each component is independent from the others, inter-component redundancy is not taken into account (thus not achieving the best compression performance). Conversely, each packet in the code-stream is only linked with one, and only one, component of the original image. Therefore, when several components of the image must be transmitted, delivered data belongs only to the requested components. Despite that the achieved coding performance is not the best, it could be of interest in an interactive scenario when users browse on reduced groups of image components because it gives the finest access accessibility to image components.

### 3.2 Transmission of hyperspectral images with wavelet transform as spectral decorrelator

When hyperspectral images are compressed performing a 1-D wavelet transform across the spectral dimension, and a 2-D wavelet transform across the spatial dimension, the inter-component redundancy is fully exploited. In this case, each spectrally-transformed component is related to several components of the original image, since there is a one to multiple relationship between components of the original image and spectrally transformed components (see an example in figure 3). Consequently, access flexibility to spectral components is decreased because decompressing an image component entails reading and transmitting the necessary components to invert the transform across the spectral domain. Note that the number of spectral components needed to invert the spectral transform depends on the length of the filter and the number of decomposition levels applied. The larger the length of the filter, or the larger the number of decomposition levels, greater is the number of spectral components needed.

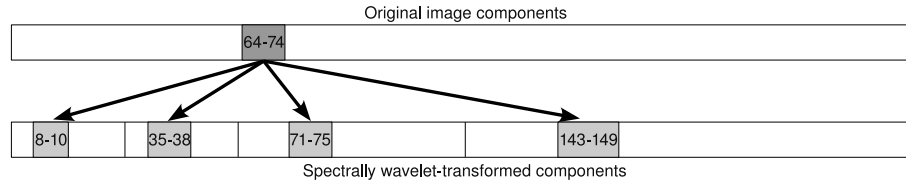


Figure 3: Relation between components of the original image and wavelet-transformed components. The DWT kernel is the 5/3 reversible and 3 decomposition levels have been applied.

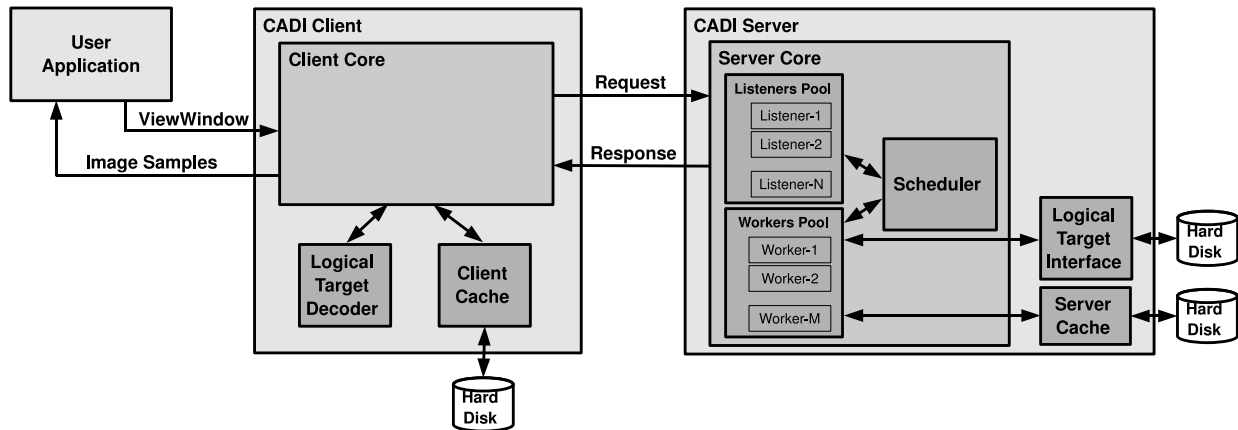


Figure 4: Modular scheme of the JPIP implementation CADI.

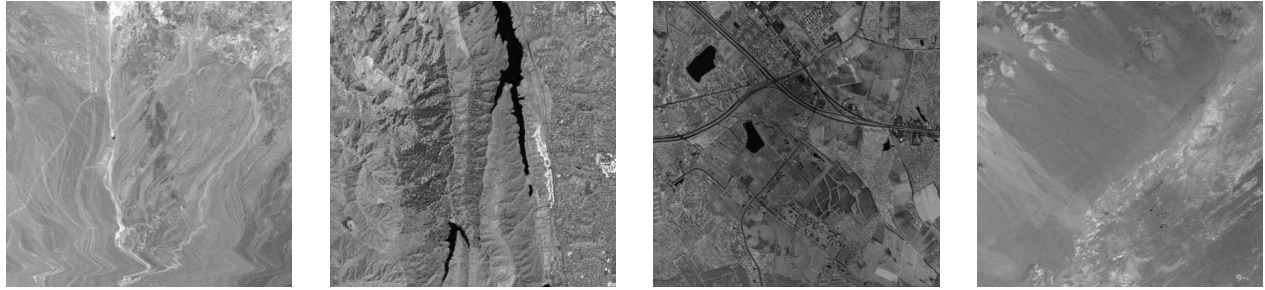
### 3.3 CADI: a JPIP implementation

The Group on Interactive Coding of Images (GICI) has developed an implementation of the JPIP protocol, named CADI. The development of CADI is focused on three main goals. The first one is that CADI has been designed with the aim to get a modular application where adding, modifying, or replacing modules was easy. Consequently, new transmission techniques and algorithms can be tested without requiring significant changes. The second purpose is to achieve a multi-platform application, thus Java has been the chosen programming language. And the last aim is that the client application has been designed to be run on personal computers or on constrained resources devices, so that both full- and light-versions may be enabled.

The CADI Software is composed by three applications. A JPIP server, *CADIServer*, a JPIP client *CADIClient*, and a graphical user interface, *CADIViewer*. Figure 4 shows the main modules of CADI's architecture and philosophy design.

**CADIServer:** It is composed by three main modules, a main module, the *server core*, and two auxiliary modules, the *logical target interface* and the *server cache*. The *server core* module receives requests of clients and it also sends responses to clients, therefore, each task is performed by two subsidiary and independent modules, *listeners pool* and *workers pool*, which are managed by the *scheduler* module. Both subsidiary modules have been implemented like a pool of threads in order to take advantage of multi-threading architectures and, as a consequence, multiple client requests can be simultaneously processed. The *scheduler* receives client requests form the *listeners pool* and it assigns them to a *worker*, where prioritization criteria could be applied. It is important to emphasize that when a JPEG2000 code-stream is requested by a client, it is indexed by a *worker* and it is kept in a shared memory among *workers* reducing the response time of new requests. Another important module is the *logical target interface*, which defines an interface between the *server core* and code-streams. It allows management of different image coding systems returning information about the image or segments of the code-stream. It is therefore very easy to add support for new image coding systems.

**CADIClient:** This application implements a JPIP client, a middleware between a graphical user interface (GUI) and a JPIP server. It has one interface to deal with the GUI and one interface to deal with the JPIP server. After receiving a



(a) Cuprite (band 64) (b) Jasper Ridge (band 103) (c) Low Altitude (band 46) (d) Lunar Lake (band 48)

Figure 5: AVIRIS hyperspectral images used in the experiments. Radiance data.

request for a particular window or region of the image from the GUI, the JPIP client parses the request and forwards it to the server, which, in its turn, processes it and delivers segments of the compressed code-stream belonging to the requested WOI back to the client. The *CADIClient* is composed by: 1) a main module, *Client*, which manages the communication with the GUI and the server, 2) the *client cache* module, which manages the cache at the client side, and 3) the *logical target decoder* module, which performs the decoding of the compressed code-stream.

**CADIVIEWER:** It is a simple graphical user interface to display images. Users can request an image placed in a remote server and they can browse on the image doing a pan, a zoom, or improving the quality. The CADIVIEWER can be replaced by any other user application in an easy way because it only requests for a specific area of the image and receives the images samples for the requested area.

#### 4. EXPERIMENTAL RESULTS

Experiments have been conducted to assess and compare the coding performance achieved when hyperspectral images are compressed and transmitted either with, or without, applying a wavelet transform across the spectral dimension. JPEG2000 standard has been taken as the baseline coding system because of its state-of-the-art competitive coding performance. Evaluation of the coding performance when applying an spectral wavelet transform has been carried out considering both the influence of the kind of wavelet kernel, and of the number of wavelet decomposition levels. With regard to the wavelet kernel for the spectral dimension, both the 9/7 irreversible and the 5/3 reversible filters are analysed. With regard to the number of decomposition levels for the spectral dimension, results are only reported for 5 and 3 decomposition levels, although more experiments have been performed. With regard to the 2-D wavelet spatial transform, results are reported for the 9/7 irreversible kernel, always with 5 decomposition levels.

BOI software v1.2,<sup>36</sup> a JPEG2000 Part 1 and Part 2 implementation, has been used to encode the images, and CADI software v1.2<sup>37</sup> has been used to evaluate the transmission within a JPIP framework.

Experiments have been performed on an Airborne Visible/Infrared Imaging Spectrometer<sup>2</sup> radiance data set. AVIRIS sensor records the visible and the near infrared spectrum of the reflected light, and is capable of producing images of size 2048 rows  $\times$  614 columns  $\times$  224 bands  $\times$  2 bytes/sample per flight. For the results here, we crop the first scene in each data set to produce image cubes with dimensions 512  $\times$  512  $\times$  224 pixels, each pixel stored in signed 16 bits per pixel per band (bpppb). In particular, Cuprite, Jasper Ridge, Low Altitude, and Lunar Lake radiance images have been used; one original component of each image is shown in figure 5.

The distortion measure for evaluating the quality of the recovered images is the Signal to Noise Ratio (SNR), defined as

$$SNR_{Energy} = 10 \cdot \log_{10} \frac{E(x)}{MSE} \quad (dB)$$

where  $E(x) = \frac{1}{N_x N_y N_z} \sum_{i,j,k} x(i,j,k)^2$  is the energy of the input image ( of size  $N_x \cdot N_y \cdot N_z$ ), and the Mean Squared Error (MSE) (or  $L_2^2$ ) is  $MSE = \frac{1}{N_x N_y N_z} \sum_i \sum_j \sum_k [x(i,j,k) - \hat{x}(i,j,k)]^2$ , with  $x(i,j,k)$  denoting a pixel in the input image, and  $\hat{x}(i,j,k)$  a pixel in the recovered image.

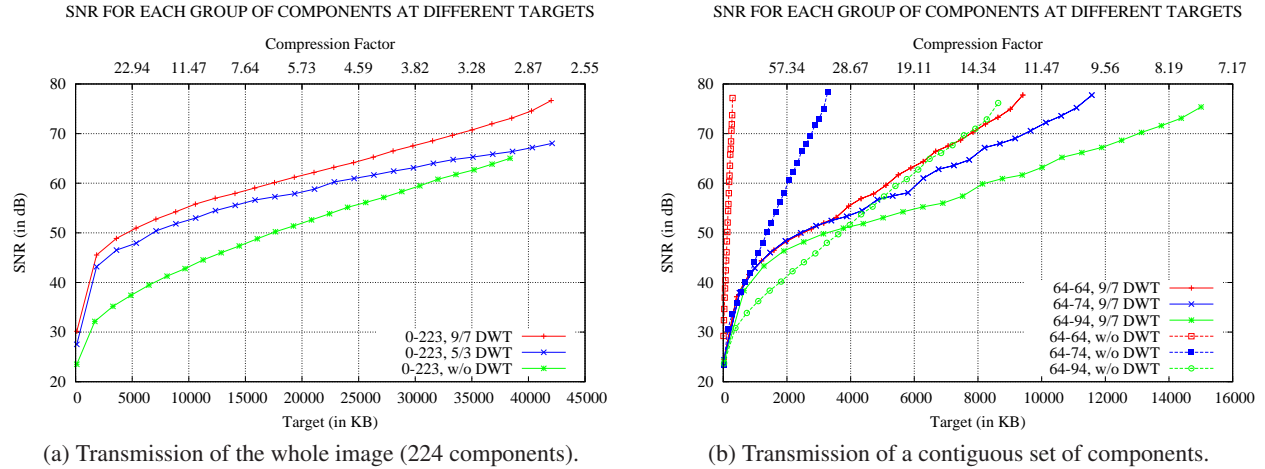


Figure 6: Performance comparison between two coding approaches: no transform across the spectral dimension versus an spectral wavelet transform approach. Cuprite radiance image.

The first experiment is focused on analysing the transmission of the whole image cube with and without applying a wavelet transform across the spectral domain. Figure 6a depicts the results for the Cuprite radiance image. The compression factor and the length of the received code-stream are reported in the horizontal axis; the SNR quality is reported in the vertical axis. Plots are provided for the 9/7 irreversible filter, the 5/3 reversible filter, and when no spectral wavelet transform has been applied. As reported in the literature, the best coding performance is achieved when the image has been spectrally transformed, because interband redundancy is removed by the wavelet decorrelator. Consistently, the 9/7 kernel provides a superior performance over the 5/3 kernel. The results for the other images of the AVIRIS data set are similar.

The second experiment is focused on analysing the transmission of only a group of components, both with (9/7 irreversible filter with 5 decomposition levels) and without applying a wavelet transform across the spectral domain. Figure 6b depicts the results for the Cuprite radiance image when only one, ten, or thirty contiguous components are transmitted. When transmitting a single component, transmission of images without spectral transform provides a superior performance, because the delivered data corresponds exactly to the requested component, meanwhile data delivered when the image has been spectrally transform includes data belonging to components that have not been requested but which are needed to invert the wavelet transform. When transmitting thirty contiguous components, and for very low bit rate, the quality of the recovered image is higher when an spectral transform has been applied; for medium to high bit rate, it is better not to apply an spectral transform. As the number of requested components increases, the performance of the spectrally wavelet transform approach improves, because of the ratio between the number of requested components and the number of components needed to invert the DWT.

The third experiment assesses the influence of the wavelet kernel in the image transmission. Specifically, the 9/7 irreversible and the 5/3 reversible kernels have been evaluated. Figure 7 depicts the results for the Low Altitude radiance image when ten, twenty, or thirty contiguous components are transmitted, for both wavelet kernels. The 5/3 kernel yields a better coding performance than the 9/7 kernel because its filter length is shorter, needing a fewer number of spectral components to invert the DWT. However, as the number of requested components gets larger, the differences in coding performance between both wavelet kernels become shorter. Recall also that when the whole image cube is requested, the 9/7 kernel provides a better coding performance (as has been reported in figure 6a).

The fourth experiment assesses the influence of the number of wavelet decomposition levels. Figure 8a reports results for the Cuprite radiance image when the whole image is requested, using 5 and 3 decomposition levels (9/7 irreversible kernel). As expected, applying 5 wavelet decomposition levels yields a higher coding performance. However, when one, twenty, or thirty contiguous components are requested, figure 8b shows that the coding performance is higher when the number of decomposition levels is smaller, because again the number of spectral components needed to invert the spectral wavelet transform is smaller.

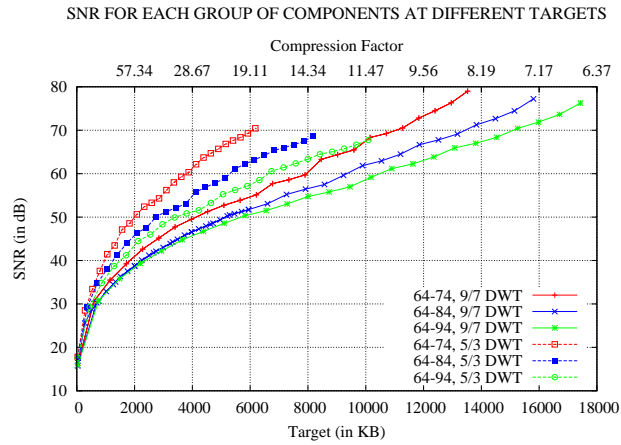
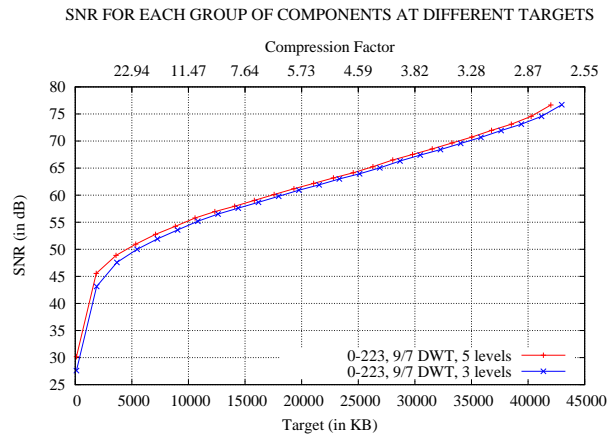
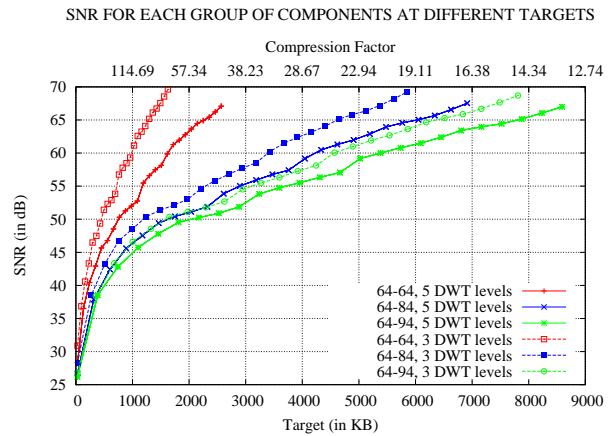


Figure 7: Coding performance comparison between the 9/7 irreversible and the 5/3 reversible filter applied across the spectral domain. Low Altitude radiance image.



(a) Transmission of the whole image (224 components).



(b) Transmission of a contiguous set of components. 5/3 reversible kernel.

Figure 8: Influence of the number of wavelet decomposition levels for spectral decorrelation. Cuprite radiance image.

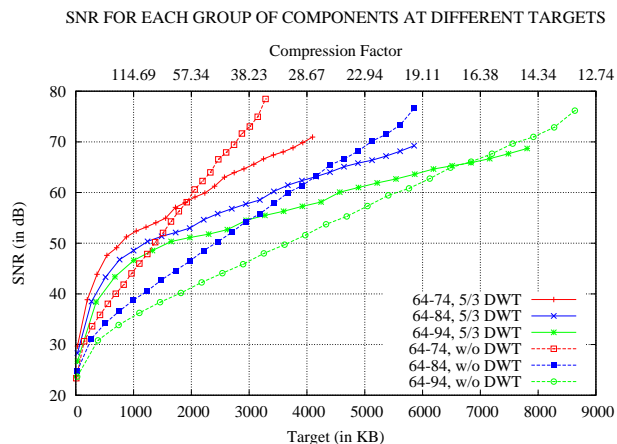


Figure 9: Performance comparison between two coding approaches: no transform across the spectral dimension versus a spectral wavelet transform approach (5/3 kernel with 3 decomposition levels). Cuprite radiance image.

According to the third and fourth experiments, and when only a group of contiguous components is requested, it seems that an spectral decorrelation performed by a 5/3 reversible filter with 3 decomposition levels wavelet transform provides a competitive coding performance. The fifth and last experiment compares, for the Cuprite radiance image, the coding performance of the two coding approaches, namely whether to apply or not a wavelet transform for spectral decorrelation. Figure 9 depicts the coding performance when the spectral wavelet transform is performed with the 5/3 kernel and with 3 decomposition levels. When transmitting ten contiguous components, and for very low bit rate, the quality of the recovered image is higher when an spectral transform has been applied; for medium to high bit rate, it is better not to apply an spectral transform. When transmitting thirty contiguous components, and for almost all bit rates, applying an spectral wavelet transform yields superior performance.

## 5. CONCLUSIONS

Previous studies have shown that the coding performance of hyperspectral image compression is improved when inter-band redundancy is exploited, for instance, by means of a Karhunen-Loève Transform or a Discrete Wavelet Transform. Although the KLT helps to achieve a higher coding performance, because of its higher computational complexity and because of several attractive features of the DWT, the wavelet transform has been selected here. This paper deals with the interactive transmission of hyperspectral images that have been spectrally wavelet transformed.

When the whole hyperspectral image is to be recovered, applying such spectral transform proves to be beneficial. However, when hyperspectral images are transmitted, users may not need the whole image cube, but only a sub-set of components. If an spectral wavelet transform has been applied, in order to invert that transform, multiple components have to be delivered, even if they have not been requested by the user. The number of needed components to invert the DWT depends on the number of components requested, the wavelet kernel employed, and the number of wavelet decomposition levels. In an interactive transmission scenario, all these items should be carefully balanced.

Within the framework of JPEG2000 coding system, and in the setting of an interactive transmission scenario like JPEG2000 Internet Protocol (JPIP), we have investigated whether applying a wavelet transform as spectral decorrelator for hyperspectral image coding is appropriate. The influence of both the 9/7 irreversible and the 5/3 reversible kernels has been examined. The 9/7 filter yields a higher performance when the whole hyperspectral image is to be retrieved; however, when only a reduced sub-set of components is requested, the 5/3 filter is preferred. Similarly, applying a higher number of wavelet decomposition levels improves the coding performance when retrieving the whole image, but when requesting a reduced sub-set of components, it pays of to employ only a 3 level wavelet decomposition.

To summarize, the coding performance when hyperspectral images are interactively transmitted is a trade-off among the DWT filter, the number of DWT decomposition levels, and the number of contiguous requested components. In addition, it evolves along the bit rate.

This paper introduces also a JPIP implementation, CADI, which allows to evaluate and try new techniques, algorithms, and coding systems in the framework of the JPIP protocol. Testing is very easy due to its flexible design, where modules

can be replaced or modified without affecting other modules. CADI's source code and documentation are under the General Public License (GPL), allowing its free use, modification, and distribution.

### Acknowledgments

The authors would like to thank Fernando García-Vílchez for his help with the implementation.

This work has been partially supported by the Spanish and Catalan Governments, by FEDER, and by the Universitat Autònoma de Barcelona under Grants TSI2006-14005-C02, MEC\_BPD-2007-1040, SGR2005-00319, and UAB2005-022.

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