Data fusion of remotely sensed images using the wavelet transform : the ARSIS solution

Thierry Ranchin, Lucien Wald

Ranchin T., Wald L., 1997, Data fusion of remotely sensed images using the wavelet transform : the ARSIS solution», Proceedings, SPIE Annual Meeting, International Symposium on Optical Science, Engineering and Instrumentation, (1997), vol 3169, 272-280.

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Thierry Ranchin and Lucien Wald

Groupe Télédétection & Modélisation - Centre d'Energétique,
Ecole des Mines de Paris, BP 207, 06904 Sophia Antipolis cedex, France·

ABSTRACT

Earth Observation satellites are often constructed to deliver a high spatial resolution image and a set of high spectral resolution images with a lower spatial resolution. Users often want to take advantage of both the high spatial and high spectral resolutions. The ARSIS concept was specially designed to fulfill this requirement and to produce high spectral resolution images with the best spatial resolution available in the set of images with respect to the original spectral content. This concept is based on the wavelet transform and the multiresolution analysis. In this paper, the concept is presented and the different parameters are discussed. Examples of application of ARSIS to real case-studies are provided. Perspectives of use of such a concept are proposed and the benefits to user discussed.

Keywords: data fusion, remote sensing, Earth observation, wavelet transform, spatial resolution, multiresolution analysis.

1. INTRODUCTION

Earth Observation satellites, e.g., SPOT, deliver images of the Earth surface with different spatial and spectral resolutions. The geometrical description of the objects on Earth surface is reached through high spatial resolution but often one spectral band given few information about the physics of the observed processes. The radiometric description of the objects are reached through high spectral resolution images which have a lower spatial resolution.
The end-users of remotely sensed data are often interested to reach the best possible description in terms of geometry and radiometry. This aim can be attained through the use of data fusion. Hence, from a set of images with different spatial and spectral resolutions, a set of images with the best available spatial resolution is constructed. Many solutions exist, but a few allow the synthesis of the images with respect to their original spectral content. The respect of the spectral content is of importance if further processing is to be applied on the synthesized images.

The ARSIS concept (from its French name Amélioration de la Résolution Spatiale par Injection de Structures) was designed to improve the spatial resolution of images in a set of images with different spatial and spectral resolutions, to the best available spatial resolution with respect to their original spectral content. This concept makes use of the wavelet transform and the multiresolution analysis. The hierarchical description of the information provided by the multiresolution analysis is combined to the wavelet transform from the image with the best spatial resolution, to synthesize the missing information in the images. This synthesis is made using a model of transformation of the wavelet coefficients which takes into account the physics of both images. Then a reconstruction is applied and the images are constructed.
An evaluation of the different methods for improving the spatial resolution of images was performed to evaluate the preservation of the original spectral content, through statistical parameters. Compared to other methods, the ARSIS concept was shown as given the best achievable results [1].

In this paper, the ARSIS concept is first described. Then, different examples of application of the concept are demonstrated. Finally, some perspectives of development of the concept and some potential uses of the resulting images are enhanced.

·Further author information -
T.R. (correspondence): Email: ranchin@cenerg.cma.fr; WWW: http://www-cenerg.cma.fr/~tr; Telephone: (33) 4 93 95 74 53; Fax: (33) 4 93 95 75 35
L.W.: Email: wald@cenerg.cma.fr; WWW: http://www-cenerg.cma.fr/sophia/tele; Telephone: (33) 4 93 95 74 53; Fax: (33) 4 93 95 75 35

2. THE ARSIS CONCEPT

The ARSIS concept is based on the use of the wavelet transform and the multiresolution analysis. The multiresolution analysis allows the computation, from an original image, of coarser and coarser approximations. In this scheme, the wavelet transform allows to represents the difference of information between two successive approximations. These tools are often represented using a pyramidal scheme as proposed Figure 1.
A more complete presentation of these tools in the field of remote sensing can be found in [2].

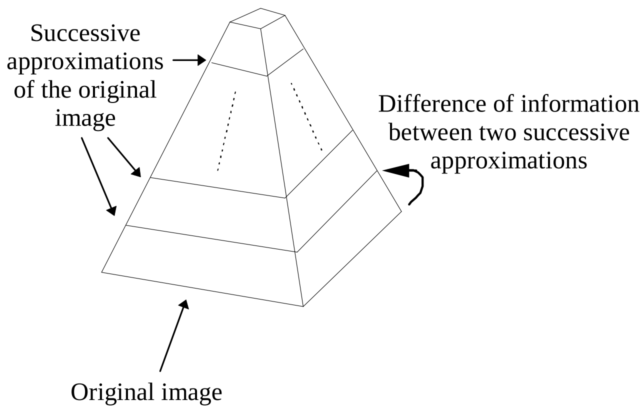

Figure 1. Representation of the successive approximations of an image by the means of a multiresolution algorithm

For all the merging processes, some pre-requisites are needed:

- images shall have different spatial and spectral resolutions,
- images to merge shall represent the same area,
- images shall be accurately registered,
- no major change shall have occurred on the area during the interval between time acquisition of the source images.

If the last requirement is not satisfied, the aim of the merging process can be the updating of the observed area [3]. These requirements are not limiting the merging process to images acquired by the same platform. The process can also apply to the merging of images acquired by airborne and spaceborne sensors. Many methods have been proposed to enhance the spatial resolution of images taking advantages of the presence of one or more images with a better spatial resolution [4,5]. But, if one of the objectives is to bring each image at the best spatial resolution available, while retaining all the spectral content of the image to enhance, only a few of them satisfy it. A comparison of the most representative merging processes has been achieved by [1,6].
In order to fulfill this objective, the ARSIS concept was first designed for the SPOT imagery and then generalized to the merging of images with different spatial and spectral resolutions. This concept uses the wavelet transform and the multiresolution analysis to decompose the two images to be merged as in Figure 2.

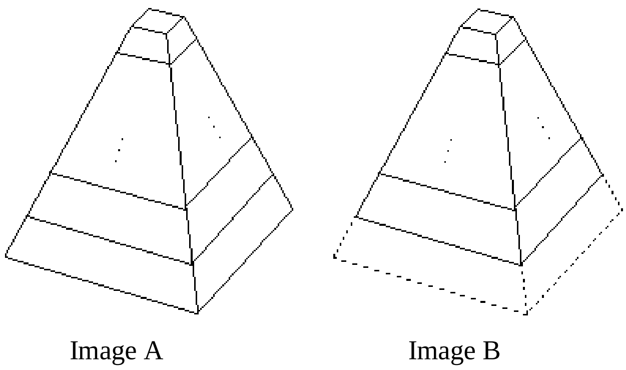

Figure 2. The use of the multiresolution analysis in the ARSIS concept.

A multiresolution analysis using the wavelet transform is applied to image A and image B, describing image A and image B at different spatial resolutions and the differences of information between the successive approximations of image A and image B. The wavelet coefficients provided by the multiresolution analysis of the high spatial resolution image A, between the scale of image A and the scale of image B, describe the missing information for the synthesis of the image B at the same spatial resolution than the one of image A.

The simplest solution is to shift the wavelet coefficients from pyramid A to pyramid B and to use them to synthesize image B at the spatial resolution of image A. If the wavelet coefficients provided by image A are used without modifications, the synthesized image B will not be equivalent to "what would be seen by sensor B if it had the spatial resolution of sensor A". Hence, to improve the quality of the synthesized image, the model, to transform the wavelet coefficients provided by the multiresolution analysis of image A in the wavelet coefficients needed for the synthesis, should take into account the physics of the environment.

Whatever this model is, the ARSIS concept preserves the spectral content of original image because of its very definition. A multiresolution analysis applied to the synthesized image B will allow the computation of an approximation similar to original image B.

As an example, Figure 3 presents the application of the ARSIS concept to the case of the SPOT imagery.

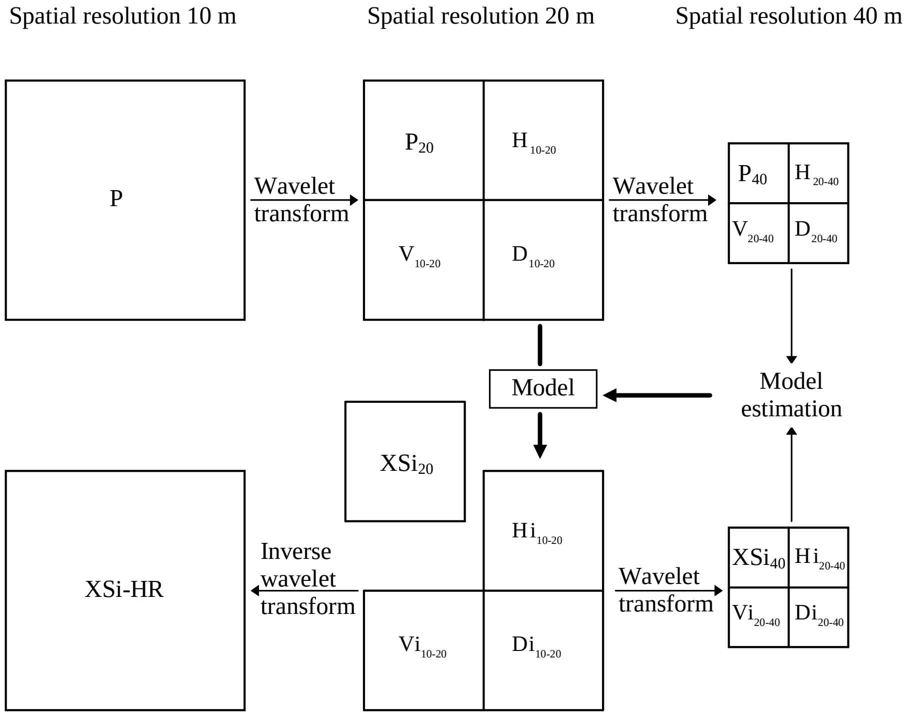

Figure 3. Application of the ARSIS concept to the SPOT imagery

The set of images is composed in this case of a panchromatic image at the spatial resolution of 10 m and three multispectral images XS1, XS2, XS3 at the spatial resolution of 20 m. The aim of the ARSIS concept is to compute the three XSi images at the spatial resolution of 10 m and to preserve the original spectral content. Two iterations of the multiresolution analysis using the wavelet transform are applied to the original panchromatic (P) image and one iteration to the original XSi image. The mother wavelet used is the one proposed by Daubechies [7]. It is an orthogonal wavelet allowing the decorrelation of the structures between the different approximations and is implemented through a four coefficients filter. A model of transformation, for each direction, from the panchromatic wavelet coefficient images to the XSi wavelet coefficient images is estimated at the spatial resolution of 40 m. This model can be of various types. The simplest one is the identity model. A convenient one can be an adjustment of the mean and the variance of the histogram of the wavelet coefficient images.

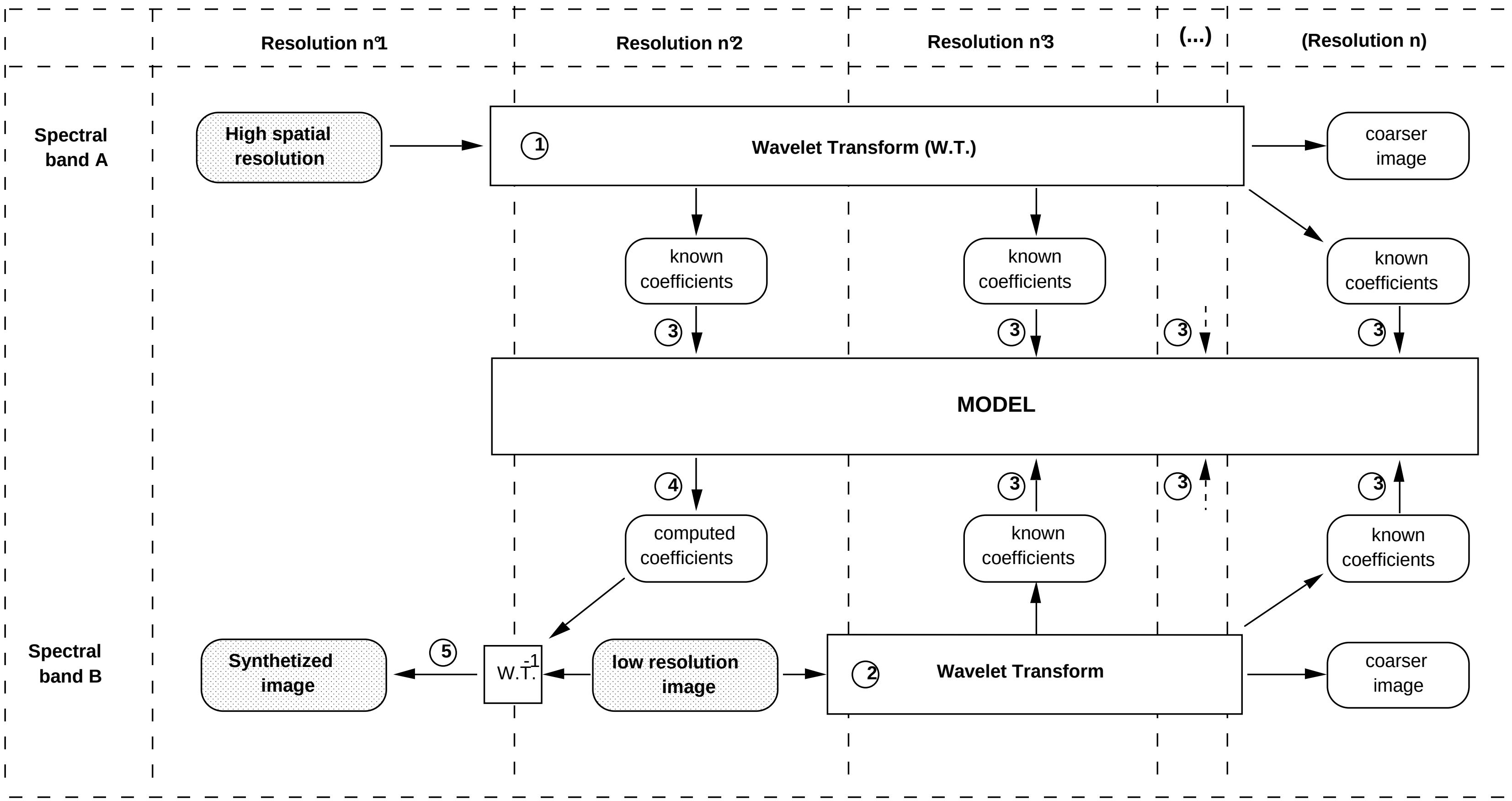

Figure 4. General scheme of the ARSIS concept.

The model must take into account the physics of both images and the correlation and anti-correlation between both images. Several models have been tested [8]. The best results were achieved with a model taking into account the local variation between the P and the XSi wavelet coefficient images. The estimated model is inferred at the spatial resolution of 20 m. Then, it is applied to the transformation of the wavelet coefficient images representing the information between 10 and 20 m of the P image, into those corresponding to the XSi image. Finally, the multiresolution analysis is inverted and the XSi image at the spatial resolution of 10 m, called XSi-HR, is synthesized from the original XSi image and from the wavelet coefficient images computed through the model.

Figure 4 presents the general scheme of the ARSIS concept. First a multiresolution analysis using the wavelet transform is used to compute the wavelet coefficients and the approximations of image A (1). The same operation is applied to the image B (2). The wavelet coefficients provided by each decomposition are used to compute a model of transformation of the known wavelet coefficients of image A into the known wavelet coefficients of image B. This model takes into account the physics of both images and the correlation or anti-correlation existing between both wavelet coefficients images (3). The model can have various forms and take into account more than one scale. This model is then used to compute the missing wavelet coefficients (4). The inversion of the multiresolution analysis (WT^{-1}) allows the synthesis of the image B with the spatial resolution of image A (5).

In this scheme, many wavelets bases have been tested. The first tests were made using bi-orthogonal wavelets, and the orthogonal wavelets provided by Daubechies [7]. The best results in the case of the SPOT imagery were achieved using the shortest orthogonal filter from Daubechies [7]. But the dyadic filters limit the application of the ARSIS scheme to a ratio which is a power of two between the images. Hence, other wavelets were used as the one provided by the iterated rational filters banks [9, 10]. These filters provide a (q-1/q) ratio between two successive approximations of the original image. These filters were used in the merging of SPOT HRV Panchromatic (10 m of spatial resolution) and Landsat Thematic Mapper (spatial resolution: 30 m). The low-pass and the high-pass filters used in this scheme have impulsional responses of respectively 21 and 11 coefficients. They introduce Gibbs effects in the synthesized images, which is degrading the visual quality of the results. In accordance to the experience, it is recommended to use the shortest filter possible in this scheme. Another solution to merge images with a ratio of spatial resolution different of a power of two is to interpolate the low spatial resolution images until such a ratio is obtained. Then the scheme could be applied and the multispectral set of images synthesized at the highest spatial resolution available.

3. EXAMPLES

The first example deals with the SPOT imagery. The SPOT HRV sensor delivers one panchromatic image with a spatial resolution of 10 m in the spectral range of 0.51 to 0.73 µm and three multispectral XS images with a spatial resolution of 20 m (spectral ranges: XS1 0.5 to 0.59 µm; XS2 0.61 to 0.68 µm; XS3 0.79 to 0.89 µm). The images were acquired simultaneously on September 11, 1990 over Barcelona (Spain). Barcelona is a large city located in the north-east of Spain, on the Mediterranean seashore. The complete area presents a harbor, an airport, urban areas with roads and motorways, rivers, agricultural lots, montaneous areas and a Mediterranean vegetation. Figure 5a presents an extract of the XS1 image on this area. This extract contains agricultural lots mixed with urban area. The roads and the motorways are clearly visible, though the interchanges on the motorways are difficult to distinguish.

Figure 5b presents the same extract as Figure 5a provided by the Panchromatic sensor of SPOT. In this extract, one can clearly evaluate the difference of spatial resolution between 20 and 10 m. In the case of the panchromatic image, the interchanges can be easily follow.

The ARSIS concept allows to synthesize the multispectral images (image B) with the spatial resolution of the panchromatic image (image A), i.e. 10 m. The resulting images are called XSi-HR. The XS1-HR image is presented Figure 5c. In order to facilitate the comparison of the images, the original XS1 image was interpolated using a nearest-neighbor algorithm. The visual quality of the XS1-HR image is due to the injection of the information extracted from the panchromatic image. This information was modeled in order to reach the requirement of being as close as possible of the one that will be provided by a multiresolution analysis if the sensor have the spatial resolution of 10 m. On the XS1-HR image, one can clearly distinguish the interchanges on the motorways, the road network in the upper left corner of the image and the large buildings.

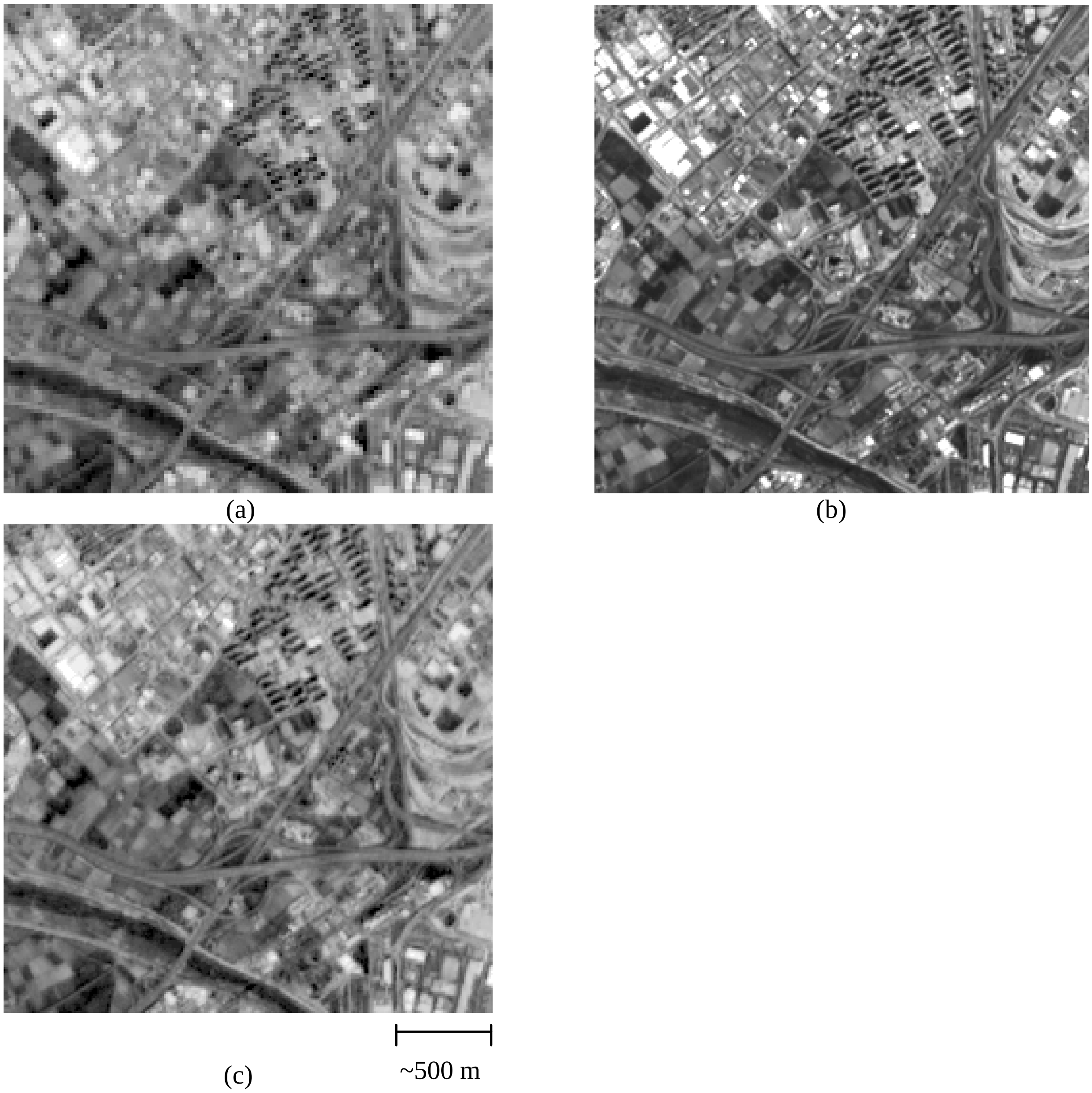

Figure 5. (a) Original XS1 image (20 m). Copyright CNES-SPOT Image (1990). (b) original panchromatic image (10 m). Copyright CNES-SPOT Image (1990). (c) Synthesised XS1-HR image (10 m).

In the second example, the set of images is composed of a SPOT XS scene of the town of Riyadh (Saudi Arabia) acquired on May 16, 1993 and a Russian image KVR-1000 of the same area acquired on September 7, 1992. The three multispectral images (image B) have a spatial resolution of 20 m and the KVR-1000 image (image A) has a spatial resolution of 2 m and a spectral range of 0.51 to 0.71 µm. Figure 6a presents a composition of the original XS images. In this image, only the very big structures are visible. One can easily understand the interchange in the upper left part of the image but will have a lot of difficulties to distinguish the buildings.

(a) (b)

Figure 6. (a) Composition of the original XS images. (b) Composition of the synthesised XS images (2 m).

The ARSIS concept allows the computation of XS images at the spatial resolution of 2 m. Figure 6b shows a composition of these synthesized images. In this case, the gap between the spatial resolution of image A and of image B is important. This area is composed of a large interchange of two urban motorways, a lot of buildings and some sandy areas. The large object at the right side of the motorway, in the lower part of the Figure 7b, is a mall. Due to the small details which appear in the synthesized image it is possible to distinguish the structures of this mall, and all the buildings in this area. The preservation of the spectral content of XS images, allows the application of a classifier, automatic or not, in order to extract the roads and the buildings.
Hence, they can be used for classification, or for other methods that need to use the multispectral content provided by the whole set of images with the best spatial resolution available. Ranchin and Wald [11] have shown the improvement brought by the use of the ARSIS concept, to extract roads in urban areas by the means of classification methods.

4. CONCLUSION

In this paper, the ARSIS concept was introduced and exposed. This concept is a general framework for the improvement of the spatial resolution of images in a set of images with different spatial and spectral resolutions. This concept fills the requirement of preserving the spectral content of the original images. In this framework, the wavelet transform is used to model the difference of information between the different images. Many wavelet bases were tested, and it was found that the shorter the filter, the better the results. The physical part of the ARSIS concept is contained in the model of transformation of the wavelet coefficients of both images.

This concept was successfully applied to the merging of SPOT 1,2,3 HRV P and XS images, of Landsat TM 6 (120 m) and other TM images (30 m)[12], of Landsat TM (30 m) and SPOT P (10 m) images [9, 10] and to KVR-1000 and XS images. It was also demonstrated that the concept can be applied to the future SPOT 4[13] and the future SPOT 5[14] cases.

In a very near future, ARSIS will be applied to the merging of airborne (0.8 m) and SPOT 5 simulated images (P: 5 m; Bi: 10 m). The concept shall also be used in the improvement of the multispectral images of the future high resolution satellites like Earlybird, Quickbird, Orbview3, IKONOS 1, ... up to the spatial resolution of the panchromatic images of these sensors.

An evaluation of the quality, the potential and the usefulness of the synthesized images will be also realized in applications such as urban mapping, air quality, ecology and geology.

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