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FUSION OF IMAGES AND RASTER-MAPS OF DIFFERENT SPATIAL RESOLUTIONS BY ENCRUSTATION:
AN IMPROVED APPROACH

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ABSTRACT

The present paper addresses the problem of the encrustation of a high spatial resolution imagette into an image of lower resolution of larger geographical extent. A method is proposed which makes use of the high resolution content of the imagette to simulate the high resolution content in the outer periphery of the imagette area. The originality of this approach lies into its ability to simultaneously attenuate the edges caused by the differences in resolution and increase the quality of the lower resolution image in the outer periphery in the sense that it becomes closer to the actual information at high resolution. These properties are demonstrated both visually and quantitatively. A SPOT image of the city of Barcelona (Spain) provides a didactic example of the problems and solutions as well as of the benefit of encrustation. The increase in quality compared with the standard raw encrustation procedure is quantitatively assessed for both the edge smoothing and the simulation of the actual information. Unsurprisingly the proposed approach provides better results than the standard method. It is illustrated by the construction of an albedo map for large Europe made up of three different images of different resolutions.

INTRODUCTION

Remote sensing images as well as maps in raster format are currently used in the studies of our environment, including areas of human activities. They have proved to be very valuable in many applications. Such images are provided either by satellite observations, or by the digitisation by a scanner of paper maps. Their digital format enables their processing by means of computers and GIS or image processing softwares. These images (satellite data, or maps) offer two characteristics: each image has its own spatial resolution, and each image has its own geographical coverage. For example, a SPOT colour image has a pixel size of 20 m and a geographical coverage of 60x60 km^2. The raster map resulting from the digitisation of a paper map at a scale of 1/ 50 000, has a reasonable pixel size of 5 m and a coverage of say 20x20 km^2 which may be partly due to the scanner characteristics. It also often happens that the geographical area of interest is only partly covered by one image and that mosaicking is required.

The present paper addresses the problem of merging images (including rasterized maps) having different spatial resolutions which overlap partly each other. It is a follow-on of previous works dealing with the merging of satellite images having different spatial resolutions published by Mangolini *et al.* (1993) and Ranchin *et al.* (1993, 1994). It mostly makes use of the same advanced mathematical tools, namely the wavelet transform and the multiresolution analysis (Ranchin, Wald, 1993a, b). Though it only deals with the merging of data presenting the same type of information, it extends the previous studies because it addresses the case of images partly overlapping each other. Specifically the present paper deals with the problem of the encrustation of a high spatial resolution imagette into an image of lower resolution with the attenuation of the discontinuities created at the edges of the imagette by the difference in resolutions.

It is assumed that both the image and imagette offer the same level of "radiometric" accuracy, *i.e.* that the measurements carried by a pixel in each image have the same accuracy. No choice can be made between both images, but for spatial resolution reasons. In that case, the encrustation of the high resolution imagette into the wider low resolution image is the best way to merge the data and obtain a final image offering the highest spatial accuracy. This is also true if the imagette exhibits higher level of "radiometric" accuracy than the image.

After having illustrated the benefit of the encrustation of high resolution data into lower resolution image, a method is proposed for the attenuation of the edges marking the limit between both resolutions and for a better simulation of the actual data at the highest resolution. A SPOT image provides a didactic example of the problems and solutions as well as a test case to assess quantitatively the qualities of the image resulting from the merging. Another case is presented which addresses the construction of a digital atlas for large Europe in meteorology.

ILLUSTRATION OF THE BENEFIT OF ENCRUSTATION

The benefit of encrustation is now illustrated by an examination of the loss (respectively gain) of information when degrading (respectively upgrading) the resolution of an image. A SPOT image of the city of Barcelona (Spain) is used in this scope (Figure 1). Its spatial resolution is 10 m. Barcelona is a large city located in North-East of Spain on the Mediterranean seashore. Its harbour is the busiest in Spain (right part of Figure 1). Very close to it is the dominating citadel of Montjuich, surrounded by a park, in light grey tones, sloping down to the oldest city. The latter offers winding and narrow streets bordered by old buildings. It contrasts with the newest ones with their spaced buildings, and their larger streets of a quadrangular architecture.

The smoothing of this image provides an image which pixel size is still 10 m, but its effective resolution is 80 m. This image is called "80 m smoothed image" in the following. It is not presented as such here because of the lack of space. However it can be seen partly in Figure 2. This Figure displays an encrusted image resulting from the encrustation of a high resolution imagette extracted from Figure 1 into the 80 m smoothed image. Thus apart the encrusted part, this image is similar to the smoothed one. The examination of images 1 and 2 and of their differences clearly demonstrates the large amount of information which is gained when the spatial resolution increases from 80 m to 10 m. Contours are blurred in Figure 2. Buildings and streets are clearly visible in the 10 m resolution image (Figure 1) while even large streets are hardly visible in the 80 m resolution image (Figure 2). The loss of information between the reference image (10 m resolution) and the "40 or 80 m smoothed

image" is quantified by computing the difference between both images for every pixel of 10 m located in two sub-areas. One is a portion of the Mediterranean Sea (right of Figure 1) and exhibits a very homogeneous aspect. The second is a portion of the city with a highly variable aspect. The differences are synthesised by a few parameters: bias, difference of variances, correlation coefficient. They are presented in Table 1, together with the ideal values for a no-loss / no-gain case. The first two parameters are expressed relatively to respectively the mean and the variance of the original 10 m image, computed for the urban area.

The bias is the difference in average values. It is small: the spatial averaging used to degrade the resolution is known to slightly alter the average values. The difference in variances expresses the difference in information. The latter can be expressed in a similar way by other parameters such as the entropy. The choice of a peculiar parameter does not affect the conclusions. If the difference is small, the loss of information is small. This is the case of the homogeneous sub-area. There are only a very few structures in this sea part with sizes comprised between 10 m and 40 m. Their disappearance in the 40 m smoothed image (not presented) does not affect the quantity of original information in a noticeable way. For 80 m, the effect becomes larger but is still small. For this homogeneous sub-area, the correlation coefficient is very close to 1; but the significance of this coefficient is low because of the lack of visible features. For the urban sub-area (heterogeneous sub-area), the situation is quite different. Many structures have a size comprised between 10 m and 40 m or 80 m. Passing from resolution 10 m to 40 m results into a loss of about half of the original information; the correlation coefficient is now only 0.87 (not presented in Table 1). For resolution 80 m, the results are worse. About three-quarters of the information is lost, and the correlation coefficient is lower than 0.7. This example clearly demonstrates the interest to have images with the best available spatial resolution and therefore the need for efficient encrustation procedures.

	40 m		80 m	
	homogeneous sub-area	heterogeneous sub-area	homogeneous sub-area	heterogeneous sub-area
Bias (no loss: 0 %)	2 %	2 %	1 %	2 %
Difference in variances (no loss: 0 %)	0%	49 %	7 %	72 %
Correlation coefficient (no loss: 1.00)	0.93	0.87	0.97	0.69

Table 1. Loss of information between the original image at 10 m resolution and degraded images at 40 m and 80 m effective resolutions.

ENCRUSTATION OF IMAGES: A NEW APPROACH

Encrustation is usually made according to the following raw approach. At first the high resolution imagette and the low resolution image of larger geographical coverage are re-mapped onto each other or onto a common geographical reference. The resulting re-mapped image and imagette offer now the same pixel size, but with different effective spatial resolutions. Then an encrusted image is computed, made of the values of the re-mapped imagette when available and of values of the re-mapped image otherwise.

In the following image and imagette denote these re-mapped image and imagette for the sake of the simplicity. As can be seen in Figure 2, the encrustation creates edges that clearly appear and which are due to the dramatic change of resolution at the periphery of the imagette. These edges are often disturbing in photo-interpretation. Also the discontinuities at the periphery (abrupt changes in derivatives) prevent digital processing methods such as edge detection and pattern recognition to function as they should do. There is a need for improved methods for encrustation. One common solution is to apply a filter to smooth the inner periphery (or even the inner and outer periphery) of the imagette. This filtering may attenuate very efficiently the edges but has a definite drawback. The high resolution content of the periphery is replaced by information of lower accuracy. If the smoothing has been applied to the outer periphery, too, it also implies a degradation of the accuracy for this area.

We developed a method for encrustation which attenuates the edges but still preserves the information content of the whole imagette and provides a better simulation of the actual information for the outer periphery, that is,

it increases the accuracy of this area. This method mostly makes use of the following advanced mathematical tools, the wavelet transform and the multiresolution analysis. These tools enable an image to be decomposed into the structures of different sizes which participate to its information content. Some examples for images in remote sensing can be found in e.g. Ranchin, Wald (1993a, b). In this paper, we do not intend to present the mathematical basis of our approach which only exposed in a simplified manner.

It has been said that the edges are due to the abrupt transition from one resolution to another at the periphery of the imagette. In the inner periphery, are present structures of any size including ones of small size (high frequencies in signal theory). In the outer periphery, are present only structures of larger size. The low resolution means an absence of structures of small size which can only be observed in the high resolution. The principle of our approach is that attenuation of the edges can be made if some structures of small size can be injected in the outer periphery. It would result in an increase of the effective resolution, thus creating a smooth transition in resolutions and attenuating the edge effects. The multiresolution analysis permits to extract small size structures from the imagette. Here only the periphery is of interest and dealt with. The wavelet transform provides for each pixel the change in information content between two consecutive resolutions, by the means of the so-called wavelet coefficients. The larger these coefficients in absolute value, the more visible the corresponding structures. For the highest resolutions, *i.e.* the smallest structures sizes, the wavelet coefficients are large in the inner periphery (high resolution) and null or very weak in the outer periphery. Increasing the latter is equivalent to an injection of structures of small size, which is our objective. The wavelet coefficients in the outer periphery are replaced by a linear combination of the wavelet coefficients in the inner periphery. The parameters of the combination are a function of the distance to the edge. Then the inverse wavelet transform is applied to obtain the encrusted image with smooth edges.

ASSESSMENT OF THE QUALITY BY APPLICATION TO A TEST CASE

The proposed method is now applied to a test case in order to prove its quality in comparison with the standard procedure (raw encrustation). The test is as follows. The SPOT image of the city of Barcelona (Figure 1) is used as a reference. An imagette is extracted from the reference image and is encrusted into the 80 m smoothed image. Processing such a case allows a good understanding of the method and quantitative assessments of its qualities since a truth is available. Two encrusted images are made according to respectively the raw procedure, and the proposed one. The results are presented and their visual aspects as well as their quantitative qualities are discussed.

An urban area has been selected for this test case because this is certainly the most difficult type of landscape to process from a numerical point of view. Hence urban areas often point out the drawbacks and qualities of algorithms. This is due to the high variability of the information induced by the diversity of the features sizes. Urban areas exhibit many structures of small sizes, but also some with medium and large sizes. Furthermore, this image offers also some homogeneous areas within the sea part, which serves as a test for the method and helps in understanding and confirming its results.

Figure 2 displays the encrusted image obtained by our method. In the encrusted image, pixels have either an effective resolution of 80 m (outside the area corresponding to the imagette), or 10 m (inside this area). Large structures such as roads and railways can be followed across the image whatever the resolution. However the change of resolution is marked and clearly affects photo-interpretation. In Figure 3 is magnified the upper left corner of the encrusted area. The left part displays the result of the raw encrustation, while the right part shows the result of our procedure. Because of the principle itself of the test case, where the same data are encrusted into themselves, the visual differences are small. However they still exist. Close examination shows that the outer periphery exhibits larger variability in right than in left. This higher variability makes a smoother transition from the high resolution part to the low resolution. Though the differences are faint, it confirms visually the better results achieved by our method. The edges have been smoothed without alteration of the features larger than 80 m. Another example is given later with larger visual differences.

Once this visual inspection done, some questions must be answered in a quantitative fashion:
- how much are smoothed the edges when compared to the raw encrustation procedure ?
- does the new information introduced by our method lead to a better representation of the 10 m reference when compared to the raw encrustation procedure ?

The answers are provided in the following by doing different comparisons of images.

As already said, a raw encrustation of a high resolution imagette into a low resolution image of larger geographical coverage creates a discontinuity along the periphery of the imagette. The disturbing effect of this discontinuity is quantified as follows. The two encrusted images are smoothed in order to have an uniform effective resolution of 80 m everywhere, *i.e.* including the high resolution imagette. These degraded images are compared to the 80 m smoothed image. The comparison is limited to the inner and outer periphery of the imagette since it is the seat of the discontinuity.

The results are presented in Table 2, using the above-defined parameters. Only the heterogeneous sub-area is dealt with since it is the most difficult case. For the homogeneous sub-area, the difference is small: because of the lack of structures of small size, the difference between the high and low resolution is small. In Tables 2 and 3, our procedure is noted "smooth encrustation". In these Tables are reported the ideal values for the comparisons. The greater the gap between the parameter and its ideal value, the greater the discontinuity. The bias is small. This is an expected result: the discontinuity only affects the spatial variations in the image (the derivatives of the signal) and not the average value. The difference of variances is rather high for the raw encrusted image. The proposed method divides it by two and therefore gets closer to the ideal value. The correlation coefficient is high in both cases, which means that in both cases the structures are mostly preserved despite the discontinuity. Recall that here the structures under concern are only those having a size larger than 80 m.

Other difference parameters (not presented in Table 2) show that forty per cent of the pixels have a similar value in the encrusted and the reference images, *i.e.* no change. Almost all of the pixels exhibit a relative error (difference between the reference and the encrusted images divided by the reference value) lower than 5 %. The better results demonstrates quantitatively the attenuation of the edge effects by the proposed method. These results are the quantitative companions of the visual inspection in Figure 4.

	ideal	raw encrust.	smooth encrust.
Bias	0 %	1 %	1 %
Difference of variances	0 %	14 %	7 %
Correlation coefficient	1.00	0.99	0.99

Table 2. Assessment of the effects of the discontinuity. Differences between the 80 m smoothed image and the encrusted images, smoothed down to 80 m everywhere.

Our approach injects information of small sizes in the outer periphery in order to decrease the discontinuity. It is now demonstrated that these alterations lead to the following result: our encrusted image is a better representation of the 10 m reference image than the raw encrustation one. In order to assess the quality of the simulation of the actual information (given by the reference image), structures of any size are dealt with, including the smallest ones (lower limit is 10 m). The differences between the reference and the encrusted images are computed for the outer periphery and presented in Table 3. The smaller the gap between the results and the ideal values, the better the simulation of the actual information.

	ideal	raw encrust.	smooth encrust.
Bias	0 %	2 %	2 %
Difference of variances	0 %	72 %	64 %
Correlation coefficient	1.00	0.69	0.74

Table 3. Assessment of the simulation of the actual information. Difference between the reference image and the encrusted images for the outer periphery of the imagette.

Of course, the raw encrustation procedure exhibits the same results than Table 1 which deals with the comparison between 80 m smoothed image and the reference image. For the proposed method, the change compared with Table 1 (therefore with raw encrustation) comes from the fact that the new approach extrapolates the structures of the smallest sizes from the imagette into its outer periphery. The bias is small in any case for the above-mentioned reasons. For all other parameters, the new approach provides better results than the raw

encrustation, *i.e.* closer to the ideal values. For example, the difference of variances decreases from 72 % (raw approach) down to 64 % for the smooth encrustation. Also the number (in per cent) of pixels having a relative error lower than 5 % amounts to 51 % for the smooth encrustation compared with 47 % for the raw one (not presented in Table). This Table demonstrates that the new approach provides a better simulation of the actual information than the other method.

We have provided answers to all questions and we have quantified the quality of the encrusted images resulting from our approach. The figures in the previous Tables depend of course upon the test case. However the conclusions drawn during this test case are likely not to depend upon the cases. Indeed they are reflecting the properties of the mathematical tools employed in our approach, which are case-independent.

APPLICATION: CONSTRUCTING A MAP OF ALBEDO

Another example is now given to illustrate the proposed method. In the course of the realisation of a digital atlas related to climatology and solar radiation for large Europe (Scharmer, 1994), we have to construct a map of albedo. The albedo is a property of any object which characterises the relative quantity of light reflected by this object. To achieve this goal, three different albedo maps were available. All three were derived from a proper processing of images taken by the geostationary meteorological satellite Meteosat according to the procedure described by Moussu *et al.* (1989). These images were re-mapped onto the same map in rectangular co-ordinates. Every pixel has a size of 5' of arc angle. Two images offer high effective resolution (about 5') but limited geographical coverage: Western Europe, and Egypt and part of Middle East. The third image offer a lower effective resolution (about three times lower) but has a larger geographical extent.

Figure 4 displays the encrusted image resulting from our approach. The background map represents the total coverage of the atlas. Albedo increases from black to white. Albedo of the sea has been set to an uniform value for the sake of the simplicity, though the authors are fully aware of the large variability of the albedo of the ocean as a function of geometry, meteorology and ocean (see e.g. Wald, Monget 1983). The benefit of the fusion of images is highly visible. Among other striking features are the improvement of the albedo values close to the coastlines and in islands of limited extension as well as of the geomorphologic structures. Indeed such an encrusted image is of high benefit in a detailed digital atlas. As a final illustration of the improvement brought by our method to the encrustation problem, Figure 5 displays a magnification of the upper part of the encrusted Middle east imagette. The raw encrustation is on the left, the smooth one on the right. Edges are less marked on right without alterations of the large structures.

This case also demonstrates the ability of our method to cope with different types of data and different resolutions. This albedo map is now part of the climatic data base available from Ecole des Mines de Paris. It should be completed for the missing part by merging this map with other maps originating from a proper processing of either polar-orbiting satellite images, or digitised paper maps.

At any geographical location the confidence level of the information of the final image is defined. If the high resolution part of the final image is allotted a value of say 1, then the other parts of the image are allotted a lower confidence level with a ratio which can be for example, the same ratio than for the spatial resolutions, *i.e.* one-third. In the outer periphery of the high resolution areas, the confidence level degrades with the distance to the edge.

CONCLUSION

We have presented a new approach for encrusting a high spatial resolution imagette into a lower resolution image of larger geographical extent. The proposed method makes use of the high resolution content of the imagette to simulate the high resolution content in the outer periphery of the imagette area. The originality of this approach lies into its ability to simultaneously attenuate the edges caused by the differences in resolution and increase the quality of the lower resolution image in the outer periphery in the sense that it becomes closer to the actual information at high resolution. We have demonstrated both visually and quantitatively these properties. The increase in quality compared with the standard raw encrustation procedure has been

quantitatively assessed for both the edge smoothing and the simulation of the actual information. It has been unsurprisingly found that the proposed approach provides better results than the standard method.

The ability of our method to cope with different types of data and different resolutions has been demonstrated. The original information content of each image is fully respected during the fusion process, except two areas. Firstly the low resolution data are replaced by the high resolution ones which is the scope of encrustation: it preserves the content of the original imagette. Secondly the low resolution data pertaining to the outer periphery of the imagette area are improved and offer now an intermediate effective resolution.

The confidence level of the information of the final image is defined at any geographical location. Thus users are aware of the quality of the data they are using, either in photo-interpretation, to draw maps for example, or in automatic processing procedures. The imagette area exhibits the most accurate information if the accuracy is defined as expressing the difference between the actual information and the information carried by a pixel. The accuracy degrades quickly with the distance to the periphery of this area, reaching a constant value for the remaining of the image. For the structures of sizes larger than the lower resolution (for example 80 m in our test case), the accuracy can be considered as constant throughout the image because of the low influence. The present approach has been developed in order to enable the application of digital techniques to get closer to the final results. This allows a better mastering of the quality of the final product and eventually decreases the amount of time spent by an operator.

Though the proposed method provides better results than the standard approach, the attenuation of the discontinuity is not strong enough to allow standard algorithms for edge detection to work properly. However these good results already achieved in both the attenuation of the edges and the simulation of the actual information indicate the strong potentials offered by methods based upon the advanced mathematical tools as used in this work.

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FIGURE CAPTIONS

Figure 1.   A SPOT image of the city of Barcelona (extract). Spatial resolution is 10 m. Copyright CNES - Spot-Image.

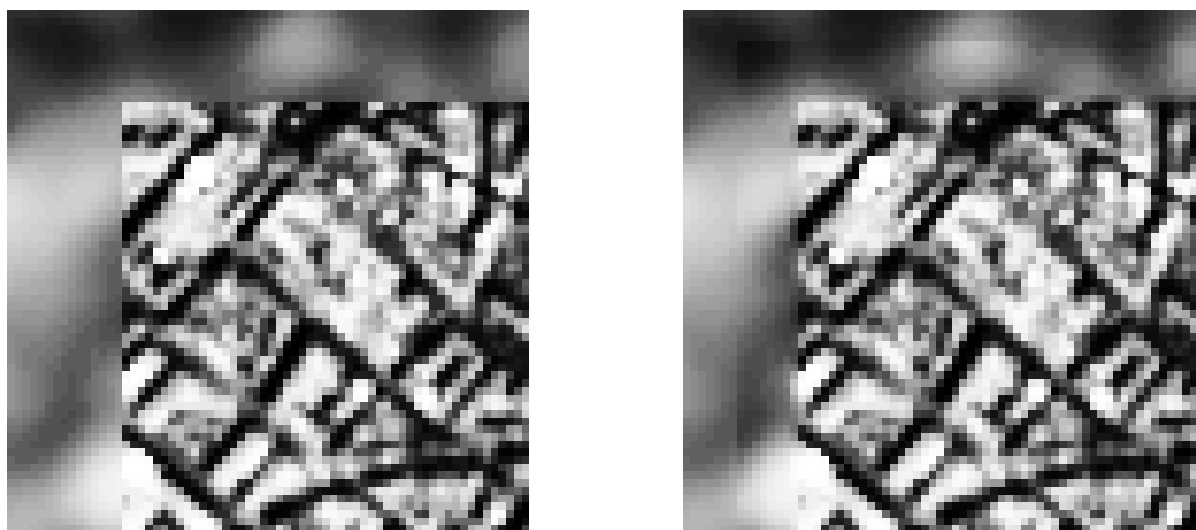**Figure 2.**   Encrusted image obtained by the proposed method.

Figure 3. Magnification of the upper left corner of the encrusted area. Left: raw encrustation, right: our procedure.
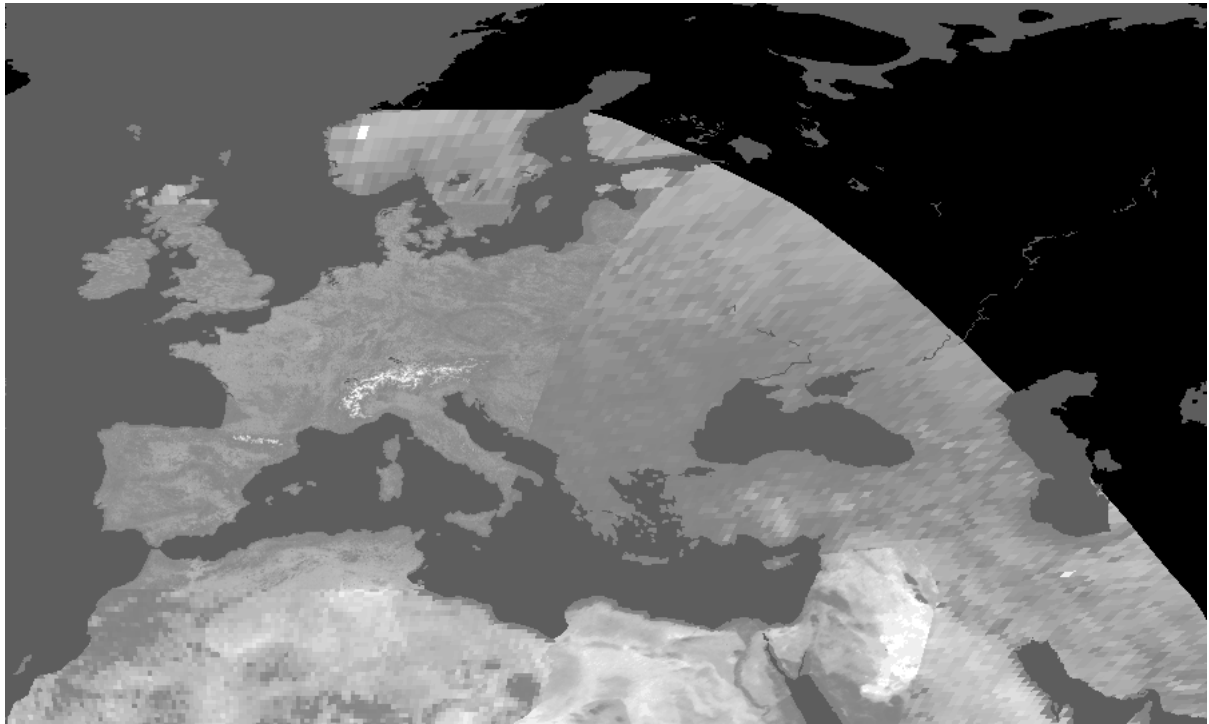
Figure 4. Final albedo image resulting from the encrustation of the high resolution imagettes into the low resolution image. The background map represents the total coverage of the atlas. Albedo increases from black to white. The high resolution albedo images cover the limited geographical coverage: Western Europe, and Egypt and part of Middle East.
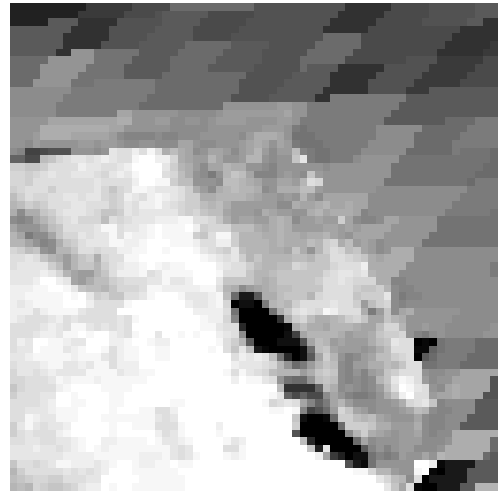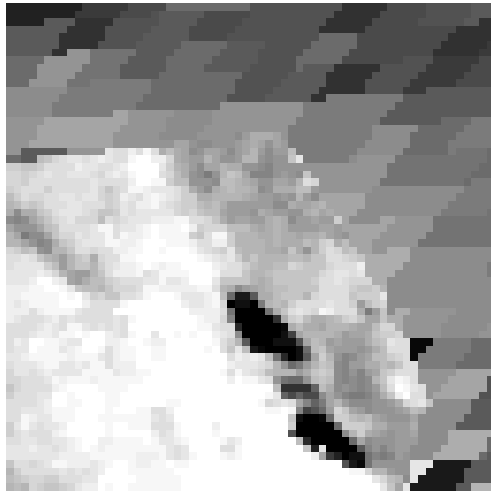
Figure 5. Magnification of the upper part of the encrusted "Middle East" imagette. Left: raw procedure, right: our procedure.