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Monitoring the sea breaking zone in northwest Portugal using Earth observation satellites

André R.S. Marçal, Ana Cláudia Teodoro & Luísa Castro
Faculdade de Ciências, Universidade do Porto (andre.marcal@fc.up.pt), Portugal

F. Veloso Gomes
Instituto de Hidráulica e Recursos Hídricos, Faculdade de Engenharia, Universidade do Porto, Portugal

Alexandra L. Nunes
Faculdade de Ciências, Universidade do Porto / Instituto Superior de Engenharia do Porto, Portugal

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ABSTRACT: The coastline of Portugal is periodically surveyed by aircraft and the photographs acquired, usually at 1:8000 scale, are used for coastal protection studies. The air photo surveys are expensive and there would be great benefits if they could be replaced by processed images from Earth Observation Satellites. This paper presents the results of an ongoing project, which aims to evaluate the applicability of passive satellite images for coastal protection studies. Images from Landsat TM, SPOT HRVIR and ASTER were used. The initial visual inspection of these images was very encouraging. Two lines of work are currently being pursued - a quantitative and an image exploration approach. The first attempts to estimate the amount of sediments present in the various areas around the sea-breaking zone, by calibrating and atmospherically correcting the satellite images, and to use an established relationship between the amount of suspended sediments and the seawater reflectance. The second approach is to use unsupervised classification and data clustering algorithms to automatically identify different areas in the sea-breaking zone. The current status of each line of work is described and the plans for future work discussed.

1 INTRODUCTION

The coastal zone is a dynamic region where multiple interactions occur, due to both natural and human induced causes. The development of urban areas and tourism activities in the coastal areas result in a need for coastal protection studies and constructions. This is a major issue in continental Portugal, where most of the population live nearby the sea.

Air photographic surveys are an important tool to support coastal protection activities. A number of air surveys have been carried out periodically, covering the whole Portuguese coast. These should ideally be done at least twice a year. However, in the last few years the air surveys were done irregularly and less frequently than required - only about once every 2 years. Figure 1 shows a detail of a photograph from one of these air surveys, at scale 1:8000. There would be great benefits if the aerial photographs could be replaced by processed images acquired by Earth Observation Satellites (EOS). A single satellite image covers a large area and the costs involved in covering the whole coastline could be significantly reduced. Furthermore, if the satellite images prove to be effective, the existing archives could be searched for images that could be used to fill the gaps in past coverage.

This paper presents the current status of an ongoing research project, the COSAT project – COastal zones monitoring using remote sensing SATellite data. It is a joint effort of two research groups, in remote sensing and in coastal protection, both from the University of Porto. The objective is to establish a methodology to extract meaningful information for coastal protection from EOS images. The final objective is to implement a Geographic Information System (GIS) with multi-temporal and multi-scale image data of the study area.

Figure 1. Example of an air photo of the coastline.

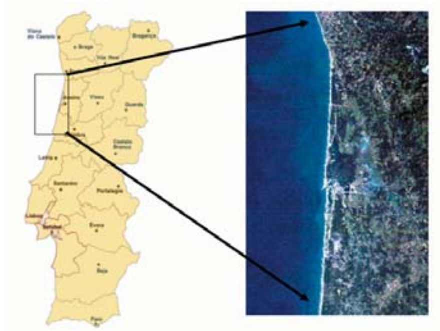
Figure 2. Study area location, NW Portugal.

2 PROJECT STRATEGY

A section of about 80 km of coast in the northwest of Portugal, around Aveiro, was chosen as a test area. This region was chosen, as it is an area where the coastline shape changes rapidly. Figure 2 shows the location of the study area. The first objectives were to establish which satellite sensors could be used and if the same sort of patterns observed in the air photos could be identified on the satellite images.

Table 1. EOS sensors providing multi-spectral images adequate for coastal protection applications.

Satellite sensor	Spatial characteristics		Spectral coverage		Temporal coverage	
	Pixel size	coverage	No. bands	Range (μm)	Frequency	Availability
Landsat MSS	80m	185 km	4	0.5-1.1	~2 weeks	since: 1972
Landsat TM	30(120)m	185 km	7	0.45-12.5	~2 weeks	1984
SPOT HRVIR	10/20m	60 km	4	0.5-1.75	~2 weeks	1986
ASTER	15/30(90)m	60 km	14	0.4-14.4	~2 WEEKS	2001
MODIS	250-1000m	1000+ km	36	0.5-1.1	daily	2001
MERIS	300-1200m	1000+ km	15	0.39-1.04	2-3 days	2003

2.1 *Satellite data sources*

The level of spatial detail of the 1:8000 air photos is very high, but the coverage of a single strip is too narrow, only about 2 km around the coastline. In addition, covering the whole coast of continental Portugal (about 800 km) requires several hundred photographs, which is costly and is a limiting factor for the frequency of data acquisition. The satellite sensors considered being the most useful for monitoring coastal areas are listed in Table 1. Landsat TM, SPOT HRVIR and ASTER provide multi-spectral images with a good spectral range and between 10 to 30 meter pixels. The new SPOT 5 satellite provides images with even higher spatial resolution, up to 2.5m (SPOT IMAGE 2004). Very high spatial resolution sensors, such as IKONOS and Quickbird, were not considered, because the coverage of the whole coast of Portugal would be even more expensive than using aerial photographs. Landsat MSS is included in Table 1 as it might be a useful source of information from the 1970s and early 1980s, although the spatial resolution is rather low. The new MODIS and MERIS sensors were also included mainly because of the good calibration accuracy and high frequency of image acquisition. MODIS data in particular can be useful, as there are currently 2 MODIS operating on TERRA and AQUA satellites and the data distribution is very convenient (MODIS web 2004).

Table 2. High spatial resolution EOS images used.

Satellite sensor	Date	Time	Tide height (m)	Comments
Landsat TM	9 Nov. 1989	10:45	2.95	
Landsat TM	4 May 1990	10:45	2.33	
Landsat TM	1 Nov. 1992	10:45	1.85	
Landsat TM	13 June 1993	10:45	2.47	
Landsat TM	24 July 1997	10:45	1.09	
SPOT HRVIR	14 Oct 1998	11:35	2.85	Fig. 3, RGB colour composite
ASTER (I)	8 Oct 2001	11:43	1.29	Fig. 7, classified image
ASTER (II)	24 Oct 2001	11:43	2.07	

2.2 *Initial evaluation*

Satellite data archives were searched for images of the test area. A total of 8 high resolution images were acquired, 5 from Landsat TM, 2 from ASTER and 1 from SPOT HRVIR. The list of images used is presented in Table 2, together with the tide height at the time of each image acquisition. Several MODIS images were also used. The use of MERIS images is also planned, following a category 1 project recently approved by ESA.

A visual inspection of enhanced RGB colour composites from the various sensors showed that these satellite images seem to contain valuable information for coastal protection studies. The same sort of patterns observed in true colour aerial photographs can be observed in enhanced RGB colour composites of the satellite images tested. In fact, using a RGB colour composite with near infrared, red and green allows for better discrimination of areas in the sea breaking zone than the true colour images. Figure 3 shows a RGB colour composite of bands 321 of the SPOT image.

In order to extract meaningful information from the satellite images, two alternative approaches were envisaged. The first is a quantitative approach, which attempts to estimate the amount of sediments present in the various areas around the sea-breaking zone. The second approach is to use image exploration techniques, such as unsupervised classification. The aim is to identify different areas in the sea breaking zone automatically, based exclusively on the uncalibrated DN values.

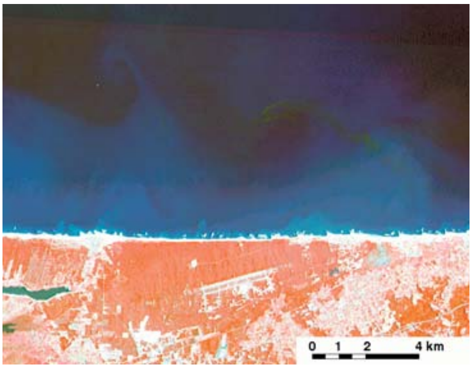

Figure 3. Detail of the SPOT HRVIR image. RGB colour composite of band 321, 14 October 1998.

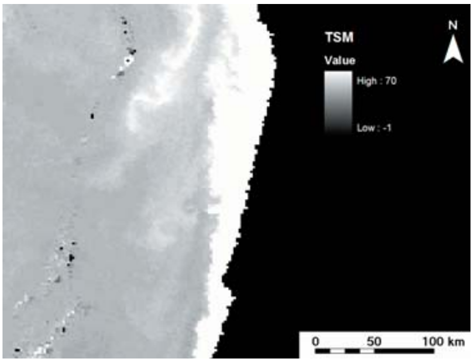

Figure 4. Example of an image with TSM values from MODIS, 24 October 2001.

3 QUANTITATIVE APPROACH

The main objective of this approach is to obtain measurements of Total Suspended Matter (TSM) from a satellite image. This task would not be necessary for low spatial resolution, as one of the several MODIS processed products (susp-solids-conc) delivered daily by NASA is TSM 1 km images (MODIS web 2004). Figure 4 shows a TSM image from MODIS of the study area, from 24 October 2001. Although the 1 km resolution is too low to replace the air photo surveys used for coastal protection, the MODIS TSM data could nevertheless be useful as a validation tool for the results obtained with higher spatial resolution images.

3.1 *Relationship between TSM and reflectance*

The dependence of the water reflectance with the amount of suspended matter is a well-known fact in remote sensing. Several studies addressed this issue in the past, with field measurements taking place in lakes (Ritchie et al. 2003), estuaries (Doraxan et al. 2002) and rivers (Froidefond et al. 2002). Although these authors provide relationships between water radiance/reflectance and the amount of suspended sediments, the sediment concentration range and type is highly variable with location and date.

As the type of sediments and corresponding spectral properties is varied, field surveys in the study area were required in order to establish a valid relationship between water reflectance and the amount of TSM. The field surveys in the breaking zone proved to be a hard task, as this is an extremely difficult area to work on. The plan was to make measurements with a spectroradiometer and simultaneous collecting water samples for laboratory analysis. Two types of boats were used but no valid measurements were recorded in the breaking zone. A field survey with a helicopter was also carried out with moderate success. The range of TSM values covered was too small in both the helicopter and the boat surveys. The most effective method proved to be a simulation using large recipients at the beach. After several attempts in different beaches in the study area, a relationship between sediment concentration and reflectance was established for the visible and near infrared parts of the spectrum. Figure 5 shows the experimental plots for 10 samples, with TSM between 14 and 449 mg/l, for the spectral range 0.4 to 0.9 μm. These plots were used together with the normalised response function of the TM, HRVIR and ASTER sensors to obtain a relationship for the expected reflectance (ρ_i) as a function of TSM (T_i), for each pair sensor/band (i). Equations (1) and (2) were used, where A_i and B_i are empirical parameters.

$$\rho_i = A_i + B_i T_i \quad (1)$$

$$\rho_i = C_i D_i^{Ti} \quad (2)$$

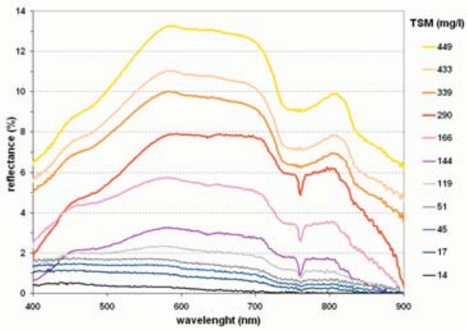

Figure 5. Experimental reflectance profile of water with various levels of TSM concentration.

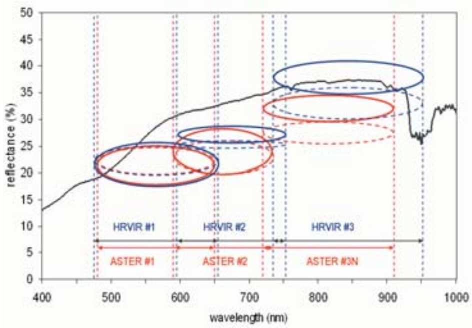

Figure 6. Atmospheric correction evaluation for SPOT (blue) and ASTER VNIR (red) bands.

The coefficients of determination (R^2) for the parameters (A, B, C, D) were quite good for all sensors bands, except for SPOT XS3. The values of R^2 were between 0.96 and 0.98 for (1) and between 0.90 and 0.94 for (2). Having a relationship between TSM and "water leaving" reflectance, the main difficulty is to accurately obtain reflectance measurements from the EOS images. This requires accurate calibration and atmospheric correction of the images. The later is with no doubt the most challenging task, particularly due to the very low reflectance of water.

3.2 *Atmospheric correction*

The atmospheric correction procedure was based on a simplified use of the 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) radiative transfer code (Vermote et al., 1997). The surface reflectance values were retrieved from the SPOT/HRVIR (14Oct.1998) and ASTER (24Oct.2001) images. The atmospheric conditions on these dates was not very clear, with the horizontal visibility between 10 and 12 kilometres. An evaluation of the atmospheric correction performance was carried out on these images. Figure 6 shows a plot where the range of reflectance values for a number of sand areas identified in the images is represented with atmospheric correction (solid line ellipses) and without atmospheric correction (dashed line ellipses). Also displayed on the graph is a plot of the average reflectance spectrum of sand, obtained from field surveys at several beaches in the study area. Under these conditions, the method showed to perform reasonably well (especially in the near-infrared region) for medium to high reflectance values. However, the performance of the method over water was rather poor. The water reflectance is very low, both in the visible and near-infrared bands. For at-sensor reflectance values in the range 0-6%, most of the recorded signal is due to atmosphere itself, and as a consequence, the 6S corrected reflectance take null or even negative values for coastal water. An alternative atmospheric correction method is currently being developed to overcome this problem, combining a 'dark target' approach (using deep sea water reflectance) and other stable reflectance targets. A new set of field measurements is scheduled for the summer of 2004, which should allow for a better evaluation of the errors associated with the use of sand areas as stable reflectance targets.

4 IMAGE EXPLORATION APROACH

An alternative to the quantitative approach is to use image exploration techniques to try to unveil the relevant information present in the satellite images, from the coastal protection application point of view. The aim is to establish a methodology that classifies or segments the satellite images consistently. The challenge is to make the method effective to compare images of the same sensor obtained in different dates, with different viewing/illumination and atmospheric conditions and, at a later stage, using images from different sensors.

The two ASTER images (I and II) were selected for initial testing (detail on Table 2). These images were geometrically corrected and the land areas were removed (set to 0), except for small areas of sand at the beach. This was necessary, as there is a much higher diversity of reflectance values in land areas than in water, even when the concentration of suspended sediments reaches high levels. If the unsupervised classifiers were run on the original image, the much higher dynamic range of land areas would prevent any discrimination in the area around the sea-breaking zone. The large majority of the sea pixels would fall into a single class. The inputs for the classifiers were images of 2560 by 4400 pixels with 3 bands (only the ASTER VNIR bands were used). A total of 7.2 million pixels were considered valid (this excludes non-observed and land areas). The standard deviation of the valid pixels in image I is only 8.7, 7.2 and 4.3 for ASTER bands 1, 2 and 3, respectively. ASTER image II has some scattered clouds, which results in higher standard deviation in the numerical values of all 3 bands.

The unsupervised classification algorithm used was the ISODATA (Tou and Gonzalez 1974), which is a modified version of the k-means algorithm. Both are iterative processes, but the k-means algorithm requires prior knowledge of the number of classes present in the data. Initially k centres are spread along the diagonal (or alternative pre-defined locations) of the multidimensional feature space. Each image pixel is attributed to the class with the closest centre, using a metric (for example the Euclidian distance). After all pixels are attributed to one of the classes, the class centres are re-calculated. The process is repeated until there are no more changes in the class centres or a pre-defined maximum number of iterations are achieved. The number of classes produced by the ISODATA classifier can vary within a user-defined range. In each iteration classes are allowed to be merged, eliminated or split in two. These decisions are all controlled by parameters established for the classifier. The output results will obviously depend on the choice of the ISODATA classifier specification parameters.

Table 3. Summary of the most relevant parameters of the unsupervised classification test with ISODATA.

INPUT:	C1	C2	C3	C4	C5	C6	C7	C8
movethrs	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
samprm	200	100	300	120	200	200	300	100
Stdv	1	3	1	2	1	1	1	2
lump	1.0	1.0	1.0	0.2	0.2	0.2	1.0	0.5
maxpair	5	5	5	4	3	3	5	4
OUTPUT:								
No. Classes (I)	13	9	11	9	13	13	12	14
No. Classes (II)	33	31	25	28	33	33	25	35

A test was carried out in order to evaluate the sensitivity of the ISODATA results with the classifier parameters. The PCI Geomatics software was used (PCI Geomatics 2001). Eight different sets of parameters were considered, and the results produced by the ISODATA classifier compared. The minimum (5), maximum (40), and initial number of clusters (20) were maintained constant for all 8 cases. The parameters that changed, listed in Table 3, are: the moving threshold below which the classes are considered stable (movethrs), the minimum sample threshold (samprm), the standard deviation above which a class is split in two (stdv); and the distance between two centres below which two clusters are merged (lump) (PCI Geomatics 2001). The number of classes varied between 9 and 14 for the ASTER image I and between 25 and 35 for ASTER II.

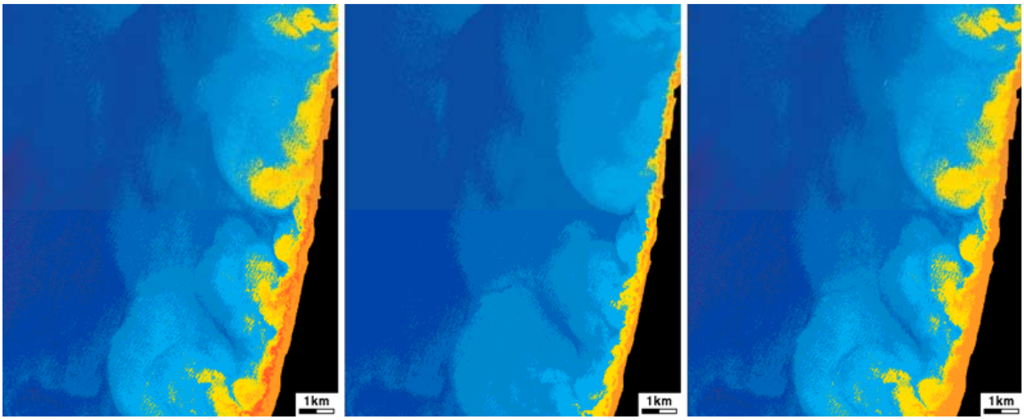

Figure 7. Detail of unsupervised classification results for ASTER (I); C1 (left), C2 (centre), C3 (right).

A visual evaluation of the output results is difficult. It often happens that two classification outputs have two fairly similar classes with different labels. The use of pseudo colour tables is helpful, but considering that there are 28 pairs of results for each ASTER image, it is an enormous task to compare all output results visually. Figure 7 shows a detail of the C1, C2 and C3 result for the ASTER image I. There is obvious similarity between the C1 and C3 results. The C2 result has some noticeable differences from the other two. It is nevertheless worth pointing out that the most significant features, perceptible on the RGB colour composites, can also be clearly identified on all 8 classified images.

A more efficient comparison between classified images can be made using similarity indices (Dubes 1987). Three similarity indices were used: Rand, Corrected Rand and Jaccard indices. The Rand and Jaccard indices range between 0 and 1, and the corrected Rand index between -1 and 1. All three take values closer to 1 when the similarity between the images increases. The similarity indices were computed for all 28 pairs of classified images produced for image I and II. The two similar images featured in Figure 7 (C1 and C3 on ASTER I) scored 0.99 in the three indices. The worst results from all 28 pairs were for C1 and C2, also featured in Figure 7, with a scored of 0.94 for the Rand index, 0.82 for the Corrected Rand, and 0.76 for the Jaccard index. The average values for all 28 pairs were 0.967 (Rand), 0.905 (Corrected Rand) and 0.869 (Jaccard). These results suggest that there is a strong consistency of the results with the variation of the ISODATA parameters. The results for ASTER II were not as good: 0.963 (Rand), 0.893 (Corrected Rand) and 0.850 (Jaccard). The presence of clouds in image II explains the wider range of classes encountered and the smaller similarity between the 8 classification results.

The initial evaluation of the image exploration approach is very encouraging. The most important features observed in the RGB colour composites seem to be also identified and separated by the unsupervised classification. The current work is being oriented towards developing a systematic method to obtain a single result from the various classified images, produced using different sets of parameters for the ISODATA classifier. Hierarchical clustering algorithms are being tested to reduce the number of classes to a common level. The use of internal similarity indices is also being analysed.

5 CONCLUSIONS

The initial objective of the COSAT project was to examine whether multi-spectral EOS images could provide useful information, around the sea breaking zone, for coastal protection studies. The initial results seem to clearly state that there is a great potential of multi-spectral EOS images for this particular application. The route from identifying the potential to actually extracting the information required in an effective way is still a long one. Two approaches are currently being pursued: a quantitative and an image exploration approach.

There are several sensors with adequate spatial and spectral characteristics, such as Landsat TM, SPOT HRVIR and ASTER. The data archives can be a useful source of historic information, and in some cases (SPOT and TM) there are nearly 20 years of data available. A successful methodology to extract information from EOS images could allow for gaps in the past coverage to be filled. Data delivery policies and costs are also important issues, as the survey of the whole coast of Portugal can require a significant number of satellite images. The frequency of the coastal surveys in the future can be significantly increased if the methodology proves effective. Lower spatial resolution sensors, such as MODIS and MERIS, might also be useful, mainly due to the frequency of image acquisition and their high radiometric and calibration accuracy.

The plans for future work include a field survey in the summer of 2004. These experimental measurements should allow for more accurate relationship to be established between TSM and reflectance for each of the satellite bands used. The atmospheric correction method also needs to be improved in order to provide more accurate reflectance values over water. Several ideas are currently being considered for the image exploration approach. The main objective of both approaches is to provide classified images, with various levels of information, which can be incorporated on a GIS.

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