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Shoreline detection: capability of COSMO-SkyMed and high-resolution multispectral images

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Abstract
This study aims to extract the instantaneous shoreline from remote sensing data acquired with very high resolution multispectral and SAR sensors. The capabilities of IKONOS, GeoEye and COSMO-SkyMed for shoreline detection are tested in the Venice littoral (Italy) by classifying the imagery into its land/water components. GPS measurements synchronously to the COSMO-SkyMed acquisitions are carried out along two transects at different tidal levels and used for validation of satellite derived shorelines. Finally, a collection of instantaneous coastlines at a specific tidal level is mapped for reconstructing the intertidal beach morphologic model.

Keywords: Shoreline, COSMO-SkyMed, multispectral images, tidal level, morphological model, Venice.

Introduction
In sandy coasts, morphologic changes are the response to a complex relationship between tidal currents and wave energy, sediment fluvial discharge and long-shore currents, eustacy and land subsidence, and the effects of human interventions. The monitoring of shoreline variations is the principal approach for providing basic indications on the dynamic of these processes. Mapping coastline position is essential for coastal management and land-use planning [Zeidler, 1997], designing coastal defence and protection infrastructure [Pousa et al., 2007], assessing coastal vulnerability and establishing risk setback lines [Morton and Speed, 1998], estimating the impact of climate change [Tosi et al., 2013b]. Thus shoreline modifications of sandy beaches are utilized for estimating coastal erosion and deposition rates [Mukhopadhyay et al., 2012], assessing sediment transport [Larson et al., 2004], and setting up hydrodynamic models [Butt and Russell, 2000].
The terms “shoreline” and “coastline” are often analogously used in coastal research communities [Graham et al., 2003; Liu et al., 2011] and defined as the instantaneous boundary between water and land. This boundary is continually changing with time because of the dynamic nature of water levels and shoreline movements may be daily observed...
due to waves [Di et al., 2003] and tidal variations, especially in smooth slope beaches in macrotidal areas [Aguilar et al., 2010].

The coastline is subject to different time-dependant evolution: i) “slow and natural” due to long-term erosion and accumulation, ii) “rapid and natural” due to environmental events such as major storms, iii) “artificial” due to man-made modification [Tello Alonso et al., 2011].

The requirements for shoreline delineation depend on the characteristics of the processes under investigation and differ for various applicative purposes and targets. Therefore specific investigation methodologies have to be used to satisfy different requirements, e.g., spatial resolution and shoreline position accuracy (from hundred to sub-meter), temporal and spatial scale of investigation (e.g., long- or medium-term analyses, regional or local scale), temporal frequency and response time for up-to-date information.

Developing and testing accurate and efficient techniques for shoreline mapping is sometimes challenging and essential in specific regions and circumstances such as transitional coastal environments. Traditionally, shorelines were measured by ground surveys (e.g. spirit levelling) and recently by GPS achieving high accuracy but they are intensive and time consuming, besides the difficulty for inaccessible environments as the marshlands and tidal flats. As well, for many decades, the shorelines were visually identified and manually delineated by expert photo-interpreters on aerial photographs, but implying high cost of image acquisition and time consuming elaborations. In Boak and Tunner [2005], a review of common shoreline detection techniques have been discussed and several indicators of the shoreline position, classified in two groups, are described. The two groups of indicators are: a) based on a visually discernible coastal feature (e.g., wet/dry boundary); b) related to a datum-based shoreline at a specified tidal level (e.g., mean high water). They pointed out the practical problems related to instantaneous shoreline detection (position of the land-water interface at one instant in time) rather than an “average” condition.

An important technical progress for shoreline mapping has come from satellite imagery: the capability of monitoring wide areas, with high temporal frequency, can provide an adequate tool for studying the highly dynamic processes that influence the coastal area, with relatively low costs [Cracknell, 1999]. The main limitation of these data source to coastal investigations is the pixel resolution: for instance, since 2008, the United States Geological Survey (USGS) provides all archived Landsat images (1976-2013), but they have too coarse spatial resolution (30 m pixel) to detect most of the changes in the shoreline within the timescale required for coastal management. Landsat images have been used for medium or long-term morphological analyses in very dynamic coastal areas like river deltas, as such those of the Nile delta in the Mediterranean Sea [White and El Asmar, 1999], the La Plata estuary in the Atlantic Ocean [Tosi et al., 2013b], or the Yellow River estuary in China [Cui and Li, 2011]. In the lagoon of Venice, Brivio and Zilioli [1996] have extracted the land/water boundary from Landsat images, in order to monitor the erosion/sedimentation processes of wetlands.

Since 2000, high spatial resolution multi-spectral satellite sensors (e.g., IKONOS, QuickBird, GeoEye, WorldView-2) with spatial resolution and accuracy similar to that provided by aerial photographs, have allowed high capability for detecting the shoreline position especially by the use of the infrared band [Di et al., 2003; Li et al., 2003].

In addition, over the last two decades, the Synthetic Active Radar satellites (SAR), such as ERS1/2, ENVISAT, RADARSAT1/2, ALOS, with a medium spatial resolution (i.e. 20-30
m pixel), have shown good capability for detecting waterline [Lee and Jurkevich, 1990; Mason and Davenport, 1996; Ding and Li, 2011] with the prominent advantage of providing ground information regardless of cloud presence, during the day as well as during the night. Today new generation of X-band SAR sensors (TerraSAR-X and COSMO-SkyMed), with very high spatial resolution (1-3 m) and revisiting time spanning from 11 to 1 days, gives the possibility to perform a quasi near-real time monitoring of coastal processes and events, e.g., oil spills [Velotto et al., 2011], land subsidence [Ferretti et al., 2000, 2011; Strozzi et al., 2009; Tosi et al., 2012a, 2012b], coastal erosion [Palazzo et al., 2012], flood extent mapping [Pulvirenti et al., 2012], never been obtained in the past. The applications of these sensors for detecting morphologic changes of coastlines are a theme of particular interest because the application of conventional image processing tools usually gives suboptimum results on SAR data. Currently, specific data analysis algorithms are still to be provided in order to ensure unsupervised and robust means for intensive and operational exploitation of COSMO-SkyMed data.

Temporally recurring and high resolution acquisitions are two essential requirements for a suitable reconstruction of the shoreline position and cross-shore profile of intertidal areas as those of Venice littoral and lagoon. The Venetian lagoon coastline is constituted by a narrow strip of sandy beaches divided into four portions (Chioggia, Pellestrina, Lido and Cavallino) by three inlets (Chioggia, Malamocco and Lido) which allow the lagoon-sea water exchanges (Fig. 1).
Tides are semidiurnal, with mean tidal range from 50 cm during neap tide to 100 cm during spring tide. The safety of the littoral is vital for the existence of the historical city of Venice and the lagoon itself. Particularly in the past century, two processes threatened this zone: the erosive action of the sea and the relative sea level rise, i.e. eustacy and land subsidence [Carbognin and Tosi, 2002]. Over the last two decades, a series of safeguard interventions has been realized to contrast the beach erosion and for reducing the risk of sea overtopping the littoral strip and the flooding of the urbanized areas.

For this study, we selected a sector located in the northern sector of the Lido Island characterized by gently slope beach and near-shore bottom where land subsidence and coastline erosion presently don’t act [Carbognin et al., 1995; Tosi et al., 2010] at such magnitude to affect the experiment.

This work is aimed at assessing the capability of COSMO-SkyMed data for i) automatically detecting of shoreline, ii) comparing the outcomes provided by X-band and multispectral high resolution sensors, and iii) providing a morphologic model of intertidal shore through the collection of instantaneous coastlines at a specified vertical elevation.

**Shoreline detection procedures**

The shoreline extraction from optical and SAR images was automatically performed following these main steps: 1) a rough separation between land and water; 2) the refinement of this boundary to extract the accurate shoreline position; and 3) the vectorization of the extracted shoreline. Refinement and vectorization of shoreline depended on the successful completion of the land-water discrimination, which had required the analysis of electromagnetic signal behaviour at the land/water interface.

In this work we considered edge detection and image segmentation methods for the detection of land-water boundary from both optical and SAR images. These methods are respectively based on two main image properties [Gonzalez and Woods, 1992; Parker, 1997; Pitas, 2000; Liu and Jezek, 2004]: “discontinuity”, i.e. the spectrum or intensity values change abruptly in close proximity of land-water interface, and “similarity”, i.e. the interface is situated between two relatively homogeneous regions, like emerged and submerged areas, each with different average values.

Before the extraction of the shorelines, the optical and SAR images were accurately and precision georeferenced to UTM (Datum: WGS84) coordinate system, using ENVI™ software (Exelis VIS). A mean value of 20 GCPs was used for each scene, trying to choose the points homogeneously over the image. The RMS errors were always kept less than the pixel unit (0.4 to 0.6). For each image, a first order polynomial transformation was applied, providing good results and keeping distortions low enough. The nearest neighbour resampling method was used, in order to create a warped image without any interpolation. Owing to the fact that the study area is relatively flat, and the regions of interest lie at the shoreline, it was envisaged that the orthorectification process to correct geometrical errors was not necessary.

In Figure 2, the summary of the satellite acquisitions and field surveys versus the sea level are reported. The satellite images included the two optical very high resolution images (IKONOS-2, acquired on September 13, 2006, and GeoEye-1, acquired on February 12, 2009) and 18 COSMO-SkyMed images for the year 2010 are reported in Figure 2.
Figure 2 - Summary of satellite images used in this study. On 1st and 9th of July, 2010, two field surveys were carried out: the tidal levels during each survey are also reported.

**Multispectral Images**

In this study, IKONOS-2 and GeoEye-1 data, acquired on September 13, 2006 and February 12, 2009 respectively, were used. They are very high resolution multispectral images, which include 4 spectral bands in the VNIR range (blue, green, red and near infrared bands) with a spatial resolution of 2 m for GeoEye-1 and 4 m for IKONOS-2, and a panchromatic band with a spatial resolution of 0.5 m and 1 m for GeoEye-1 and IKONOS-2, respectively. The combination of multispectral and panchromatic bands was performed using HighView (http://www.geosage.com/highview/imagefusion.html), a GeoSage commercial software, in order to make the best use of high resolution of panchromatic band. The obtained pan-sharpened colour image had the same spatial resolution of the panchromatic image, with very little spectral distortion, according to Zhang and Mishra [2012].

The land-water separation method for multispectral data was based on the hypothesis that the reflectance of pure water is quite completely absorbed in the near-infrared (NIR) wavelengths with a rapid decrease from red to NIR bands [Brivio et al., 2006]. On the other hand, the spectral signature of land has higher value at all wavelengths, especially at NIR range [Lillesand & Kiefer, 1987; Ryu et al., 2002]. Using this rationale, we investigated the radiometric response of water and land in the different spectral bands, pointing out the marked drop signal of each band along different transects perpendicular to coastline in both multispectral images. Such signal slope was enhanced also through band-ratios and normalized differences (NDVI). Figure 3 shows changes in digital number values across the sea-land boundary in the 4 bands, NIR/RED ratio and NDVI for the IKONOS image. Among all, the NIR band (757-853 nm for IKONOS-2 and 780-920 nm for GeoEye-1) showed the highest gradient between land and water with an abrupt change in an interval of no more than three pixels. The NIR bands was well suited for discriminating water from wet and dry sand because water absorbs quite completely near infrared light and minimizes possible perturbations by the shallow bottoms [Alesheikh et al., 2007]. Therefore, the NIR band was used in the shoreline extraction procedure.

As a matter of fact, NIR wavelengths were not completely absorbed in water pixels next to
the shoreline and their values were higher than zero, because the water reflectances were influenced by particulate matter in the water column and by bottom albedo. For this reason, each multispectral image should be dealt with separately. The best threshold value was selected after the analysis of various beach profiles, identifying firstly the meaningful discontinuity of NIR band at the land-water boundary and then the pixel value interval within which the water/sand threshold could be placed. Within such interval, the first pixel corresponded to land and the last to sea: it was possible to suppose that the shoreline could be placed in an intermediate position between them. The DN value of the threshold was obtained with a simple geometric equation [La Monica et al., 2008]. All the pixels lower than the selected threshold were classified as water; all the pixels higher than the selected threshold were classified as land. Finally, we extracted the rough shoreline with the edge detection technique, based on the identified threshold. Due to the small size of our study area, atmospheric effects were assumed to be constant over adjacent pixels of each image [Yu et al., 2011]. Moreover, according to Song et al. [2001], the atmospheric correction was unnecessary, because the multidate signatures are derived from the images to be used in the multidate analysis. Thus, a pixel-wise atmospheric correction was not required.

The post processing was based on visual analysis, i.e., elimination of weak detected edges, linking of edge pixels separated by small breaks, correction of ambiguities in the shoreline. It was necessary in order to manually refine the coastline and then the vectorization of the shoreline was performed.

![Figure 3 - Selection of the suitable band for a corrected identification of the land-water boundary on IKONOS image. The chart reports the values of the pixels, along the transect 1 (see location in RGB image) from the beach to the sea; NDVI and NIR/RED (dashed lines) are referred to right Y-axis. The marked drop signal corresponds to the land/water boundary.](image)

**X-band Radar Images**

**Ad-hoc de-speckle processing**

61 COSMO-SkyMed Stripmap HIMAGE Mode images, covering the entire Lagoon of Venice and acquired between March 2010 and July 2011, with 3 m of spatial resolution, were used. The COSMO-SkyMed constellation consists of four satellites, each equipped with a multi-mode SAR, operating at X-band, which measures the backscatter responses to the incoming radar.
signal. The revisiting time of each satellite with the same looking angle is 16 days, however, if more satellites are used, a revisiting time as short as 4 days is available. More information on the technical specifications of the COSMO-SkyMed constellation can be found in Battazza et al. [2009]. In this research project, data from 2 satellites (COSMO-SkyMed 1 and COSMO-SkyMed 2) have been acquired by the Italian Space Agency thus achieving a minimum revisiting time interval of 8 days.

In general, one of the major problems in using amplitude SAR images for ground features detection is represented by speckle noise. Speckle noise is typical for all the coherent imaging systems since it comes from the random phase combination of the scatterers within the resolution cell of the system (3 m in the case of COSMO-SkyMed). In particular the speckle noise makes it difficult to identify the contours of land-water boundaries. Speckle noise of a single SAR image can be strongly reduced at the cost of a reduction of spatial resolution thus vanishing the benefit of high resolution imaging systems in shorelines detection. A de-speckle method that save the spatial resolution by exploiting the full acquired data stack have been recently developed by Polimi and TRE [Ferretti et al., 2011]. The full data stack is first analyzed to estimate those pixels that belong to homogeneous targets. This multi-image de-speckle technique identifies within a search window those pixels that are statistically homogeneous following the Kolmogorov-Smirnov test. The amplitude of neighboring pixels of each image belonging to a homogeneous target is then averaged to reduce the speckle effect. A statistical analysis of the resolution preservation offered by this speckle reduction method has not been carried out yet. However, it is clear that its capability to correctly identify homogeneous targets, thus preserving the full spatial resolution of the SAR images, is improved with respect to any “single image” method since the necessary statistical analysis is performed on many more data. The quality improvement that is achieved by means of this technique when compared to the usual “single image” de-speckling filtering techniques is clearly visible in the example shown in Figure 4. Here the original single look detected SAR image is compared to the filtered single image by means of low-pass and median filters and the de-speckled image obtained by means of the proposed technique.

![Figure 4 - A) Original full resolution detected image. B) Low-pass filtered detected image. C) Median-filtered detected image. D) De-speckled image by means of the proposed multi-image technique.](image-url)
This multi-image de-speckling technique has been applied to all the full resolution images acquired on the Lagoon of Venice. A detail of Venice is shown in Figure 5 where the de-speckle effect together with the conservation of spatial details can be appreciated.

![Figure 5 - A detail of Venice obtained by de-speckling a COSMO SkyMed image using the technique developed by Polimi and TRE.](image)

**Land-water boundary identification**

Land and water surfaces have different scattering properties and, as a consequence, they have different responses to the incoming radar signals [Curlander and McDonough, 1991; Thompson et al., 1996]. On COSMO-SkyMed images, the land-water separation was based on the hypothesis that water surfaces are generally much smoother than the dry land, characterized by diffuse scattering [Horritt et al., 2006] and consequently, the backscattered energy by the land is higher than the one returned by the sea surface. This is applicable only with low-to-moderate winds, because if the water surface has excessive roughness due to intense wind, water is brighter than the inland zone, resulting in poor water - land contrast. The detection of shoreline was only performed on images with low wind speed (< 7 m/s) and characterized by a detectable contrast between homogenous land and sea areas. According to this consideration, we adopted the shoreline extraction method proposed by Liu and Jezek [2004], based on image segmentation using locally adaptive thresholding method. An anisotropic diffusion algorithm [Perona and Malik, 1990; Sohn and Jezek, 1999] was also applied to the de-speckled images to enhance the edges along the coastline and suppress the interior variations inside the land or ocean masses in the images, produced by features due to breaking waves, coastal morphology or topography.

The capability of separating land from sea regions was tested by a statistical analysis of image intensity values. In some images, the intensity values of the land and the water regions slowly varied and the resulting histogram shown a quasi-unimodal distribution. Only the images represented by intensity value histogram with a bimodal shape (two dominant modes with relatively different mean value) were analyzed (Fig. 6). The issue of determining the land-
water boundary consisted of assigning each image pixel to one of the two distributions on the basis of an optimal threshold value corresponding to the histogram minimum (the valley point). According to the method proposed by Liu and Jezek [2004], the optimal threshold value was computed by solving a quadratic equation formula, derived from the method of maximum likelihood, which minimized the probability of misclassification [Chow and Kaneko, 1972; Gonzalez and Woods, 1992]. The computed threshold was different for each image, depending on intensity value distribution, and ranged between 0.20 and 0.40. After the threshold computation, the segmentation algorithms divided the input image into homogeneous land and water regions using the selected thresholds.

The post-segmentation processing was necessary to vectorize the contours obtained, delete the small objects (e.g., boats, breakwaters, image noises and other unwanted objects smaller than a few tens of meters, whose boundaries are not the coastline) and refine the coastline.

**Figure 6 - Identification of the land-water boundary on COSMO-SkyMed.** A) COSMO-SkyMed image acquired on May, 6th 2010 quasi unimodal pixels distribution; B) COSMO-SkyMed image acquired on July, 1st 2010 bimodal pixels distribution. B shows an example of land and water regions with homogeneous values, well differentiated between each other, resulting into a bimodal distribution.

**GPS survey**
Differential GPS (DGPS) measures were used for assessing the accuracy of the shoreline positions extracted from the COSMO-SkyMed imageries and for validating the results. Two DGPS surveys were collected on July, 1st and 9th, with optimal weather (sea and wind). The
master station was installed on a GPS benchmark of the Venice levelling-GPS network and WGS84 data were transformed in the Italian local coordinate system [Tosi et al., 2007, 2013a]. The DGPS surveys were carried out in simultaneous occurrence of the COSMO-SkyMed descending mode acquisitions. The shoreline positions were detected in relation to different tidal levels. The shoreline detection were performed from 11:30AM to 6:15PM (UTC), along two transects at intervals of 30 minutes (Fig. 7). At transect 1, COSMO-SkyMed acquisitions and GPS measurements were perfectly synchronous. At transect 2, the measurements were delayed by no more than 15 minutes from the COSMO-SkyMed acquisitions.

**Result and discussion**

The shorelines contours were obtained by the segmentation and edge detection processing of X-band and multispectral satellite images, respectively. In order to appreciate the precision of the methods, the derived coastlines have been superimposed as background to the original satellites images (Fig. 8).

Concerning the accuracy of extracted shorelines, it was strictly dependant on the spatial resolution of the image. The accuracy of the edge detection method applied to multispectral images has been visually evaluated, because no synchronously ground truth measurements were available. Considering 40 random points on the extracted shoreline, we calculated the minimum horizontal position difference between the extracted shoreline and a shoreline manually identified in the original satellite image. The accuracy of shoreline extracted from IKONOS-2 images is 1-2 pixels, which is equivalent to 1-2 m for pan-sharpened
multispectral bands and 4-8 m, using original multispectral bands. Similar results have been found also by Li et al. [2003], Iandelli and Pranzini [2008]. Higher accuracy is shown by GeoEye-1, which is evaluated here for the first time for detecting shorelines. GeoEye error range is estimated of 1-2 pixels, which corresponds to 2-4 m and 0.5-1 m, using original multispectral and pan-sharpened bands, respectively. The inherent accuracy of shoreline extracted from COSMO-SkyMed data is 1-2 pixels. In order to validate the COSMO-SkyMed results and evaluate the error of the coastline position obtained from segmentation processing GPS ground truth data were used as a reference. The difference between the coastline positions obtained by synchronous GPS and extracted from COSMO-SkyMed data acquired on July, 1st and 9th 2010 is 3-4 m.

We also assessed the suitability of COSMO-SkyMed to provide a morphologic model of the shore. The reconstruction of the intertidal beach morphology was made through the collection of instantaneous coastlines at a specified vertical elevation, defined by the tide gauge measurements at the time of the COSMO-SkyMed image acquisitions. A number of images with different tidal levels and possibly acquired within short period is required because no significant morphologic changes should occur in the intertidal zone. For the study area, the climate is considered optimal on June-July. According to tidal interval clusterization, 7 instantaneous coastlines were selected from the

![Figure 8 - Shoreline detection: A) instantaneous shorelines superimposed IKONOS, B) GeoEye, C) COSMO-SkyMed (CSK). D) Shorelines with similar tidal level condition in the area shown by the green polygon of Figure 8 C.](image-url)
whole COSMO-SkyMed database (Tab. 1).

Table 1 - COSMO-SkyMed images selected for morphologic model and climate conditions.

| Acquisition Date (dd/mm/yyyy) | Tidal level (m) | Wind speed (m/s) |
|-------------------------------|----------------|-----------------|
| 01/07/2010                    | 0.28           | 0.80            |
| 02/08/2010                    | 0.34           | 3.30            |
| 17/07/2010                    | 0.42           | 6.40            |
| 09/07/2010                    | 0.49           | 4.30            |
| 22/05/2010                    | 0.59           | 3.90            |
| 23/06/2010                    | 0.64           | 4.10            |
| 07/06/2010                    | 0.69           | 2.30            |

The clusterization allows selecting the suitable image with a low wind speed within each tidal cluster. This effort should be done, with the purpose to make comparable the obtaining results, particularly with regard to extraction accuracy.

Figure 9 shows the morphologic model built with the selected vectorized shorelines. The morphologic model has been validated along a cross section by GPS measures. The correlation between shoreline positions extracted by COSMO-SkyMed and measured by GPS at the same tidal level is significant, as shown in Figure 10.

The low average beach slope (about 2.5%) caused a waterline displacement of about 0.4 m for a variation of astronomic and baric tides within 1 cm. As a consequence, only a variation
of a tidal level greater than 7-8 cm could be virtually identified in COSMO-SkyMed images.

Figure 10 - Transect 1. A) Cross-shore morphologic model obtained by COSMO-SkyMed and waterline positions measured by GPS. Error bars shown the 3-m uncertainty due to the pixel size. B) Correlation between shoreline positions extracted by COSMO-SkyMed and measured by GPS at the same tidal level.

Conclusions
The capability of COSMO-SkyMed, GeoEye-1 and IKONOS-2 images for detecting and mapping shoreline position has been successfully tested in a sandy beach located in the northern part of the Lido littoral, demonstrating the interesting potentiality of such satellite images. The optimal goal is to achieve an accuracy of 1 pixel for the shoreline detection. Depending on the image quality, influenced by weather condition, the extracted coastlines show accuracies of 1-2 pixels for multispectral images and 1 pixel for COSMO-SkyMed. The pixel sizes are 3 m and 0.5-4 m for X-band and multispectral images, respectively. With a few months of satellite acquisitions, records of shoreline positions at different tidal levels are obtained from COSMO-SkyMed images, providing an innovative methodology for the reconstruction of the morphologic model of intertidal zone. These results can be easily achieved thanks to the very short revisiting time of COSMO-SkyMed constellation. In coastal zones like that of the northern Adriatic Sea with about 100 cm tide level spanning, a daily acquisition within two weeks is sufficient for collecting shorelines at different tidal levels and consequently providing a morphologic model of the intertidal beach shore. The use of Spotlight instead of StripMap images (i.e. 1 m of spatial resolution, instead of 3 m) for local investigations would be the next step of this study.

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