Estimation of coastal bathymetry from wave parameters retrieved with Synthetic Aperture Radar Data.

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Abstract:

Small-scale topographic features can change relatively fast due to storms. These rapid changes are not easily measured by traditional methodologies and, therefore, methods that rely on Earth Observation are valuable for the monitoring of the coastal bathymetry.

In this study, coastal bathymetry is derived with a wave-tracking algorithm using wave parameters retrieved from Synthetic Aperture Radar (SAR) data. The algorithm tracks down the shoaling waves from the intermediate waters until the wave breaking zone and, through the linear wave dispersion relationship, estimates the water depth using the wavelength and direction. The output of the algorithm is a 2D bathymetry field that results from the interpolation of the estimated depth at each tracking point.

Two case studies at different locations off the Portuguese Coast will be presented. The operational capabilities of the algorithm and the synergy between SAR and Optical data to retrieve high-resolution bathymetry in shallower waters will be discussed.

Key words: Coastal Bathymetry, Synthetic Aperture Radar Data, Wavelength, Wave Direction, Earth Observation

1 INTRODUCTION

The global bathymetry at 1 km resolution is already known and available through multiple different data sets (e.g General Bathymetric Chart of the Ocean [GEBCO]). However, small-scale shallow water topographic features, like sand banks, reefs and bars, can change frequently due to storms, and may not be correctly marked on the official charts. These changes can be relatively fast and are not easily captured by traditional hydrographic surveying methodologies and, therefore, methods that rely on Earth Observation from space can be valuable for the monitoring of the coastal bathymetry.

In this study, coastal bathymetry is derived with a ray-tracing algorithm (RTA) through wave parameters retrieved from Synthetic Aperture Radar (SAR) images from the Sentinel-1 satellites, following a similar methodology as proposed by Pleskachevsky and Lehner (2011).

The estimation of bathymetry from SAR data through this method relies on the detection of long surface gravity waves and how the wave properties are modified as they propagate towards the shore, which can be related to the bottom topography.

One of the greatest advantages of using SAR images to retrieve the underwater topography is that radar image acquisitions can occur at any time, since they are not significantly affected by meteorological conditions (e.g. clouds) nor the need of sunlight, which are limitations when using multispectral images for the derivation of bathymetry. Thus, the use of satellite SAR imagery to derive the bathymetry can be particularly useful for many coastal applications, due to their global coverage, high resolution, and daylight and weather independency.

The present work is a part of a research application developed within the EU H2020 Coastal waters Research Synergy Framework (Co-ReSyF) project, to demonstrate the operational capabilities of the platform.

Several case studies at different locations off the Portuguese Coast will be presented (Fig. 1), using high resolution SAR images from Sentinel-1.

Fig. 1. Areas of interest (AOI), Aveiro and Sines, delimited by the inset boxes.

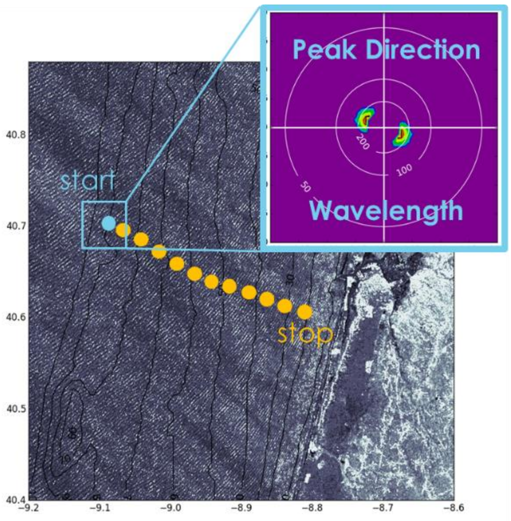

Fig. 2. SAR image (Sentinel-1A over Aveiro, Portugal) superimposed with isobaths from the reference bathymetric model (GEBCO) and an example of the tracking positions (yellow circles) in a single wave ray. Inside the blue box is the direction spectrum obtained for a 1km² sub-image centered at the initial tracking position (blue circle).

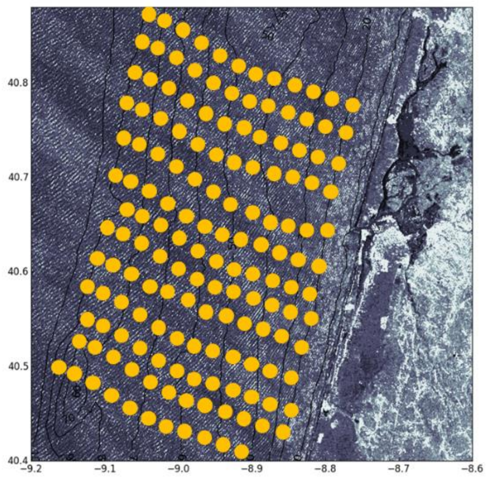

Fig. 3. Example of tracking positions for some of the wave rays traced by the algorithm for the same SAR image as Fig. 2.

2 DATA and METHODS

2.1 Synthetic Aperture Radar data

C-Band SAR data from Sentinel-1A and 1B with a spatial resolution of 10-m are used in this study. The pre-processing of the SAR images for each AOI (Aveiro and Sines) was done with the freely available software SNAP (*Sentinel Application Platform*: http://step.esa.int/main/toolboxes/snap/).

The processing steps consisted of sub-setting the image according to the latitude and longitude limits of each AOI, followed by a geometric ellipsoid correction with a geolocation-grid, to transform the image into WGS84 reference. Then, the image was calibrated to transform the pixel values into actual physical values of backscatter and finally a speckle filter was applied at the end. The image was then saved into nectdf format, ready to be ingested by the algorithm (implemented in Python 2.7) for the estimation of bathymetry. All these processing steps were automated using the Graph Builder and Batch Processing tools of SNAP, allowing for a consistent pre-processing of all SAR images, divided according each AOI.

2.2 Study Domain

Even though the objective of this work, in the frame of the Co-ReSyF project, is to deliver a full operational tool that will allow the computation of the coastal bathymetry anywhere in the world, the development, testing and validation of this tool is being performed at specific locations along the Portuguese coast (Fig. 1). The coastal region around Aveiro was considered as the main setting for the development and testing of the methodology. The region around Sines was considered as the region for the validation of the method and as a test case region for the development of a synergetic product that combines the coastal bathymetry derived from SAR and the littoral high-resolution bathymetry derived from Optical data (Vilar *et al.*, 2018).

2.3 Wave parameters from SAR

SAR is an active remote sensor that provides two-dimensional information on the normalized radar cross-section based on the backscatter echo. In case of surface waves, the radar return echo is dominated by Bragg scattering of short ripple capillary waves, in the order of centimetres, produced by wind at sea surface (Hasselmann *et al.*, 1985). These small capillary waves are modulated by longer surface waves which will create the wave-like stripe patterns observed in SAR images. Thus, the sea surface roughness and slope, which influence the radar echo, can be measured, and a two-dimensional wave spectra can be retrieved, which will contain information on the peak direction and wavelength.

2.4 Bottom depth estimation

The derivation of bathymetry through wave parameters retrieved from SAR images uses the first degree (linear) dispersion relationship for shoaling waves, which relates the depth with the wave's length and frequency:

$$\omega^2 = \frac{2\pi}{L} g \tanh\left(\frac{2\pi h}{L}\right) \tag{1}$$

Where $g = 9.8\text{m.s}^{-2}$ is the acceleration of gravity, ω is the wave frequency, L is the wave length and h is the water depth. By inverting this relationship, the depth can be derived from:

$$h(L, \omega) = \frac{L}{2\pi} \tanh^{-1}\left(\frac{\omega^2 L}{2\pi g}\right) \tag{2}$$

This relationship holds when the waves are affected by the bottom topography, and, normally, an acceptable limit for this depth is $h = L/2$.

2.5 Ray-Tracing Algorithm

Traditionally, the derivation of bathymetry from SAR images relies on the assumption that the wave period is constant throughout the image, which can be approximately true for a relatively small domain during optimal swell conditions (Pleskachevsky and Lehner (2011)). In the Ray-Tracing Algorithm (RTA) proposed in this study, however, this assumption is slightly modified. Here, the period of the shoaling waves is only assumed constant for each wave ray. This allows for a certain degree of heterogeneity of the wave field across the image but still requires the need of consistent swell conditions during the time of the sensing.

In the RTA, the shoaling waves are tracked down from a starting point (which mark the intermediate waters) with a known depth obtained from an independent bathymetric source (GEBCO - global 30 arc-second interval grid; www.gebco.net), until the wave breaking zone. The RTA starts by computing the FFT analysis in a sub-image with 1 km length, centered at the starting position. The mean wavelength and wave direction at this sub-image is estimated through the directional image spectra that results from the FFT analysis. The next sub-image is centered at a position reached by the displacement of one wavelength in the wave direction (Fig 3). This procedure is repeated until the wave breaking zone. Then, the depth is calculated at each tracking position with the wavelength obtained from the FFT and maintaining the frequency retrieved at the first tracking position of each wave-ray (Eq. 2).

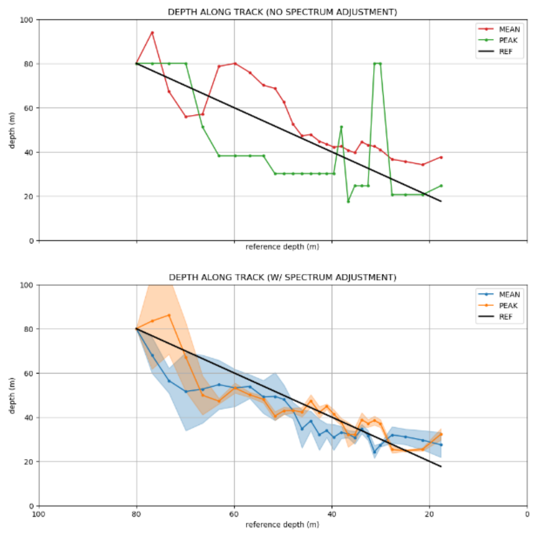

Fig.4 –Depth estimated in a single wave ray. Top: Depth estimated without wave spectrum adjustment using the peak (green) and mean (red) wavelength. Bottom: Mean depth estimated using 10 independent wave spectrum adjustments, using the peak (orange) and mean (blue) wavelength, shaded areas correspond to +/- of the standard deviation considering 10 wave spectrum adjustments using 5000 random points. Black line for both plots indicate the reference bathymetry values (GEBCO) for that wave ray.

This process is repeated for a number of wave-rays chosen to obtain the best resolution of the final bathymetry without compromising the performance of the algorithm (Fig. 4).

2.6 Improving the result from the FFT analysis

The wavelength discretization is limited by the pixel resolution and the size of the SAR sub-image where the FFT is applied. The low discretization in the wavelength domain results in either constant or steep variations of the depth estimated across adjacent tracking points, especially when using the peak value of the spectrum. Here, a new methodology to increase the discretization in the wavelength domain, is proposed. This methodology relies on the adjustment of the two-dimensional spectrum, which is integrated in the directional dimension, to a Pierson-Moskowitz unidimensional function, using 5000 random points across the unidimensional spectrum curve. This method allows for a better discretization of the wavelength and consequently a better estimation of depth (Fig. 4). However, the fitting of the curve at the same tracking position produces different results, since the 5000 points are chosen randomly. This results in significantly different depth values obtained for each fit at the same tracking point. To minimize the randomness of the result, the fitting procedure is repeated 10 times for the same tracking point, and the final depth value results from the average of all the fitting results.

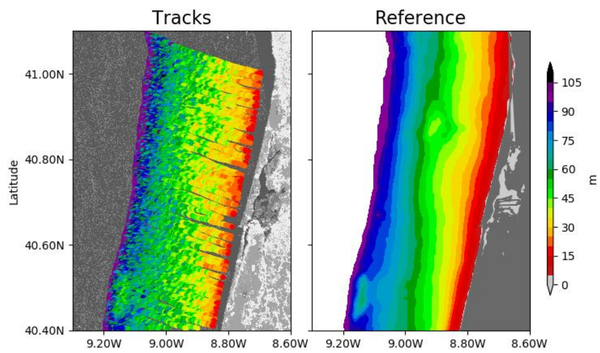

Fig.5 – Depth estimated using the RTA for a SAR image over the coastal region near Aveiro, Portugal.
(image reference: S1B_IW_GRDH_1SDV_20170401T183449 _20170401T183514_004971_008B0C_FA9F)

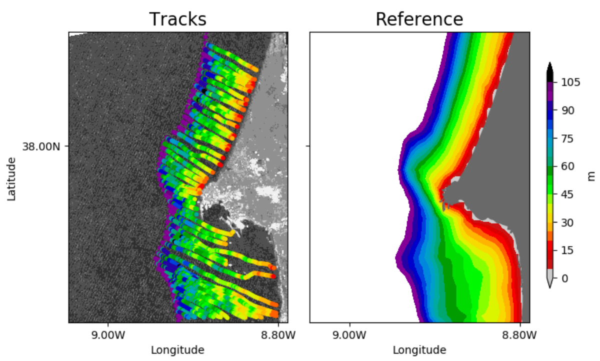

Fig. 6 - Same as Fig. 5 but for the region near Sines, Portugal (image reference:S1A_IW_GRDH_1SDV_20170206T183457_ 20170206T183522_015167_018D0A_F984)

3 MAIN RESULTS

The depth estimated using the RTA for the Aveiro and Sines region can be seen in Figures 5 and 6, respectively. The reference bathymetry (GEBCO) is also plotted for comparison. Overall the main structures and slope were reproduced by the RTA, especially in the Aveiro region (Fig. 5), where the topography is smoother. In the southside of Sines (Fig. 6) the SAR-based algorithm fails since swell waves are refracted towards the south by the cape. For the Aveiro region, the average error for the absolute depth was approximately 15%, but a few tracking points showed more than 50% error on the absolute depth value, mainly due to small scale variability of the SAR image (e.g. the swell was not consistent for that sub-image). More quantitative tests need to be performed but so far the results are indicative that the bathymetry using SAR data should result from an ensemble of several images, in order to reduce the small scale variability which strongly affect the depth estimated at some tracking points.

4 DISCUSSION AND FUTURE WORK

The resulting bathymetric models show most of the underwater topographic structures and reproduced the correct slope, with an average of 15 to 20% errors for the absolute depth values, which are close to the error values obtained by Pleskachevsky and Lehner (2011). These errors seem to be connected to mainly to the small scale variability of the single SAR image. In the future, the final bathymetry for a given region will result from the average of multiple images, in order to reduce the high variability obtained by individual images. Several tests will be performed to evaluate the best averaging methodology (e.g, averaging according to seasonality, averaging with weights based on the standard deviation of the spectrum adjustments for each tracking position, etc.) across multiple individual SAR images.

Ultimately, tests will also be performed to analyze the best methods to interpolate the bathymetry between each tracking point, in order to obtain a bathymetric model in a uniform 2D grid.

The developed algorithm presented here will soon be implemented in the Co-ReSyF platform (https://geoportal.coresyf.eu) where the user will be able to define a region of interest and a 2D bathymetric model from that region will be derived through a set of available SAR images.

SAR derived bathymetry looks promising and can provide topographic information at higher resolution, especially in remote areas where the traditional hydrographic surveying methods are not performed regularly. The fusion of SAR and Optical data to provide higher coverage and resolution over shallower waters is under development. These two methodologies are rather complementary, since satellite derived methods based on multispectral images can provide bathymetric information up to 10 m, in preferably calm sea conditions (Vilar *et al.*, 2018), while depth estimation from SAR covers the areas between 100 to the wave breaking zone (which typically lies between 5 and 10 m depth), in preferably swell and moderate wind conditions. The main challenge will be focused on the fusion methodologies of both bathymetric models, especially in cases of overlapping regions with disparate results from both methods or a large region with no data between the two bathymetric. Tests of this synergy will be conducted in the region around Sines, in the southwestern coast of Portugal (Fig. 7).

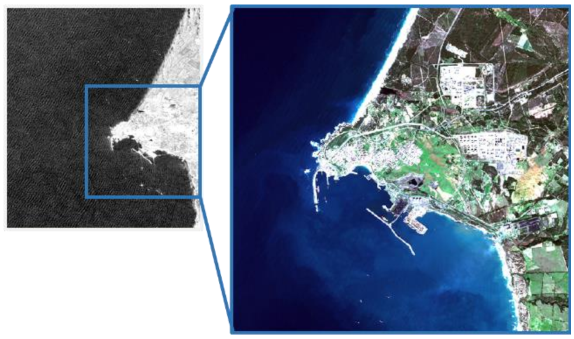

Fig. 7 – Zoom of the region around Sines, on the southwestern coast of Portugal Left: SAR image from Sentinel-1B and Right; Optical data from Sentinel-2.

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