Bathymetry derived from Sentinel-1 Synthetic Aperture Radar data

Stefan Wiehle, German Aerospace Center, Henrich-Focke-Str. 4, 28199 Bremen, +49 421 24420 1863, stefan.wiehle@dlr.de, Germany
Andrey Pleskachevsky, German Aerospace Center, andrey.pleskachevsky@dlr.de, Germany

Abstract

This paper presents the use of Sentinel-1 Synthetic Aperture Radar (SAR) satellite data to derive bathymetry, the topography of the sea floor. With the growing efforts in global shipping and offshore constructions like wind parks, the knowledge of bathymetry becomes increasingly important. An automatic algorithm is used to retrieve the peak wave lengths of long swell waves from SAR acquisitions of coastal seas and calculate the bathymetry using the shoaling effect, which leads to waves becoming shorter when approaching shallower waters. The peak wave period, required for solving the dispersion relation, is also automatically retrieved by comparison to existing datasets.

1 Introduction

With the advance of satellite remote sensing, the continental topography can be accurately measured by Synthetic Aperture Radar (SAR) satellites, as recently done globally by the TanDEM-X mission [4]. However, about 70% of the Earth are ocean, where the sea floor topography cannot be measured by a single spaceborne Earth Observation technology today. Conventional means of measuring the bathymetry use ship-mounted echo sounders; plane-mounted techniques like LIDAR are only possible in very shallow waters. The high costs connected to these ways of measurement are a major reason why the current knowledge of bathymetry is very poor. Free datasets like GEBCO (General Bathymetric Charts of the Oceans) [2] are available, but in many areas based only on interpolation or deprecated measurement data. Even projects like EMODnet bathymetry [1], where many individual bathymetric sources are combined for European waters, still have coverage gaps.

Many of such gaps can be closed using different satellite remote sensing technologies. In shallow waters, the bathymetry can be derived from optical satellites based on sun-light reflection analysis of the sea floor, accounting for chemical and physical characteristics of the water [9]. In deep waters several kilometers off the shore, altimeter satellite data can be used to detect underwater structures which modify the local gravity, creating a measurable change of elevation at the sea surface [10].

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In this paper, we use a technique based on SAR satellites which was first presented in [7] using TerraSAR-X data. The method requires the presence of long swell waves and light to medium wind, as explained in the following section. Hence, not every SAR acquisition of coastal waters is suitable for bathymetry derivation. While TerraSAR-X has higher resolution acquisition modes and better imaging of the ocean surface due to a comparably low orbit altitude, data are only available when previously ordered. Sentinel-1 data, on the other hand, is acquired constantly and fully accessible from the Copernicus data hub, which simplifies the retrieval of suitable scenes worldwide. To make use of this, the algorithm was since extended to work on Sentinel-1 data and run automatically.

2 Method

The principal method of the algorithm used here was presented in [7]. It requires long swell waves because of the shoaling effect, which causes changes in wavelength and wave height when the underlying topography changes. This effect occurs in waters with depths of less than half of one wavelength, approximately, where the waves interact with the seafloor.

The detection of sea surface phenomena by SAR is dependent on the availability of wind [5], which is present in oceanic scenarios most of the time. Even very low wind speeds, about 2 m/s, are sufficient to create ripple waves, centimetre-sized distortions of the otherwise smooth water surface [8]. The characteristics of the radar echo averaged over a subscene can directly be related to wind speed and local variation of intensity can be related to wave height by image spectra analysis [6]. When swell waves, reaching wavelengths of up to several hundred meters, and ripple waves are present, the swell waves are visible on the SAR image as regular brightness modulations. Too strong local wind speeds, however, may cause white capping and wave breaking, which is seen as strong smearing in the SAR image, so the individual wave crests can no longer be discriminated. Hence, detecting wave lengths is possible for low to medium wind speeds only. Very shallow waters lead to increased wave steepening and finally breaking, which means depths below about 10 m are also not suitable for this type of analysis.

Swell waves are a result of distant wind fields and can travel several thousand kilometres across the ocean. A swell system usually has an extension of many kilometres
parallel and perpendicular to the wave direction and becomes more homogenous in wavelength with increasing distance from its origin [3]. Hence, the incoming swell in deep water is considered constant in wave period and wavelength in this analysis.

Using a linear approach and neglecting local circulation currents, the connection between peak wavelengths and depth is described by the dispersion relation

\[ d = \frac{L_p}{2\pi} \tanh^{-1} \left( \frac{2\pi L_p}{g T_p^2} \right), \]  

(1)

where \( d \) is the water depth, \( \omega_p = \frac{2\pi}{T_p} \) is the peak wave frequency, \( T_p \) is the peak wave period, \( L_p \) is the peak wavelength and \( g \) is the gravitational acceleration. From Eq. (1), it follows that two parameters are required to calculate the water depth: the peak wavelength \( L_p \) and the peak wave period \( T_p \).

The retrieval of the wavelength is performed as shown in [6]: a Fast Fourier Transformation (FFT) is applied to subsets of the SAR scene, the wavelength can then be retrieved from the resulting spectrum. The wave period cannot be directly derived from the SAR scene as it lacks temporal information. It could be taken from measurement data, but these are only sparsely available and, hence, this is approach would only be suitable in limited areas. A manual way to derive the wave period is to take the retrieved wave length in an area with constant depth in a sea chart and calculate the wave period using this depth. We have improved and automated this manual procedure by using an external dataset like GEBCO, which is available worldwide but might not be accurate. Other datasets can be used when available, for example EMODnet bathymetry data in European waters. For each FFT calculation box in the satellite scene, a range of depths is calculated by iterating through possible wave periods. The minimal wave period can be calculated from Eq. (1), while about 1.5 times the minimum value was found to be sufficient as maximum investigated wave period. The best wave period is found using a minimum root mean square difference (RMSD) analysis of these depths to the external dataset. This provides an automatic way to determine the wave period without local measurement or manual interaction.

Figure 1: Retrieved bathymetry from a Sentinel-1 scene of West Africa, acquired on 2017-03-08. The colored depths within the satellite scene are retrieved by the presented algorithm, the depths shown outside the scene are from the GEBCO dataset. Background image by OpenStreetMaps.
3 Results
While the algorithm can be applied to many coastal waters worldwide, we present here the results for a Sentinel-1 IW scene in West Africa, acquired on 2017-03-08. Only the VV image is used since sea state is better imaged in this mode compared to the VH image also acquired. The Sentinel-1 IW mode has a pixel spacing of 10 m in both directions and a swath width of 250 km. Figure 1 shows the retrieved depths as colored area within the Sentinel-1 scene used for the calculation. Outside of the colored areas, no depth could be retrieved because the water was too deep for wave interaction or the wave length could not be determined in the FFT subscene. The depths displayed outside the Sentinel-1 scene are GEBCO data. For this investigation, an FFT boxsize of 5.12 km was used, where the FFT boxes were arranged in a gridded pattern offset by 700 m. With external data from the GEBCO 2014 dataset, the automatically retrieved wave period is 12.31 s. The RMSD between both datasets for this wave period is 12.45 m. Since the investigated depths are up to 90 m, this value is withing 15% accuracy. Also, the GEBCO dataset used for comparison cannot be considered to contain fully accurate bathymetry in this region. Further possible sources of error that are not incorporated in the calculation are ocean currents, which change the surface wave lengths, and tidal effects changing the water level compared to values in sea charts or datasets.

4 Conclusions
We have presented an algorithm to automatically derive the bathymetry from SAR images. A Sentinel-1 acquisition on the West African coast was presented as a case study. The offset to the GEBCO dataset was about 15%, which is within the scope of offset also encountered in other areas. While this SAR-based bathymetry cannot match ship-based survey data in terms of accuracy and resolution, it’s cheap costs make it a viable application when the requirements for accuracy and resolution are not too high or as a pre-study that helps limiting the area that has to be surveyed in an expensive shipping campaign. The use of the method is, however, limited to coasts which regularly encounter long swell waves and have extended areas with waterdepths below 100 m. Due to the high amount of acquisitions freely available, Sentinel-1 is a good choice for global data coverage and the IW mode provides sufficient resolution for long swell waves.

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References