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Bathymetry and tidal flat topography from Sentinel-1 acquisitions

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Abstract

Algorithms for automatic processing of bathymetry in shelf oceans as well as the creation of topography for tidal flat areas from Sentinel-1 Synthetic Aperture Radar (SAR) satellite data were developed. SAR bathymetry processing is applicable in oceans with water depths of about 10 m to 100 m. This is a crucial depth range for many offshore construction areas like wind parks. The high costs of bathymetry generation with conventional ship surveys are a major reason for the lack of accurate bathymetry data worldwide. Using radar satellites like Sentinel-1 and automated algorithms, the effort of generating bathymetry data on suitable coasts worldwide is strongly reduced. The developed algorithm tracks changes of the lengths of long swell waves interacting with the seafloor, shortening the wave length due to the shoaling effect when waves reach shallower waters. In tidal flat areas like the Wadden Sea at the Danish, German and Dutch North Sea coast, the morphodynamics of seabed structures are significant; the soft seabed can change within days during severe storms. Data from past measurement campaigns using expensive ship soundings and airborne LIDAR scanning, deprecates quickly as the positions of islands, sandbanks or tidal inlets change. An automated algorithm was developed to retrieve the waterline from SAR images. For tidal flats of the Wadden Sea analysing time series of acquisitions at similar tidal states allows estimating rates of change as well as sediment transport and a combination of several images acquired within a short time frame at different tidal states allows estimating the topography. Acquisitions from the Sentinel-1 (S1) A/B SAR satellites cover most coasts worldwide. In contrast to optical satellites, SAR acquisitions are independent of illumination and cloud cover and reliably deliver new images.
Keywords: SAR, bathymetry, coastline, tidal flats, Wadden Sea

1. Introduction

In this paper, advances in two different areas of oceanic change monitoring with Synthetic Aperture Radar (SAR) data are presented: bathymetry for shelf oceans and topography for tidal flats. Both areas strongly benefit from the use of the Sentinel-1 A/B satellites and their high amount of acquired and available data.

1.1 Bathymetry

About 70% of the Earth is covered by water. Measuring the bathymetry using conventional means like ship-mounted echo sounders causes high costs, which are one of the major reasons for the lack of current bathymetric data worldwide. Free datasets like GEBCO (General Bathymetric Charts of the Oceans) [1] are available, but in many areas based only on interpolation or deprecated measurement data. Also the EMODnet bathymetry project [2], offering multibeam data gathered by many European countries, still has large coverage gaps. Many of such gaps can be closed using different satellite remote sensing technologies. In deep waters, altimeter satellite data can be used to detect underwater structures modifying the local gravity, causing a measureable change of elevation at the sea surface [3]. The depth of shallow waters can be retrieved from optical satellite data based on sun-light reflection analysis of the sea floor, accounting for chemical and physical characteristics of the water [4].

Intermediate depths of about 10 m to 100 m can be determined by an ocean wavelength analysis technique. Based on TerraSAR-X acquisitions, this was presented in [5] and recently extended to Sentinel-1 data in [6]. The approach requires the presence of long swell waves and light to medium wind. Hence, not every SAR acquisition of coastal waters is suitable for bathymetry derivation.

1.2 Tidal flat topography

Tidal flats are coastal areas covered by sea water during high tide but exposed during low tide. In case of the Wadden Sea, stretching through large parts of the Danish, German, and Dutch North Sea coast, tidal flats extend up to 20 km off the coast. Monitoring topographic changes in these extended areas is an important task for the safety of coastal inhabitants and ship traffic. Especially with river modification projects like the deepening of the Elbe, frequent monitoring is imperative. Using SAR imagery acquired at low tide, tidal flats can be identified by their different reflectivity compared to open water.

For coastline detection from SAR images, tidal flats pose additional challenges compared to coastlines without tidal flat areas. The Normalized Radar Cross Section (NRCS) of tidal flats varies strongly depending on factors like surface roughness and remaining surface water, so depending on the water brightness increased by wind speed, tidal flats may appear darker or brighter in a SAR intensity image. Methods solely relying on brightness can therefore not be used for tidal flat scenes. For frequent monitoring purposes, methods using interferometric, polarimetric, or multi-band SAR data are limited by the availability of the respective data.

For determining the boundary between land and water in these tidal flats automatically, an algorithm was presented in [9] for single-polarization TerraSAR-X acquisitions. It was later improved and extended to Sentinel-1 [10]. A further improved version is used in this paper.

1.3 Use of Sentinel-1 data

The data model of Sentinel-1 differs from those of other satellites. For example, TerraSAR-X offers higher resolution acquisition modes which would be preferable in this study due to better imaging of waves and mudflat structures, but data are only available when previously ordered. While tides are relatively well known in advance even many weeks before the acquisition date, swell waves and wind conditions required for bathymetry derivation are known only one or two days before, often too short for regular acquisition orders. Without the appropriate sea state conditions, no bathymetry can be derived from the scene.

Sentinel-1 data, on the other hand, is acquired regularly without the need to order and is fully accessible from the Copernicus data hub [11]. Although no high resolution modes comparable to TerraSAR-X StripMap's 3 m resolution are available, it's the availability of data which enables applications like bathymetry retrieval: even if scenes containing a suitable sea state are rare, some may be found in the archive, especially when the rate of change of the seafloor is rather low and using a scene acquired several months ago is not a concern. Also, even when an area was not investigated before, there is a high chance data will be available since most coastal areas worldwide are covered regularly by Sentinel-1 acquisitions.

All scenes used in this paper were acquired in the Interferometric Wide Swath (IW) mode, commonly used over land and coastal waters in non-polar latitudes. The swath width is 250 km with a pixel spacing in the GRD (Ground range detected) product of 10 m.

2. Bathymetry retrieval

2.1 Algorithm description

The algorithm for automatic bathymetry retrieval is presented in [6]. The method uses the shoaling effect, which causes a reduction of wavelengths for waves entering shallower waters. The linear dispersion relation for ocean surface waves

$$\omega^2 = \frac{2\pi g}{L_p} tanh\left(\frac{2\pi d}{L_p}\right) \quad (1)$$

with $\omega = 2\pi / T_P$ and the gravitational acceleration g can be reformed to

$$d = \frac{L_p}{2\pi} \tanh^{-1}\left(\frac{2\pi L_p}{g T_p^2}\right) \quad (2)$$

for the determination of the water depth d. Two parameters are required: the peak wavelength L_p and the peak wave period T_p.

The peak wavelength is determined using a frequency analysis on small subsections of the scene; details are given in [7].

While the peak wave period cannot be determined directly from a SAR scene, a comparison to available bathymetric data as first guess and error minimization was introduced in [6] to allow a fully automatic determination of the bathymetry. A similar approach was also presented by [8].

2.2 Data and study area

The area investigated for this study is a part of the Bay of Biskay at the French coast. To the west, it is open to the northeast Atlantic Ocean. The area has suitable conditions for the SAR bathymetry method: exposure to swell waves and extended areas of less than 100 m water depth.

The Sentinel-1 acquisition used was acquired on 25.03.2018 on 18:04 UTC. While land is only in the very eastern part of the scene, the western half is too deep for bathymetry derivation. GEBCO data is used as first guess bathymetry for initial initialization of the wave period. A single subsection for processing extends 5 km x 5 km; an overlapping grid was used to increase the resolution to about 700 m.

2.3 Results

Figure 1 shows the resulting bathymetry map on top of the Sentinel-1 scene; depths plotted outside of the scene are GEBCO data. The limits of the depth calculation are subscenes reaching land, or waters becoming too deep compared to the peak wave length, which was about 180 m for this scene. The effect is visible in the deeper water areas in Fig. 1. The automatically retrieved wave period used for the calculation was 11.03 s.

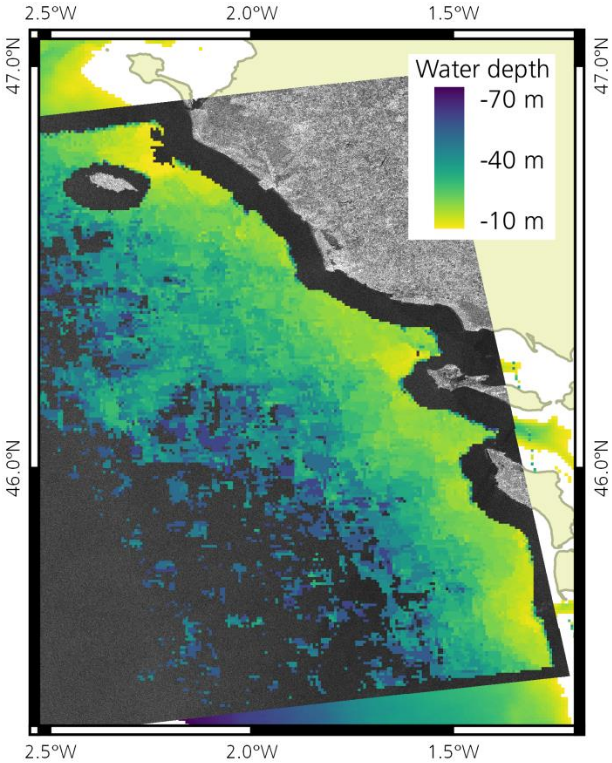

Figure 1: Bathymetry in the Bay of Biscay derived from a Sentinel-1 scene; depth values outside of the scene present GEBCO data. The bathymetry is derived from 10 to 70 m water depth. For depths over 70 m the sea state was too short to reflect the sea bottom structures.

The Root Mean Square Deviation (RMSD) of the retrieved data to the GEBCO dataset is 12.35 m with a scatter index of 0.27. This error can have multiple sources: inaccuracies of the bathymetry data used, tidal effects changing the water level at acquisition time compared to the database values, or surface currents modifying the detected wave lengths.

Recently, a theoretical study on the accuracy of this method was carried out [12], resulting in an error of 8-15% dependent on the gradients in the seafloor profile. Hence, even with an accurate bathymetry for comparison, no tidal effects and no surface currents, a similar error would have to be expected from the method. The accuracy can be increased by merging the results of multiple scenes [6].

Although the method cannot reach the accuracy of multibeam measurements, it offers fast availability with low creation effort for large areas of coverage and may prove useful for pre-studies of extended area

3. Coastline retrieval

3.1 Algorithm description

The algorithm used for automatically retrieving the land-water-line in a SAR scene was presented in [9,10]. After initial smoothing, edge detection followed by iterative edge selection is applied to determine the relevant boundaries. Flood filling is then used to create a land-water-separation. Thereafter, boundary areas are tested for mean brightness differences to remove areas wrongly marked as land, and very small areas marked as land, mostly ships or buoys, are removed.

Two major new aspects were improved in the algorithm for this paper: a switch to a contrast-based land mask and extended gap closing.

3.1.1 Contrast-based land mask

The algorithm previously used a brightness-based land mask as first guess approach. While this works most of the time, in some scenes land reflections are darker than water. This land mask was now replaced by a contrast-based land mask. Using the result of the initial edge detection step, the resulting edge strengths are summed over small areas of the image and automatically classified as land or water using a threshold found by Otsu’s method [13]. Since contrast on land and also on tidal mudflats is generally higher than on water, this land mask yields a more reliable first guess. While the resolution is rather poor due to the summation over image areas, resulting in a scene divided into 50 x 50 regions, the final boundaries are not determined by this land mask, so this limited resolution does not worsen the final result.

3.1.2 Extended Gap closing

With an algorithm relying on flood filling to determine land and water, having closed boundaries is crucial. While a gap closing step was present before, it only worked on dead-end edges; a connection point was searched following the last direction of the edge. However, since the lines always follow the strongest edges, situations occurred where a line would take a turn instead of going straight or simply ending, often leaving only a few pixels of coastline open. Through these, large areas of land behind it were filled with water during the flood filling step.

The identification of this type of gap uses the fact that large water bodies connected to the sea by only very small outlets are not present in the Wadden Sea. To find these gaps, all land in the land mask is grown pixel by pixel. In case of a narrow inlet, this will lead to large isolated patches of water in the land mask. When these occur and their size is above a chosen threshold, the respective gap is identified and closed along the shortest path. This solution does not affect narrow tidal channels, since they become narrower farther away from the sea and, hence, do not form broad isolated water bodies.

3.2 Data and study area

The Elbe River connects the port of Hamburg, the largest port in Germany and third largest in Europe, to the North Sea. Its estuary is part of the Wadden Sea with extended tidal flat areas. While the main fairway is frequently monitored by sounding ships, the surrounding areas are only sounded every 6 years due to the high effort requiring combined measurements with ships and planes at the appropriate tidal conditions. However, topographic changes occur in much shorter timescales and the identification of morphologic developments is important for the future planning of dredging requirements as well as civil and maritime safety.

For this paper, a low tide study using Sentinel-1 data is presented. Waterlines from different dates are compared: Winter 2014/2015, shortly after the launch of Sentinel-1, Spring 2016, when the most recent measurement campaign was conducted, and Summer 2018, as a very recent dataset. Gauge data are taken from the Cuxhaven gauge station. Both are shown in Table 1.

Table 1: Dates of Sentinel-1 scenes used for the study and respective waterlevel at Cuxhaven tidal gauge.

Date	Cuxhaven tidal gauge [cm]
19.01.2015	343
04.05.2016	348
26.07.2018	350

Using Sentinel-1 data, an acquisition at low tide is available almost every two weeks. Figure 2 shows an exemplary period of one month of Sentinel-1 acquisitions and the respective water level. Almost two full tidal cycles are contained therein. However, since there are sometimes periods of 60 hours between two consecutive acquisitions, a low tide state might occasionally be missed. Nevertheless, even a monthly acquisition of a low-tide state is sufficient for monitoring purposes.

3.3 Results

For each scene, the developed algorithm was first used to delineate the land-water-line. However, some errors remained, especially for bigger ships which were not removed and tidal channels which were not fully followed. The respective corrections were applied manually. The following figures show the changes between the different times.

Figure 3 shows the retrieved changes in the tidal flats of the Elbe estuary between the three investigated dates. Most mudflat boundaries have changed, but a common trend cannot be derived; some areas showed a southward movement, other areas moved northwards. The strongest change is seen for the sandbank Kratzsand, opposite of Cuxhaven, which has moved more than 1 km southwards during the observation time, which is more than 1 m per day.

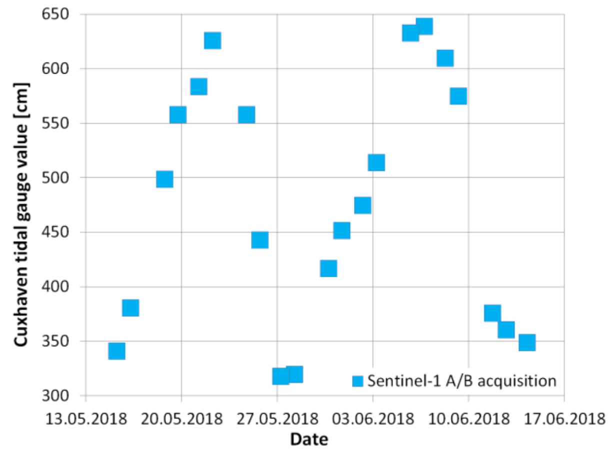

Figure 2: Example for Sentinel-1 acquisitions of the Elbe estuary for one month, May 15 to June 14, 2018, and the respective water level at Cuxhaven tidal gauge. 21 scenes were acquiring during this time, covering almost two full tidal cycles.

Further development and specialization of the applied algorithm will reduce the effort currently required for manual corrections of the automatically delineated coastline. For improved accuracy of water line elevation, the change of the water level at different locations due to the tidal cycle and natural topography has to be considered, for example by using modelling results.

With this case study, using the full time range of currently available Sentinel-1 data, the benefit of SAR remote sensing for tidal flat monitoring is demonstrated. Changes in tidal flat locations and boundaries can be easily determined and areas which require increased attention can be identified. While the current surveying frequency for the Elbe estuary tidal flats is six years, relocations by more than 1 km were seen during the 4 year period of this case study.

6. Conclusions

Bathymetry retrieval and coastline delineation both strongly benefit from the automatically acquired and publicly available SAR data from Sentinel-1, offering multiple acquisitions a month for monitoring and a high amount of archived data. While satellites like TerraSAR-X offer acquisition modes with higher resolution, which, for example, allow more precise coastline delineations, data takes need to be ordered in advance and are often not available for past dates since no acquisitions were requested during the respective time. Sentinel-1 data, on the other hand, are generally available even if an area of interest is identified after the time when acquisitions are needed. However, the coverage of Sentinel-1 acquisitions in the IW mode used in this paper only extends to coastal areas; especially remote islands and ocean areas still require data from

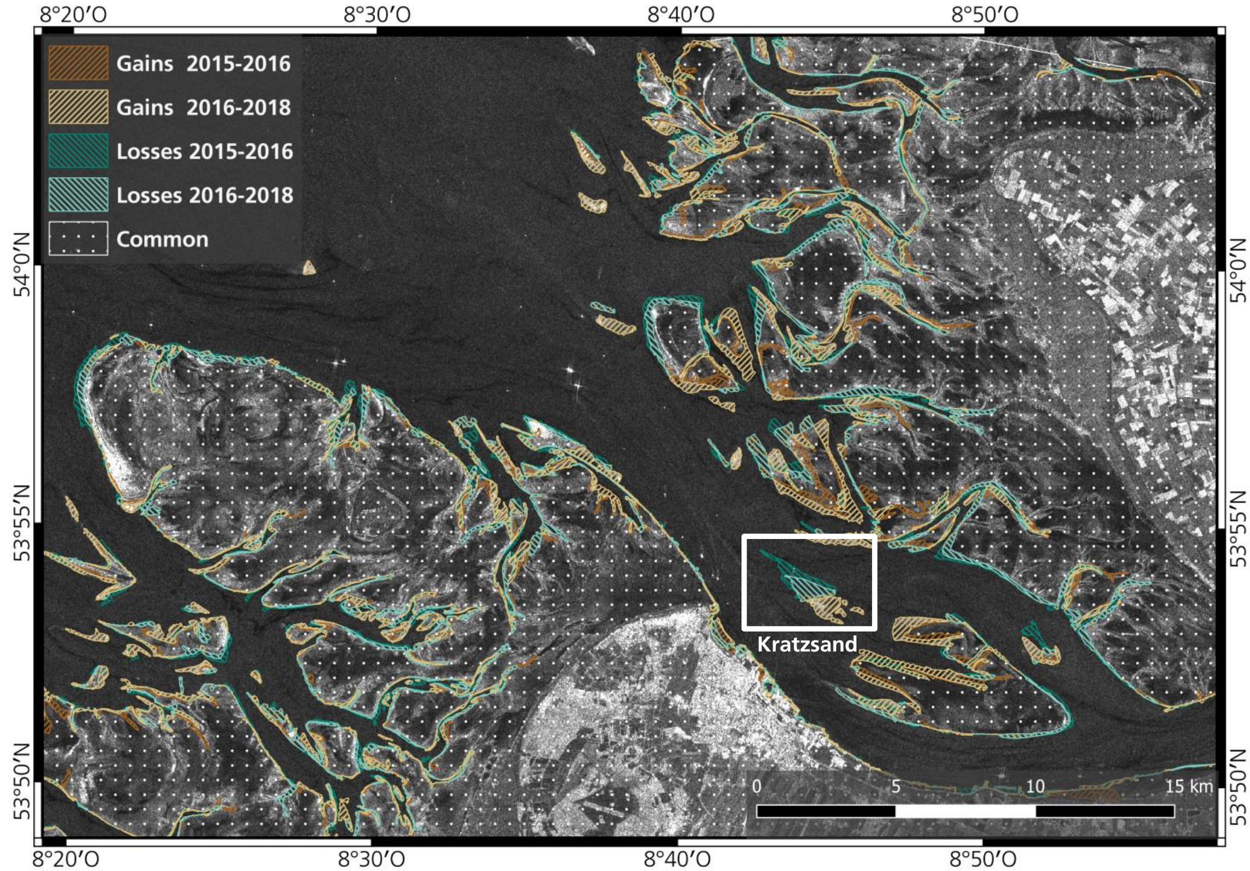

Figure 3: Changes of tidal flats in the Elbe estuary between 2015, 2016 and 2018.

other SAR satellites such as TerraSAR-X for monitoring.

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