ESTIMATION OF UNDERWATER TOPOGRAPHY USING SATELLITE HIGH RESOLUTION SYNTHETIC APERTURE RADAR DATA

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ABSTRACT

A method is presented to obtain underwater topography for coastal areas using state-of-the-art remote sensing data and techniques worldwide. Synthetic Aperture Radar (SAR) data from the new German satellite TerraSAR-X with high resolution up to 1m are used to render ocean waves. As in shallow areas, bathymetry is reflected by long swell wave refraction governed by underwater seabed structures, the depths can be derived using the dispersion relation from observed swell properties. To complete the bathymetric maps, optical data of the QuickBird satellite are used to map extreme shallow waters, e.g., in near coast areas.

The implications of remote sensing data for bathymetry estimation from SAR and optical data are based on different physical backgrounds and mathematical applications, but the results complement each other. The optical data provide depths in shallow water from 0m to about 20m depending on underwater reflection during calm weather condition. The depths estimation from SAR covers the areas between about 100m and 10m water depths depending on sea state and acquisition quality. The depths from about 20m to 10m are the domain where synergy of data from both sources can be applied.

In our study we present the processing of a depth map for Rottnest-Island, Australia. Radar data from TerraSAR-X and optical data from QuickBird satellite have been used. The depths estimated are aligned on two different grids: a uniform rectangular mesh of 150m horizontal resolution, which corresponds to average swell wavelength in a SAR image and on the irregular mesh of 150m resolution for deeper SAR domain up to ~20m depth and 2.4m resolution for the shallow domain imaged by optical sensor. These new imaging techniques provide a platform for the mapping of shallow marine bathymetry over a broad area at a scale that is relevant to marine planners, managers, and offshore industry. The information about detected shallows like reefs and bars can be successfully applied for ship security for the near real-time services.

1. INTRODUCTION

In this paper the different remote sensing data are combined to collect the underwater topography in coastal areas worldwide. In spite of the fact that the worldwide bathymetry should already be known, and there are no “blank spots” on global maps, at least for 1 nautical miles resolution data sets (e.g. global topography by NOAA, ETOPO 1-Minute Global Relief, [19]) the local depth variation e.g. sand bank, bars and reefs on the one hand and temporal morphodynamic development of seabed structures on the other hand can be significant in littoral zones. E.g. in the German Bight (North Sea), the soft seabed topography can changes relatively fast due to storms [7] so that the official charts can be quite out of date.

Generally, the remote sensing techniques to obtain high resolution bathymetry can be divided in to two groups, based on the physical background of algorithms:

1. depth estimation from remote sensing data, based on sunlight reflection analysis and governed by chemical and physical characteristics of sea water, e.g. the bottom reflection. This kind of investigations is covered by optical methods: processing optical satellite data allow physical approximations of the water depths by correcting sunglint, atmospheric effects and the influence of the water column in the earth observation data [12][8].

2. depth estimation based on observation of hydrodynamic processes, which are influenced by topography in a different way and thus reflect the underwater structures. This group of technique can be performed using SAR, RAR (marine Real Aperture Radar, e.g. WAMOS, [10]) and optical data [21].
This paper is focused on SAR-based method. The new high resolution TerraSAR-X (TS-X) images allow to estimate bathymetry from observed long wave refraction. The results are combined with depths estimated by optic-based methods in order to retrieve the complete topography. The investigations are carried out near Rottenest Island, Australia, where SAR, optical and echo-sounding in-situ measurement data are available. The area investigated is indicated by a sliced shore line, complicated underwater topography which includes numerous underwater reefs and is a real challenge for an algorithms “robustness test”.

The paper is structured as follows: in the introduction the bathymetry estimating techniques are briefly discussed and the area investigated is described. The section 2 deals with SAR-methods and results by TS-X. Section 3 presents the fusion of bathymetry derived from SAR and optical data. The discussion in section 4 treats the question of applicability for the SAR-based methods.

1.1. SAR data and depth estimation by circulation currents

The techniques based on observation of hydrodynamic processes use the effect of modification of surface currents and ocean waves by bathymetry. Since both of them are influenced by underwater topography in coastal areas, the change of their properties reflects the underlying depths. As the physical background is known and the connection between observed characteristics and topography can be applied, the depth maps can be derived.

The circulation currents are governed by the law of conservation of mass, their acceleration in the shallows is connected to underwater structures. The changing of currents, in turn, produces a change of surface roughness and this effect can be imaged by remote sensing. Since the launch of the SEASAT satellite in 1978 a series of investigations of ocean features by spaceborne SAR’s have been performed and a method based on changing of water surface reflection by strong surface currents was presented by Alpers and Hennings in 1984 [2]. As mentioned, this SAR-based method to estimate underwater topography uses the effect of variation of circulation currents: if a strong current flows over a sand bank, the speed of the current is higher over the ridge than before or after, due to the law of conservation of mass. Due to this interaction, the spatially changed currents affect the roughness of the surface by small-scale Bragg waves which are responsible for the radar backscatter of the sea surface. Thus, underwater bottom topography becomes visible in SAR images by modulating the image brightness [26]. Using this approach one can only compute relative spatial changes of the underwater bottom topography. To obtain the complete bathymetry map the input of water depths are required for several reference points from external data sources.

1.2. SAR data and depth estimation by refraction of long swell waves

In this paper a new approach to retrieve bathymetry from SAR images is used. The long ocean waves propagating towards the costal line are investigated. Since the launch of the new German satellite TerraSAR-X in 2007, radar data of a new quality stage with high spatial resolution up to 1m allow using new techniques. Ocean surface waves can be resolved down to wavelength of about 30m [5]. High resolution TS-X images allow measuring individual long-wave properties, refraction, shoaling effects, etc. due to improved SAR parameters. SAR-image analysis via Fast Fourier Transformation (FFT) results in directional image spectra. From these spectra, the peak wavelength and directions of swell waves visible in the image are extracted [6].

The swell wave propagation presents the conversation of the wave energy flux, influenced still by energy dissipation due to bottom friction and breaking (relates to the peak period as well). Thus, in shallow areas, depth-forced wave length shortening is compensated by wave height increase (shoaling effect). Since the wavelength can be mathematically connected with local depth via the dispersion relation equation, depth can be estimated from swell wavelength observations.

1.3. Study area Rottenest Island, West Australia

In this paper the underwater topography for the Rottenest Island, Australia is investigated. The selection of this domain has several backgrounds:

1. depth data from sonar measurements of fine spatial resolution are available,
2. the water attenuation (the island is a fossilized coral reef) allows depth estimation using optical data in the coastal zone.
3. the storms in the south-west of Australia create well developed and reliably forecasted long swell directed to the study area.
Rottenest Island is situated about 50km off the coast of Western Australia (Fig.1a, 115°30’E, 32°00’S) near of the city of Perth. The Island is about 10.5km long and 4.5km wide and located on the relatively flat continental shelf off the Perth coastline. The Island presents the seaward end of the shallow Murray Reef System; thus the western end of Rottenest Island can be considered a headland. The notch of the angular-shaped shelf edge, which is the beginning of the Perth submarine canyon, is located off the island’s western end [1].

Fig.1b shows the coarse depth field (ETOPO 1-Minute Global Relief (NOAA, NGDC’s GEOphysical DATA System, http://www.ngdc.noaa.gov/mgg/gdas). Fig.1c presents the measurements from a ship-installed echo depth-sounder with high spatial resolution of about 50m [8]. The island is composed of quaternary limestone and dune sand. Fringed by limestone reefs, the Island’s topography is temporarily quite stable [22]. The coastal line is sliced and the depths fall strongly around the island up to about 50m in the space of about 1km. A coral-reef belt around the island appears in the form of underwater benches and bars. Nutrient and chlorophyll concentrations in sea water around the Island are low in comparison with other typical west coast situations [20]. The Island was originally given the name Eylandt Rottenest meaning “Rats Nest Island” by the Dutch navigator Willem de Vlaming in 1696, the name is because of the rat-like animal quokka, which still abounds there [23].

Figure 1: Rottenest Island, Australia located on the globe (A), ETOPO 1-Minute Global Relief by NOAA (B) and ship sonar measurements by Murdoch University, Perth (C).
As the Rottenest Island is arranged in the front of the Southern Australian coast margin, it is exposed to the largest waves of the global ocean, having been generated by Southern Ocean extra-tropical storms [9]. Rottenest exhibits most southerly wave directions, reflecting the greater distance from the Southern Ocean generating storms and demonstrates highly energetic extreme events a predominance of swell over wind sea states. The Island represents interest in terms of ecology and oil industry: Perth already has three large oil exploration leases near Rottenest Island.

2. UNDERWATER TOPOGRAPHY ESTIMATION BY TERRASAR-X

This section aims to obtain underwater topography using SAR information from TerraSAR-X images. The question of SAR imaging of sea surface and SAR-based techniques to retrieve the swell properties are discussed. The bathymetry is estimated from SAR information using effect of long wave’s refraction, a comparison with in-situ echo-sounding measurement data and errors are given.

2.1. SAR imaging of sea surface created by waves

Synthetic aperture radar SAR is an active remote sensor, which provides two-dimensional information of the normalized radar cross section $\sigma_0$ (NRCS). The principle of synthetic aperture is to replace a snapshot of a large antenna with many images of a small, moving antenna installed on e.g. satellite. Making use of the rapid platform motion, airborne or space-borne SAR systems achieve a high resolution both in flight (azimuth) and across flight (range) direction. If the path of the real antenna is known, and the scenery is static, one can synthesize a large antenna aperture from intensity and phase of the received radar echoes and a high spatial resolution in the azimuth direction can be achieved.

The NRCS represents the ability of a surface to reflect the radar signal and is defined as the normalized energy flux scattered by a unit area of the surface into a given direction. The backscatter is governed by the surface roughness on the scale of the radar wavelength, which is $\lambda_{SAR}=3.1\text{cm}$ for the TS-X SAR. With incidence angles between 20° and 55° the SAR signal falls into the Bragg regime following Bragg condition:

$$\lambda_B = 0.5\frac{\lambda_{SAR}}{\sin \theta}$$

where $\theta$ is the SAR signal incidence angle. If the roughness of the surface imaged approximately satisfies the Bragg condition, constructive interference in the direction of the sensor occurs.

In the case of surface waves the radar return echo is dominated by Bragg scattering of short ripple capillary waves of order of centimeters, produced by wind at sea surface (e.g. [28]). Conventionally, the SAR imaging mechanism of sea surface created by waves as described in literature bases on Real Aperture Radar (RAR) mechanism with additional specifics connected to SAR and consists of three main parts:

1. The local radar backscattering mechanism, which is governed by the sea surface roughness on a centimeter scale (short waves created by wind called Bragg-waves). In case of total lack of wind (total calm weather condition) the surface is smooth and reflects the radar signal aside, but not to the sensor; from a mirror surface the sensor get no radar echo and swell waves can not be imaged.

2. The modulation of the local backscatter processes by long waves (longer than twice the SAR resolution cell) as described by the Real Aperture Radar (RAR).

3. The impact of Doppler shift of surface facets imaged (velocity bunching effect), which is associated with wave motion towards the SAR sensor.

The dominant RAR modulation mechanisms are presented by e.g. [27]:

1. Tilt modulation: long waves modulate the surface slope. The local incidence angle of radar signal is changed and the radar return is influenced according to the Bragg condition (eq.1).

2. Hydrodynamic modulation: This interactions (due to wave orbital motion of longer waves) lead to the modulation of energy contained in the Bragg waves: wave crest and trough are moving in opposite directions, the zones of convergence and divergence of local velocities occurs leading to shortening and stretching of capillary surface waves. This results in changes of the sea surface roughness.

3. Range Bunching: a geometric effect, which leads to a modulation of SAR image intensities associated with surface slopes caused by waves. This effect is more important for a radar system installed not high over water surface. Moreover for e.g. ship-installed radar one wave can screen the wave behind.

Summarized, SARs image the ocean waves, especially long swell waves, by measuring of the sea surface roughness and slope, which influences radar echo. Due to their high resolution, daylight and weather independency and global
coverage, space borne SAR’s of new generation are particular suitable for many ocean and coastal applications [14]. In the presented paper the data from TS-X are used [4]. For more details about SAR imaging of ocean waves by TS-X and statistics see Appendix.

2.2. TerraSAR-X satellite and acquiring of swell waves

The German X-band SAR satellite TS-X was launched in June 2007 (www.dlr.de/TerraSAR-X). Since January 2008, data and products are available for researchers and commercial customers. TS-X operates from a 514km height sun-synchronous orbit. The TS-X ground speed is 7km·s⁻¹ (15 orbits/day). It operates with wavelength 31mm and frequency 9.6GHz. The repeat-cycle is 11 days, but the same region can be imaged with different incidence angles after three days dependent on latitude. There are four different imaging modes with different spatial resolution, technical parameters of the different modes are provided in table 1. The resolution of TS-X images have been visible improved in comparison to earlier SAR missions (about 2m for Spotlight mode against 25m for ENVISAT ASAR). Typical incidence angles for TS-X range between 20° and 60°.

Table 1. TerraSAR-X imaging modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Swath Width (ground range)</th>
<th>Azimuth resolution</th>
<th>Range resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScanSAR</td>
<td>100km</td>
<td>18m</td>
<td>1.7m – 3.5m</td>
</tr>
<tr>
<td>StripMap</td>
<td>30 km</td>
<td>3.3m</td>
<td>1.7m – 3.5m</td>
</tr>
<tr>
<td>Spotlight</td>
<td>10km × 10km</td>
<td>2 m</td>
<td>1.5m – 3.5m</td>
</tr>
<tr>
<td>High-Resolution Spotlight</td>
<td>5km × 10km</td>
<td>1.7m</td>
<td>1.5m – 3.5m</td>
</tr>
</tbody>
</table>

Compared to earlier SAR missions like ENVISAT ASAR, TS-X offers besides higher resolution a number of further advantages: e.g. the Doppler-shift of a scatterer, moving with velocity \( u_r \) toward the sensor (radial velocity) at distance \( R_o \) (slant range) is reduced. For instance, for the same incidence angle 22° and \( u_r = 1m/s \) the target’s displacement in azimuth \( D_a = (u_r / V_{sw}) \cdot R_o \) is reduced by a factor about two and results in ~73m for TS-X (~115m for ENVISAT) due to different platform velocity \( V_{sw} (7.55 km/s^2 \) for ENVISAT) and slant range \( R_o \) (ENVISAT altitude is 800km) [18]. Fig.2. shows examples for TS-X different modes acquired over Rottenest Island: VV polarized Stripmap on September 23, 2009 at 10:53 UTC and Spotlight on 20.10.2009 at 21:36 UTC.

Fig.3. shows the effect of the achieved higher resolution comparing images of ENVISAT with a pixel size of 12m to TS-X images. The ENVISAT scene was acquired on December 21, 2008 over Rottenest Island; the sub-scenes for location in front of the east-coast of the Island are shown for TS-X Spotlight, Stripmap and ENVISAT. Although the waves are detectable in ASAR images, extraction of wavelength <200m and obtaining refraction of quality necessary for underwater topography estimation is not possible (zoomed image see Appendix Fig.A1).

The Spotlight TS-X SAR image acquired over Rottenest Island on 20.10.2009 is shown in Fig.4. The long-swell waves induced in Ocean due to storm (storm peak about 1500km south-west from the area three days before) and propagating towards the island are visible in the TS-X image and the refraction is well pronounced. The scene was specially ordered to acquire the long swell waves for bathymetry estimation. The wave forecast model WAVEWACTH-III (NOAA, http://polar.ncep.noaa.gov/waves/viewer.shtml?multi_1-latest-hs-aus_ind_phi) was used to determine the appropriate acquisition time. The forecasting information was applied one week before TS-X image acquisition.

The ocean waves represent a periodic displacement of the sea surface. The linear wave theory describes sea state as a superposition of elementary sinusoidal components \( j=1,N \), which are propagating in all directions. The surface elevation by one wave component with small amplitude is [13]:

\[
\zeta_j = a_j \cdot \cos(k_j x - \omega_j t + \phi_0) \tag{2}
\]

where \( a_j = 0.5H_j \) is the \( j \)-wave amplitude with wave height \( H_j \), \( \omega_j = 2\pi f_j = 2\pi/T_j \) (\( T_j \) is the wave period) is the angular frequency for frequency \( f_j \), \( k_j = 2\pi/L_j \) the wave number, \( \phi_0 \) is the initial phase, \( L_j \) is the wavelength, \( x \) means the horizontal coordinate and \( t \) is the time. The whole 2-D surface elevation can be presented as function of
Figure 2: Different modes of TS-X images acquired over Rottenest Island: VV polarized Stripmap on September 23, 2009 at 10:53 UTC (left) and Spotlight on 20.10.2009 at 21:36 UTC (right).

Figure 3: Effect of achieved resolution by TerraSAR-X. ENVISAT ASAR image from December 21, 2008 acquired over Rottenest Island and TS-X Stripmap and Spotlight images sub-scenes from Fig.2.
location \( \mathbf{r} (x, y) \) and time:

\[
\zeta (\mathbf{r}, t) = 0.5 \sum_{j=1}^{N} \left[ a(\mathbf{k}_j, \omega) e^{i(k_j - \omega t)} + a^*(\mathbf{k}_j, -\omega) e^{-i(k_j - \omega t)} \right],
\]

where Fourier coefficients \( a \) and \( a^* \) are complex and complex conjugated amplitudes, including phase information and wave number vector \( \mathbf{k}_j = (k_x, k_y) \). The wave action is mathematically described using wave spectrum which presents a distribution of wave energy (proportional to wave height squared) in direction and frequency (or wave number) domain. Proper integration of spectra results in integral wave parameters as significant wave height, mean period and direction.

The sub-images in Fig.4 show the NRCS and random surface simulation for a location. The surface is obtained by applying linear wave theory (eq.3) to wave spectra simulated using a spectral numerical wave model. The model runs at a mesh with horizontal resolution of 1nm (NOAA topography dataset Fig.1), input data are wind field and swell at boundary, obtained from TS-X Rottenest-Island scene. Important to notice, although the imaging mechanism for TS-X is non-linear, the replacing of the facets remains inside one wave length by swell wave for TS-X characteristics (ground speed and slant range) according to theory. The wave is imaged “turned” in location of its own, the image is focused around wave crest and the imaged waves keep original wavelength value (for more detail see Appendix).

2.3. Refraction of long wave and its tracking to obtain underwater topography

The method is based on observation of consecutive waves along their propagation from a start point up to the coast. The wave-rays technique is already well known and widely used as an application for the wave model results (e.g. [31]). The wave rays can be obtained also from wavelength and wave direction observed on SAR images.

Fig.5 shows a scheme of the method: around a selected point on the image (start point of the wave track) a sub-image is selected. By computing the FFT-analysis for the selected sub-image a two dimensional image spectrum in wave number space is retrieved. The peak in the 2-D spectrum marks mean wavelength and mean wave direction of all waves visible...
Algorithm for tracking wave rays: by computing the Fast Fourier Transformation (FFT) for a sub-image a 2-D image spectrum is retrieved in wave number space. The peak in the 2-D spectrum marks wavelength and wave direction. Starting in open sea the box for the FFT is moved in wave direction and a new FFT is computed. Data filtering is taken into account for the wave direction (cross sea) and wavelength (wind sea and wind streaks). The procedure is repeated until the corner points of FFT-Box reaches shoreline (A), an example of one wave ray (B).

Values for wavelength and angle of wave propagation can be estimated as follows:

\[
L_p = \frac{2\pi}{\sqrt{k_{x}^2 + k_{y}^2}} \quad \theta_p = \arctan \left( \frac{k_{x}}{k_{y}} \right)
\]

where \(L_p\) is the peak wavelength, \(\theta_p\) is the peak wave direction with respect to the image (azimuth), \(k_{x}\) and \(k_{y}\) are the image spectra peak coordinates in wave number domain with axes \(x=\) satellite flight direction (azimuth) and \(y=\)range.

The retrieved wave directions have an ambiguity of 180° due to the static nature of a SAR image. This ambiguity can be resolved using SAR cross spectrum or first guess information from other sources. In coastal areas where wave shoaling and refraction appears, the propagating direction towards the coast is visible on the image.

Starting in the open sea the box for the FFT is moved in wave direction by one wavelength (or with a constant specified shift) and a new FFT is computed. This procedure is repeated until the corner points of the FFT-Box reaches the shoreline. This way waves can be tracked from open sea to the shoreline and changes of wavelength and direction can be measured. Fig.5b shows a principle of tracing and an example of one tracked wave ray. Wind streaks (structures on the sea surface of the image, produced by airflow turbulent eddies at boundary layer) and wind sea patterns are removed from the spectra by filtering wavelengths between about 80 and 300 meters (background values must be checked for every scene). After moving the FFT-box to the next point in swell propagation direction the next peak is restricted to deviate no more than +/- 15° compared to previous peak direction in order to avoid switching to another wave system in case of cross sea.

To retrieve water depth, the linear dispersion relation for ocean gravity waves was applied. The solution of the dispersion relation with respect to water depth \(d\):

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

where \(g\) is the acceleration of gravity, \(\omega_p\) is the angular wave peak frequency (\(\omega_p=2\pi/T_p, T_p\) is the peak period). The method was approved for different areas and sea states ([6], [24]) i.e. for the Duck Research Pier (North-Caroline, USA), Port Phillip (Melbourne, Australia), and around Helgoland Island (German Bight, North Sea).

Where surface currents occur, the dispersion relation, which connects the depth with wave number and frequency, must be modified [6]:

\[
\omega_j^2 = g k_j \tanh(k_j d) + U k_j
\]
where \( U \) is the vector component of the surface currents to \( j \)-wave propagation direction. In this study, the effect of current can be neglected, since the currents are weak (in order 0.01m\( \cdot \)s\(^{-1} \) - 0.05m\( \cdot \)s\(^{-1} \) in the area around Rottenest Island, [1]). The shallow areas where the long-shore currents effects appear (e.g. due to wave-breaking induced flow) are taken out from processing. These areas are covered by depth estimation using optic-based methods.

Fig.6a shows examples of obtaining one wave ray for the Rottenest-Island Spotlight scene. 40 wave rays overlapping the area are shown in Fig.6b. The numerical simulation using spectral wave model are carried out on a grid with horizontal resolution of 150m (bathymetry is based on NOAA interpolated dataset, Fig.1b). The model inputs are wind field and swell at boundary estimated from TS-X data (XMOD and XWAVE algorithms, [16]). The model results (Fig.6c) present significant wave height and direction. The refraction and shoaling near the coast (strong increasing of wave height) are indicated. Generally, the refraction by model agrees well with observations, except for an area located in the north: since the reef-bank (see echo-sounding observation Fig.1c) in the north of the Island is not present in the coarse NOAA bathymetry, no refraction occurs at this location in model simulation.

2.4 Estimation of underwater topography using TerraSAR-X data

For the practical use, obtaining topography is divided into five workflow steps:

1. Scene first-check: simulation of some wave tracks (e.g. ten reference tracks). Reference tracks overlap the study domain in different areas. First-checking is applied to evaluate the validity of the scene, to obtain the threshold for filtering of wavelengths and directions. Further, the peak period is estimated: this determination is based on a combination of first-guess for the depths and analysis of reference-tracks.
2. Obtaining wavelength map using wave ray technique: a dense coverage of the area with waves tracks. For uniform mesh (150m resolution) 400 wave rays were necessary for sufficient dense area coverage.
3. Obtaining wavelength using raster method: in the areas where coverage of wave tracks is not dense enough, a raster approach is used: the FFT-boxes are moved not in the wave direction, but at a certain distance \( dx \) and \( dy \).
4. Obtaining resulting wavelength field: after filtering, wavelength is interpolated, extrapolated and smoothed on a uniform grid (a reasonable resolution for topography is the averaged wavelength, for Rottenest Island the raster \( dx=dy=150m \) was applied).
5. Estimation of corresponding depths: using the dispersion relation the depth field is derived.

The peak period, needed in eq.6 is obtained using combination of first guess and analysis of the tracks (\( T_p=13.25sec \)). The longest observed wave in the image is \( L_p^{\text{max}}=245m \). The threshold for minimal peak period for this wavelength, obtained from deep water relation \( T_p^{\text{min}}=(2\pi L_p^{\text{max}}/g)^{0.5}=12.25s \) (solutions of dispersion relation in Fig.11 shows that for periods smaller than 12s, wave of length of 245m belong to deep water domain, where it can not be influenced by bottom. Then again the wave length changes in the SAR image that evidences the bottom influence, thus \( T_p>T_p^{\text{min}} \)).

Fig.7 shows the scene processing results: derived wave field (Fig.7a), derived underwater depth field (rectangular mesh of 150m horizontal resolution, shown 3-D, Fig.7b). Fig.7c presents the scheme for comparison of retrieved data with sonar measurements: The TS-X scene is underlying, a white line marks the area for which a comparison is done. The sonar measurement data from different echo-sounding campaigns (measurement errors unknown) are also integrated and interpolated on rectangular uniform grid \( dx=dy=150m \), relative error between both data sets is shown in Fig.7d: assuming the interpolated sonar depths present the real values, then about 50% of the compared area has an error range of about +/-10% (shown in white color). There are also more variations (one is located in the north of the Island, between a bank and the coast - the swell waves are slowed down and dissipated over a reef and do not build up anymore in a “bag” between two reef-banks. The wave breaking zones, in front of the coast (depicted by streaks, produced by water particles flying in air) destroy the processing of sub-images and do not allow obtain the wave length accurately. They are masked and taken out from depth estimation processing.

3. FUSION AND SYNERGY OF SAR AND OPTICAL DATA

The Synthetic Aperture Radar (SAR) satellite and optical data provide underwater structures and fields in different depth domains. The depths estimation from SAR covers the areas between about 100m and 10m water depths, depending on sea state and acquisition quality. The optical methods require other physical conditions and provide the depths shallower than 20m. The depths between 10m and 25m are a potential synergy domain where data from both sources can be incorporated. In our paper we use the bathymetry obtained from a QuickBird scene with resolution of 2.4m [8], [25].
Figure 6: TerraSAR-X Spotlight acquired on 20-10-2009 over Rottenest Island (Australia). NRCS and one wave track with spectra are shown. Sub-scene shows the wavelength along the track and obtained underwater topography for its trajectory. In the top-right corner the quicklook of the scene is shown (A). 40 wave rays overlap the area are shown (B). Numerical simulation presents significant wave height and refraction (direction shown by arrows, model inputs are wind field and swell at boundary estimated from TS-X data, horizontal resolution is 150m, bathymetry is based on NOAA dataset, Fig.1). The shoaling areas are presented by strong increasing of wave height; since the bank in the north of the Island is not present in the coarse NOAA bathymetry, no refraction occurs at this location in model simulation (C).
3.1. Synergy and data fusion approach

The SAR-based and optic-based methods cover different domains. In order to obtain incorporated depth field the study area is divided into three sub-areas:

1. SAR data domain: area deeper than about 20m. In this area, only the SAR data can be used, as for optical methods the seabed is too deep.
2. synergy area with depths between about 20m and 10m. In this region, the estimated depths from SAR and optic overlap each other.
3. optical data domain: coastal shallow waters shallower than 10m: in this area only optical data can be applied, the swell waves becomes nonlinear and break.

Fig.8 shows the approach for the study area (150m raster, black line on the image marks the area where the depths from SAR are obtained).
The obtained depth data can be applied to provide different products: uniform raster, which corresponds to resolution of SAR-based data (150m by 150m, case A). Original resolution from both sources can also be stored, the resulting field keeps original non-uniform information 150m by 150m for SAR domain and 2.4m for optical and synergy domains (case B).

3.2. Bathymetry on a uniform raster

In order to obtain the depth field for a uniform raster (case A) the optical data must be averaged for the coarser resolution and incorporated with SAR obtained data. Different methods for data combination can be used, e.g. method of optimum interpolation (e.g. [17]). This method is widely used for data assimilation. The depth $D_A^i$ for a grid cell $i$ can be obtained as follows:

$$D_A^i = D_S^i + \sigma_S^i \sum_{j=1}^{Nobs} W_{ij} \frac{D_O^j - D_S^j}{\sigma_S^i}$$

where value of $D_A^i$ at each grid point $i$ is produced using a linear combination of $D_S^j$ (SAR) and $D_O^j$ (optical). The simplification by definition of coefficients $\sigma_S^i$ and $W_{ij}$ leads to reductive formula for coarser grid (150m):

$$D_A^i = D_S^i + 0.5 \left( \overline{D_O} - D_S^i \right)$$

where $\overline{D_O}$ is the simple average of optical data for $i$-cell in 150m raster, used for synergy of both data sets. More complete investigation of $\sigma_S^i$ and $W_{ij}$ for TS-X and QuickBird data will be done in future.

Fig.9 presents the resulting depth filed on a uniform rectangular raster of 150m horizontal resolution. The depths between 60m and 20m is based on SAR data only, the depths lower then 20m are combination of SAR and optical information. The presented underwater depth field includes bathymetry up to mean sea level and can be combined with above-water topography. Thus, the data from TanDEM-X can be incorporated in order to retrieve the complete digital elevation model.

3.3. Bathymetry on a non-uniform raster

The data are combined also without averaging and keeping original information. The Fig.10 shows the data aligned on an irregular mesh (150m for SAR-domain and 2.4m for optic domain). The borderline between the two data sets was defined by visual means at a depth of 18m to 20m, where the results of the ‘optical’ depth analysis start to decrease in reliability.
Figure 9: Depth field obtained from TS-X SAR and optical QuickBird data after fusion and synergy were applied on uniform raster with horizontal resolution of 150m by 150m. The resulting bathymetry field covers the area about 8km by 8km.

Figure 10: Depth field obtained from TS-X and optical data applied on non-uniform raster (150m for SAR domain and 2.4m for optical domain).
Figure 11: Dispersion relation for different wave lengths. The domain where the swell waves react to the depth change and the latter can be estimated is shown. In TS-X SAR images, the swell wavelength is observed to be in range 80m - 350m and representing depth in range about 10m – 120m [6]. Longer waves with higher period occur rarely, but their appearance is quite possible, especially in the front of an ocean coast. This allows depth measurements up to about 200m.

4. DISCUSSION

In this chapter the applicability of SAR and optical techniques to retrieve underwater topography is discussed. The topography estimation for different areas shows that the SAR method is practically applicable if swell waves with height over 0.5m are present in the wavelength range >80m [6]. As long as the orbital velocity profile of the wave reaches the seabed, wavelength will be modified. This takes place for depths less than 70m for swell waves of about 200m length generally. The solutions of dispersion relation for different wave length $L$ (50m - 400m) and periods (5s - 20s) are presented in Fig.11. In TS-X SAR images, the swell wavelength is observed to be in range 80m - 350m and representing depth in range about 10m – 120m [6]. Longer waves with higher period occur rarely, but their appearance is quite possible, especially in the front of an ocean coast. This allows depth measurements up to about 200m.

In the North Sea, the duration of swell is relatively short and its prediction is more difficult in comparison to open coast of Australia, where the storms are longer and the coast are not protected by islands. However, an acquisition of long waves is possible as well: e.g. in a TS-X scene acquired in the North Sea on March 25.02.2009 over Helgoland Island, swell waves of about 0.3-1m height are depicted propagating towards the coast of the German Bight. The simulated wave rays show a definite connection with underlying depths and shallows, although the depth estimation can not be completely processed for the whole scene. The information derived from the scene is insufficient to retrieve the precise depth map, but more than sufficient to detect underwater bars and sandbanks [16]. This kind of information is important for German Bight, where the soft seabed can be changed relatively fast due to storms, so that the official charts can be out of date: it is technically complicated and costly to measure in-situ the entire German Bight frequently enough.

The SAR images include non-liner effects by imaging of moving sea surface. The origin of these structures is connected to displacement of the moving objects by Doppler-shift and can be divided in two groups:

1. reflection of water particle moving inside of water body with corresponding wave velocity: their projection to satellite (radial velocity) can be changed strongly during SAR integrating time. The smearing due to this effect can be reduced and the obtained results can be improved by meeting following conditions:
   a. incidence angle should tend to minimal possible value (reduced slant range),
   b. wave height of swell should be in range 0.5m to ~5m,
   c. the acquisition (descending or ascending mode) should be selected in order to avoid azimuth traveling waves in SAR flight direction (rather opposite to azimuth traveling waves).
(2) reflection of water particle pulled out from the surface and flying in the air: this take place by e.g. wave breaking due to its critical steepness or due to hindrance like reef or by ship bow. The signatures in the image are the streaks-pattern in location where the wave breaks. Assuming the speed of the flying water particles is equal to orbital velocity at wave crest before breaking, the length of these streaks can be connected with wave amplitude before breaking. The height of the breaking waves is also an indirect proof on underwater topography and can be used to detect dangerous locations (underwater reefs). This information can be applied for ship security.

5. SUMMARY

A new way to explore and obtain underwater topography by remote sensing data and using synergy of different data sources is presented. The depth can be obtained with accuracy of order +/- 15% for depths 60m-20m using SAR methods depending on image acquisition quality, sea state and the complexity of the topography (e.g. reefs cause wave breaking). The SAR method covers the areas with depth between 100m and 10m, the optic-based method covers the areas up to 25m dept. Both methods require different physical condition of sea state but the results complement each other: SAR method is based on long wave refraction and can not be used during calm weather condition, needed for optical methods (waves influence the attenuation by mud resuspension). The fusion and synergy of SAR and optical remote sensing data open a new possibility to find out the underwater structures, to produce the coastal depth maps worldwide. The combination the obtained bathymetry with for above-water topography from TanDEM-X satellite mission can be applied to retrieve the complete digital elevation model.

The SAR-based methodology allows also certain detecting shallows (underwater mountains, reefs, deposited sand bars) with depths <30m, even the quality of sea state does not allow obtaining the topography exactly. Such a product can be applied to specify an exact instruction for vessel measurement: the appropriate measurement must be performed in any case in order to incorporate such underwater phenomena into an official chart. This kind of information is important for e.g. German Bight, where the topography changes relatively fast due to soft seabed, so that the official charts can be out of date: it is complicated technically and financially to measure in-situ the entire German Bight synoptic and frequently. The information about shallows detected (reefs) can be applied for ship security.

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APPENDIX: NRCS, RAR modulations and azimuthal cut-off.

The normalization of NRCS is done by dividing by the incident power. The basic object imaged by a SAR is the complex reflectivity \( r \), with a magnitude related to the NRCS as follow:

\[
\sigma_o = |r|^2 \tag{A1}
\]

and a phase, which accounts for possible phase shifts taking place in the scattering process. Since the phase of reflectivity \( r \) is very sensitive to the detailed geometry of the local scattering process, it is usually taken as a random circular Gaussian process with second moments related to the NRCS by eq.1. The angle brackets mean an averaging over a resolution cell. The NRCS is a dimensionless variable denoted by \( \sigma_o \), which is usually given in dB values (Holt, 2004).

\[
\sigma_o^{\text{dB}} = 10 \cdot \log_10(\sigma_o/A) \tag{A2}
\]

where \( A \) is the calibrations constant (“energy reflected in an isotropic way” – scatter back to antenna over a specified area [11]).

The NRCS is related to the spectral wave energy \( F \) contained in the short ripple waves (surface capillary waves with \( f >10^{-1}\text{Hz} \)) with Bragg wave number \( k_B \) by

\[
\sigma_o = \gamma_G [F(k_B) + F(-k_B)] \tag{A3}
\]

where \( \gamma_G \) is a factor depending on incidence angle, polarization and the dielectric constant of sea water ([32], [3]). All three RAR modulation mechanisms are assumed to be independent, the expression for the sum-effect for the respective transfer functions is:

\[
T_k^R = T_k^{\text{tilt}} + T_k^{\text{hydr}} + T_k^{\text{rb}} \tag{A4}
\]

where \( T_k^{\text{tilt}} \) is the tilt modulation (local sea surface slope changing by wave), \( T_k^{\text{hydr}} \) is hydrodynamic modulation (surface roughness influenced by orbital wave motion) and \( T_k^{\text{rb}} \) is range bunching (geometric effect by slanting line-of-sight).

For the moving antenna an ocean wave imaging mechanism, which in general has to be taken into account for scanning systems like SAR is the so called scanning distortion. This effect causes a shearing of the imaged ocean waves due to the radar platform velocity [30]. As the ocean wave phase speed \( c_p \), the mechanism can be readily modeled by applying the following transformation in the spectral domain [27]:

\[
k' = k - \frac{c_p}{V_{\text{SAR}}} \tag{A5}
\]

where \( (k_x, k_y) \) are the original wave-numbers referring to the underlying ocean wave field and \( (k'_x, k'_y) \) are the corresponding wave-numbers in the respective scanned image. As the ratio of phase speed to platform velocity \( c_p/V_{\text{SAR}} \) for space-borne SAR systems like the TS-X SAR is negligibly small (<0.01), it can be neglected it in this study. However, it for airborne systems the effect can be significant [29].

The sea surface motion by waves leads to a velocity component \( u_r \) of a backscattering ocean surface facet towards the radar (slant range). SAR determines the azimuth position of backscattering objects by recording the Doppler history of the returned signals The resulting effect is a shift of the corresponding SAR imaged point in flight direction by a distance [32]

\[
D_x = \frac{R_o}{V_{\text{SAR}}} u_r \tag{A6}
\]

The sign convention for \( u_r \) is such that positive velocities indicate a movement of the imaged facet towards the radar. For SAR imagery acquired over land this effect is known as the “train off the track” effect. In case of the ocean waves the periodic movement of the surface leads to an alternate stretching and bunching of image intensities in azimuth (velocity bunching). This effect is particularly strong for in azimuth direction traveling waves. It culminates in the fact, that azimuth traveling waves which are shorter than a certain threshold are not visible by imaging in SAR. This threshold is called SAR azimuth cut-off wave length. When the wave height is too large, wave orbital velocities also grow large, and the scatterers can be shifted more than one long ocean wavelength in azimuth. This effectively degrades azimuth resolution. An empirical solution for the minimum detectable azimuth wavelength by a SAR, cut-off wave length \( L_{\min} \) is given by:

\[
L_{\min} = C_0 \frac{R_o}{V_{\text{SAR}}} H_s^{1/2} \tag{A7}
\]
where $H_s$ is ocean significant wave height, $C_0$ is a constant of order 1 with units ($m^{1/2} \cdot s^{-1}$) \cite{11}. This latter limitation is a crucial factor in SAR wave images. For polar-orbiting free-flying SAR satellites, $R_o/V_{SAR}$ is about 120s. Thus, for a $H_s = 4$ m, the minimum detectable azimuth wavelength is 240 m, with resolution further degrading in higher sea states \cite{11}. For ENVISAT this parameter is about 114s by altitude 800km, $V_{SAR}$=7.55km/s $^{-1}$ and $\theta$=22$^\circ$. For TS-X $R_o/V_{SAR}$~77s for incidence angle $\theta$=22$^\circ$ and $L_{min}$ according to eq.\ref{eq:7} $L_{min}$=155m for $H_s$=4m and 109m for $H_s$=2m. Due to its lower orbit compared to ERS1/2 and ENVISAT, TerraSAR-X has a quite short azimuth cut-off wave length of around 100m according to theory for a sea state of 2.0 m significant wave height. Therefore TerraSAR-X is able to detect shoaling of short waves. The shortest near shore azimuth-traveling waves observed in TS-X scenes have a wavelength of 70m \cite{16}.

Fig.\ref{fig:A2} shows the scheme for of radial velocity originates from orbital motion and velocity bunching for imaging of azimuth traveling waves (Fig.\ref{fig:A2a} and Fig.\ref{fig:A2b}). The scheme displays that for the swell waves of 100m wavelength and traveling in azimuth direction is the wave imaging mechanism non-linear. However, the SAR-imaged waves keep original wavelength value. Although the wave is imaged “turned” in location of its own, the image is focused around its crest.

Statistics for distribution of peak wavelength over direction from 100 TS-X scenes acquired in North Sea are shown in Fig.\ref{fig:A3a} \cite{5}. A number of images were acquired over buoy locations in order to investigate the TS-X capability of wave imaging. Fig.\ref{fig:A3b} shows a scatter-plot for peak wavelength derived from collocated buoy measured peak period by deep-water relation and TS-X derived peak wave length for NDBC buoy 44066 ($39^\circ 34' 59''$N $72^\circ 36' 2''$W) and buoy located near Ekofisk oil platform in North Sea, ($56^\circ 10' 03''$N $3^\circ 32' 32''$E). The statistical comparisons (scatter index is 0.19, correlation is 0.95, mean square error 0.89) shows a good agreement with in-situ data.

Figure A1: Rottenest-Island, ASAR (resolution ~25m, image pixel size 12m) and TerraSAR-X Spotlight (resolution ~2m, image pixel size 0.75m): Although the waves are detectable in ASAR images, extraction of wavelength <200m and obtaining refraction of quality necessary for underwater topography estimation is not possible.
Figure A2: Imaging of waves ($L=100\text{m}$ $a=1.5\text{m}$, $T=10\text{s}$, $u_{orb}=0.98\text{m}\cdot\text{s}^{-1}$) traveling in azimuth and in opposite to satellite flight direction. Velocity bunching due to wave orbital velocity ($D_x=R_v u_{o}/V_{sar}=75\text{m}$ for $\theta=22^\circ$): although the imaging mechanism is non-linear, the replacing of the facets remains inside of one wave length by swell wave for TerraSAR-X characteristics (ground speed and slant range). The wave is imaged “turned” in location of its own, the image is focused around wave crest. The 3-D image (A) shows projection of orbital velocity to sensor, image (B) shows 2-D scheme of wave imaging.

Figure A3: Distribution of peak wavelength over direction from 100 TS-X scenes acquired in North Sea – the cut-off is grey colored (wavelength about 30m for range and about 100m for azimuth directions) (A). shows scatter-plot for peak wavelength derived for collocated buoys (NDBC 44066 28 entries and by Ecosfisk Platform 27 entries) and TS-X(B).