METEO-MARINE PARAMETERS AND THEIR VARIABILITY OBSERVED BY HIGH RESOLUTION SATELLITE RADAR

Sven Jacobsen (1), Susanne Lehner (1), Andrey Pleskachevsky (1), Wolfgang Rosenthal (2)

(1) German Aerospace Center, Remote Sensing Technology Institute , Maritime Security Lab, Henrich-Focke-Strasse 4,
D-28199 Bremen (Germany), Email:sven.jacobsen@dlr.de
(2) OceanWaveS GmbH, Hansekontor,Vor dem Bardowicker Tore 6b, D-21339 Lüneburg (Germany)

ABSTRACT

An estimation of swell wave energy fluxes is presented based on remote sensing data. The energy flux being the product of wave energy density and group velocity is estimated based on information about local wave height, wavelength and period. Wave parameters are determined from TerraSAR-X high resolution radar images using the newly developed empirical algorithm XWAVE-2. An analysis of the spatial variation of relevant variables is presented for selected areas along the south coast of Java island (Indonesia). Wavelength reduction of shoaling waves moreover yields estimates of the local bathymetry. An examination of sea state parameters in combination with the derived local underwater topography permits the identification of the best-suited locations for wave power plants. The information is a valuable constituent in the site selection process for ocean renewable energy facilities as part of the bilateral Indonesian-German project *Science for the Protection of Indonesian Coastal Marine Ecosystems* (SPICE).

1. INTRODUCTION

Information about the wave impact on the coast and beaches is important for risk assessment in coastal management and a substantial part in the planning of structures in coastal waters like oil platforms or power plants facilities. For ocean renewable energy (ORE) facilities, statistical sea state analysis can furthermore provide estimates of the local power potential.

The use of remote sensing techniques to obtain this information for larger areas has several advantages. In-situ measurements with wave rider buoys provide wave parameters at the buoy location and yield the local wave energy. Energy flux and dissipation can be extrapolated to the coast to a certain extent. However, this method does not allow the estimation of the spatial energy distribution. Another common approach is using wave models which yield the spatial distribution of integrated sea state parameters. However, numerical modelling of coastal areas has its drawbacks: the physical processes in shallow water, caused by interaction between waves, currents and bottom topography become important and are not actually implemented in numerical schemes by coupling of waves and circulation. Moreover, computer simulations are dependent on a-priori information such as initial and boundary conditions as well as spacial and temporal information about wind inputs. Collecting these datasets in sufficient accuracy poses further challenges to modelling approaches.

Spaceborne sensors, on the other hand, combine spatial coverage and independence from additional input data as opposed to in situ methods and simulations, respectively. Spaceborne synthetic aperture radar (SAR) is a unique sensor providing two dimensional information of the ocean surface and is particularly suitable for many ocean and coastal observations due to its high resolution in combination with global coverage and the independence of daylight and cloud conditions. Recent development of wave height assessment with X-band SAR images allows to obtain wave information over large areas at high resolution and thus represents a valuable complement to *in-situ* measurements and model results.

A number of new high-resolution X-band radars have been launched like German TerraSAR-X (TS-X), Tandem-X (TD-X) and Italian COSMO-Skymed satellites. The latest generation SAR sensors acquire images of the sea surface with a resolution up to 1m. Individual ocean waves with wavelengths under 30m are detectable. This opens new perspectives for the investigation of the spatial variability of the sea state parameters and related processes, which is particularly important in coastal areas.

The overarching goal of the SPICE program (*S*cience for the *P*rotection of *I*ndonesian *C*oastal Marine *E*cosystems) [1] is to address the scientific, social and economic issues related to the management of the Indonesian coastal ecosystems and their resources. One central research topic is dedicated to the estimation of the power potential from ORE facilities in Indonesia and to identify suitable locations. The exploitation of Earth observation data with the above methods can thus contribute to both, the identification of promising ORE potential on a regional scale along the extensive Indonesian coastline and to the small scale micro-siting process for possible facility locations. The results are also intended to be used for numerical model validation and *in-situ* campaign conception.

2. SATELLITES AND DATA

The X-band SAR satellite TerraSAR-X (TS-X) was launched in June 2007 and its twin TanDEM-X (TD-X)

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in June 2010. TS-X and TD-X operate from 514km height at sun-synchronous orbits, the ground speed is 7km·s^{-1} (15 orbits per day). Both satellites are orbiting in a close formation with typical distances between satellites of 250m to 500m. They operate with a wavelength of 31mm and frequency of 9.6GHz. The repeat-cycle is 11 days, but the same region can be imaged with different incidence angles after three days dependent on scene latitude. Typical incidence angles range between 20° and 55°. The coverage and resolution depends on satellite mode: StripMap covers 30km by 50km with a resolution of about 3m, Spotlight covers 10km by 10km with resolution of about 1m [2].

One characteristic of SAR imaging is that targets which are moving towards or away from the SAR sensor will not be imaged in their real position, but will be shifted in flight direction. This phenomenon is also known as train-off-the-tracks effect and can be contributed to the Doppler shift of the echo related to the target's motion. As the sea surface is continuously moving, this effect is omnipresent in the imaging of waves and makes the image analysis more difficult. However, compared to earlier SAR missions like ENVISAT ASAR, TS-X offers a number of further advantages besides higher resolution: e.g. the dislocation of scatterers, moving with velocity u_r towards the sensor (radial velocity) at distance R_o (slant range) is reduced. For example, for the same incidence angle of 22° and a target motion of u_r=1m·s^{-1}, the target's displacement in azimuth direction is given by

$$D_x = \left(u_r / V_{sar}\right) \cdot R_o \tag{1}$$

It adds up to ~73m for TS-X but is considerably larger, for ENVISAT (~115m). This can be contributed to the different platform velocity V_{sar} and slant range R_o (ENVISAT altitude was 800km). Thus, the smoothing of moving wave crests also called "bunching effect" is noticeably reduced. Hence, TS-X imaging of the ocean surface is more stable compared to previous missions and the shortest waves that can be identified have wavelength as short as 25m-30m.

3. METHODS

Synthetic aperture radar is capable of providing wind information over the ocean by measuring the roughness of the sea surface. A new algorithm XMOD-2 has recently been developed for TS-X data that takes the full nonlinear physical model function into account and yields high-resolution wind fields [3]. Simultaneously, the corresponding sea state parameters can be estimated from the same image. A new empirical model function XWAVE-2 has been developed for X-band data to derive wave parameters [4]. The newly developed algorithm allows the assessment of the significant wave height H_s directly from TS-X SAR image spectra without using *a-priori* information and without temporal transferring into wave spectra. Both methods were fitted and validated with collocated hindcast model results and buoy data and showed a high performance with a scatter index of 16% for wind speed and 21% for significant wave height. The algorithms are capable to resolve fine-scale variations and this high-resolution two-dimensional information and have been successfully applied to validate numerical models [5].

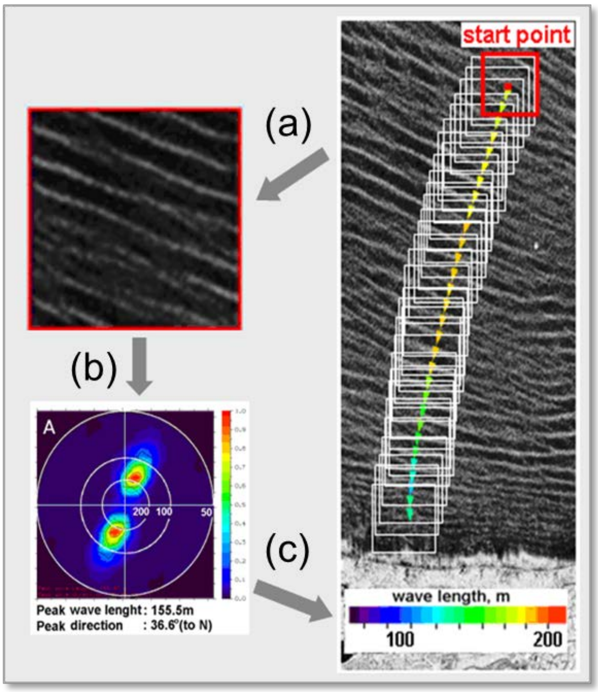

Figure 1: *Wave tracking principle: a) A subscene is extracted in an area of interest. b) The local image spectrum is calculated and wave length and direction are derived. c) The extraction window is translated in the wave propagation direction and the procedure is repeated. The resulting wave length profile along the wave propagation direction can be converted to a water depth profile using the dispersion relation.*

The quantification of onshore wave refraction and shoaling allows the estimation of the underwater topography via the dispersion relation that links wavelength and water depth. The algorithm scheme is illustrated in Fig. 1. We obtain swell wavelength and direction from TS-X SAR image based on FFT (Fast Fourier Transformation) analysis of sub-scenes around 800m×800m. By computing the FFT for the selected sub-image a two dimensional image spectrum in wave number space is retrieved. Wind streaks and wind sea patterns are removed from the spectra by band-pass filtering wavelengths between 50m and 300m. (These values should be adjusted for every scene.) The remaining peak in the 2D spectrum determines peak wavelength and peak wave direction of all swell waves in the sub-image. The retrieved wave directions have an

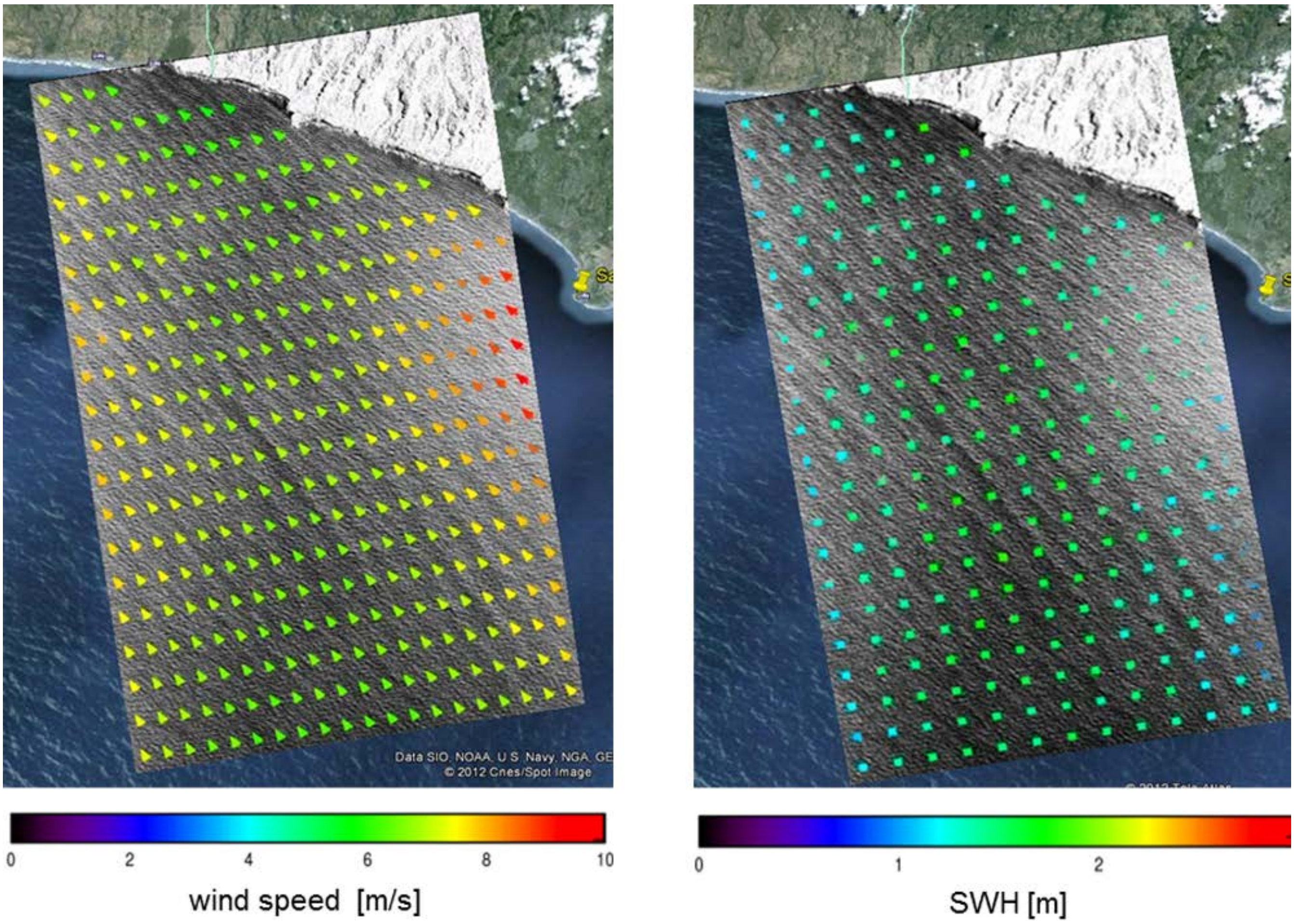

Figure 2: *Example of wave, wind and ice measurements from TerraSAR-x satellite observations acquired over Santolo Beach (south Java, Indonesia) in July 2011. Wind and wave parameters are estimated using XWAVE and XMOD2.*

ambiguity of 180° due to the static nature of a SAR image. In coastal areas where wave shoaling and refraction appears, the propagating direction towards the coast is unambiguous. Starting in the open sea, the box for the FFT is translated in wave propagation direction and a new FFT is computed. This procedure is repeated until the corner points of the FFT-Box reach the shoreline. Thus, a wave can be tracked from the open sea to the shoreline and changes of wavelength and direction can be measured. Using the wave dispersion relation the observed changes in wavelength can be converted to water depths. Hence, the wave tracking technique can provide bathymetry measurements along the wave propagation direction [6].

Wave tracking in combination with the obtained wave heights represents a new possibility that arises with high-resolution Earth Observation (EO) data to obtain the wave energy flux. The wave propagation represents the flux of wave energy which is subject to energy dissipation by bottom friction and wave breaking. The wave energy flux F_w is the power transported by wave action and given by

$$\boldsymbol{F}_w = E_w \boldsymbol{c}_g \tag{2}$$

where E_w is the mean wave energy density per unit horizontal area ($J \cdot m^{-2}$) and $\boldsymbol{c}_g$ is the wave group velocity vector. E_w can be obtained using the significant wave height H_s deduced from the TS-X image.

The group velocity can be estimated by means of phase speed c_p of swell using wavelength from corresponding location (sub-image) of tracked wave rays. The phase speed c_p is well approximated by

$$c_p = \sqrt{\frac{gL}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)} \tag{3}$$

and the group velocity can be approximated for intermediate depth d as well by

$$c_g = \frac{1}{2} c_p \left(1 + k \cdot d \frac{1 - \tanh^2(k \cdot d)}{\tanh(k \cdot d)} \right) \tag{4}$$

where *d* is the water depth, *k* is the wave number, *g* is the gravitational acceleration and *L* represents the wavelength.

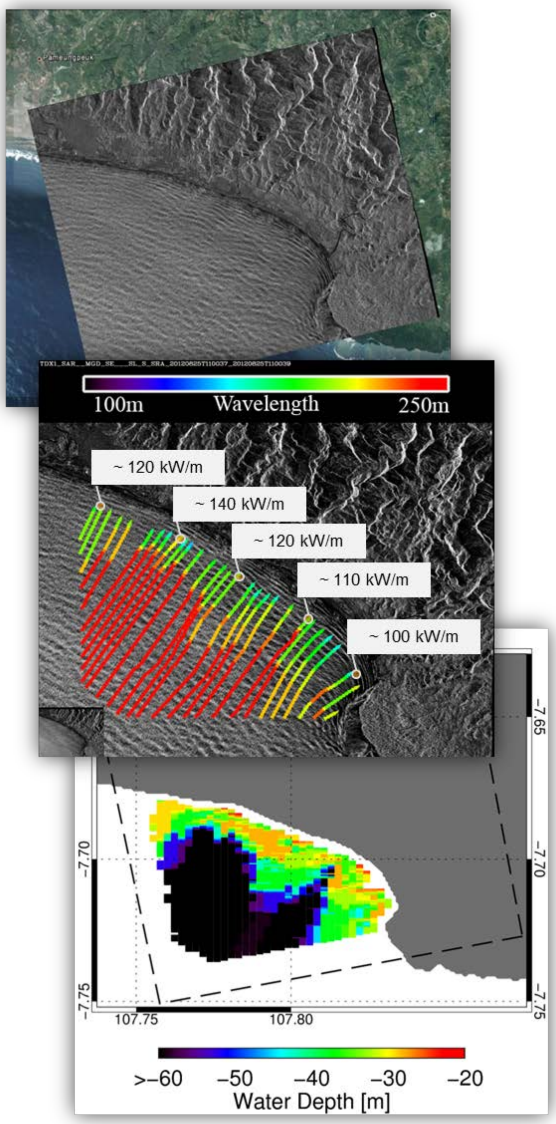

Figure 3: *TerraSAR-X Spotlight image acquired near Santolo Beach, Indonesia on August 25, 2012. NRCS (top), wave rays covering the area of interest with color-coded wave length and energy flux estimates (middle), depth field derived from TS-X scene on a uniform raster (bottom).*

In shallow areas, depth-forced wave length shortening is compensated by wave amplitude increase. This phenomenon is commonly known as shoaling effect. An increase of wave height can be roughly estimated using shoaling coefficient or EO data and occurs until wave steepness exceeds a certain threshold where wave breaking takes place.

4. RESULTS

The results shown in this section are given exemplary for an area on the south Java coast. We intended to stress the possible benefit of the methods introduced rather than providing a full quantitative analysis of available scenes along the coastline.

Fig. 2 shows wind and significant wave height fields estimated from a TerraSAR-X Stripmap scene acquired over Santolo Beach, southern Java, Indonesia. It illustrates considerable variation of the above parameters. While the wind field varies between ~6m/s and ~9m/s, the significant wave height ranges from ~1.2m to ~2m.

The middle panel of Fig. 3 illustrates the wave tracking technique. The wavelength is represented in the color code. We observe shortening of the wavelength from initially ~250m to ~170m. The values are converted to local water depth and extrapolated to a regular grid in the bottom panel of Fig. 3. The resulting bathymetry gives a good estimate of the underwater topography. However, depths below 60m cannot be resolved.

The middle panel of Fig. 3 moreover contains examples of the derived wave energy flux along the imaged coastline. It was obtained by combining the information about wavelengths and wave heigths (not shown here) for the scene. We observe a considerable variation along the coast segment of 40%.

5. CONCLUSIONS

We successfully applied novel techniques for the assessment of high-resolution sea state parameters, underwater topography and the wave energy flux. Considerable spatial variations of the parameters have been found. The results will be included in the micro-siting process for ocean renewable energy facilities on the Indonesian coast within the SPICE project. Fine-scale numerial models and the planning of in-situ campaigns will benefit from the provided data.

6. REFERENCES

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