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Meteo-marine parameters for highly variable environment in coastal regions from satellite radar images

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ABSTRACT

The German Bight of the North Sea is the area with highly variable sea state conditions, intensive ship traffic and with a high density of offshore installations, e.g. wind farms in use and under construction. Ship navigation and the docking on offshore constructions is impeded by significant wave heights H_S > 1.3 m. For these reasons, improvements are required in recognition and forecasting of sea state H_S in the range 0–3 m. Thus, this necessitates the development of new methods to determine the distribution of meteo-marine parameters from remote sensing data with an accuracy of decimetres for H_S. The operationalization of these methods then allows the robust automatic processing in near real time (NRT) to support forecast agencies by providing validations for model results.

A new empirical algorithm XWAVE_C (C = coastal) for estimation of significant wave height from X-band satellite-borne Synthetic Aperture Radar (SAR) data has been developed, adopted for coastal applications using TerraSAR-X (TS-X) and Tandem-X (TD-X) satellites in the German Bight and implemented into the Sea Sate Processor (SSP) for fully automatic processing for NRT services.

The algorithm is based on the spectral analysis of subscenes and the model function uses integrated image spectra parameters as well as local wind information from the analyzed subscene. The algorithm is able to recognize and remove the influence of non-sea state produced signals in the Wadden Sea areas such as dry sandbars as well as nonlinear SAR image distortions produced by e.g. short wind waves and breaking waves. Also parameters of very short waves, which are not visible in SAR images and produce only unsystematic clutter, can be accurately estimated. The SSP includes XWAVE_C, a pre-filtering procedure for removing artefacts such as ships, seamarks, buoys, offshore constructions and slicks, and an additional procedure performing a check of results based on the statistics of the whole scene.

The SSP allows an automatic processing of TS-X images with an error RMSE = 25 cm and Scatter Index SI = 20% for total significant wave height H_S from sequences of TS-X StripMap images with a coverage of ~30 km × 300 km across the German Bight. The SSP was tuned spatially with model data of the German Weather Service's (DWD) CWAM (Coastal WAve Model) with 900 m horizontal resolution and tuned *in situ* with 6 buoys located in DWD model domain in the German Bight. The collected, processed and analyzed data base for the German Bight consists of more than 60 TS-X StripMap scenes/overflights with more than 200 images since 2013 with sea state acquired in the domain H_S = 0–7 m with a mean value of 1.25 m over all available scenes at buoy locations.

The paper addresses the development and implementation of XWAVE_C, and presents the possibilities of SSP delivering sea state fields by reproducing local H_S variations connected with local wind gusts, variable bathymetry and moving wind fronts under different weather conditions.

1. Introduction

The paper introduces an algorithm and processor for meteo-marine parameter estimation. The implementation for practical applications requires the investigation of specific properties of the SAR imaging of coastal sea state, the design of the processor and also the data collecting/processing. The paper addresses in the first place the SAR oceanography community and users of remote sensing data such as meteorological offices. In Section 1, the general background of the subject is reviewed, while the methodology and data used are described in Section 2. Section 3

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is dedicated to data processing and results. Conclusions are summarized and discussed in Section 4.

1.1. Synthetic Aperture Radar Satellites for oceanography

Space borne SAR (Synthetic Aperture Radar) as a remote sensing instrument is a unique sensor which can cover large areas and provide two dimensional information of the ocean surface. Due to its high resolution, daylight and weather independence and global coverage, space borne SAR sensors of the latest generation are particularly suitable for ocean and coastal applications.

In comparison to *in-situ* buoy measurements at a single location, the satellite borne SAR data allows the coverage of large areas and estimating the spatial distribution of investigated characteristics. The spatial validation of forecast data, i.e. sea state and surface wind, by remote sensing data can improve the forecast quality and contribute to explaining natural phenomena beyond regular conditions such as storm front propagation, wind gustiness and occurrence of wave groups with extreme wave heights (Lehner et al., 2012, 2013; Pleskachevsky et al., 2012).

Synthetic aperture radar (SAR) is an active remote sensor providing two-dimensional information of the normalized radar cross section σ^0 (NRCS). The principle of synthetic aperture is to replace a snapshot of a large antenna with many images derived from of a small, moving antenna installed on e.g. satellites. The NRCS represents the surface reflectance of 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 λ_{SAR} = 3.1 cm for the TS-X SAR. If the roughness of the imaged surface approximately satisfies the Bragg condition, constructive interference of the reflected radar signal in the direction of the sensor occurs.

Ocean surface measurements have been carried out based on SAR data since the first space borne SAR missions. They include such well-known missions as L-band SAR SEASAT launched in 1978, C-Band European Radar Satellites ERS-1 and ERS-2 launched in 1991 and 1995, ENVISAT (Environmental Satellite) with C-Band Advanced Synthetic Aperture Radar (ASAR) in 2002 and others. The extraction of surface ocean waves and wind parameters received priority in a number of other tasks. Different inversion schemes, e.g. Hasselmann and Hasselmann (1991), Krogstad (1992), Engen and Johnson (1995), Hasselmann et al. (1996), Mastenbroek and de Valk (2000), Chapron et al. (2001), Schulz-Stellenfleth et al. (2005), Collard et al. (2009) were developed in order to estimate wave spectra from SAR data.

In fact, in the case of surface waves, the radar return echo is dominated by Bragg scattering of short ripple capillary waves of the order of centimeters, produced by wind at the sea surface. A SAR image exhibits the reflectance of radar signal by the sea surface: the surface roughness is produced by waves at all scales from small capillary waves to large ocean surface swell waves. As moving and non-stationary targets, the waves are often deformed, defocused and smoothed in the SAR images. Conventionally, the mechanism of SAR imaging of waves the sea surface (e.g. Hasselmann et al., 1985) is based on the Real Aperture Radar (RAR) mechanism with additional specifics connected to SAR. The classic approach is the estimation of the image spectrum from a subscene and converting this spectrum into a wave spectrum using a transfer function based on a series of assumptions.

The first generation inversion method of Hasselmann and Hasselmann (1991) was based on a maximum likelihood matching of the first guess (*prior* information) available from a wave model and the data provided by the SAR image spectrum. From the first-guess wave spectrum, the forward transform is applied to firstly compute the associated SAR wave image spectrum. It is undisputed that second-generation retrievals, which use the complex information of the image cross spectra to remove the directional propagation ambiguity, are inherently superior to first generation retrievals using only SAR image variance spectra (Li et al., 2010). Empirical algorithms were considered to retrieve integral wave parameters for C-band SAR data (Schulz-Stellenfleth et al., 2007) for the ERS missions. This approach was further extended for use for SAR data acquired by ENVISAT (Li et al., 2008) without *a priori* information. Nevertheless, approaches of both generations engaged only the study of waves and disregarded wind information. However, in natural processes wherein the waves are strongly related to the local wind, the addition of such cross information can significantly improve the performance of sea state recognition.

1.2. Improving of sea state recognition in intertidal zones of the North Sea

Over recent years, a number of new high resolution X-band radar satellites have been launched which provide the possibility to image and measure the sea surface with high resolution, e.g. TerraSAR-X (TS-X), TanDEM-X (TD-X) and COSMO-Skymed satellites. This opens a new perspective for investigating sea state and connected processes in coastal areas, where spatial variability plays an important role. A wide spectrum of features and signatures describing the sea surface are simultaneously involved and can be observed in high resolution images including surface wind and gusts, individual waves and their refraction, wave breaking effects, etc. Knowledge of basic geophysical processes and their imaging mechanisms are necessary for the successful processing of images and for organizing NRT services to provide the information to interested users such as national meteorological services. Fig. 1 shows two examples of coverage for TS-X satellite by different orbits in southern North Sea. A sequence of TS-X StripMap images (scene) can cover strips of 300 km × 30 km across the German Bight allowing observation of the local variations in wind and wave fields. A zoom over Helgoland Island demonstrates the performance of TS-X SAR-images: the individual waves up to 30 m wavelength and their refraction can be distinguish.

The German Bight in the North Sea includes a part of the Wadden Sea and is characterized by a strong dependence on tides in complex topography with a large number of islands and shoals. The tidal changes can reach several meters and corresponding variations of the local currents are more than 2 m s^{-1}. The appearance of numerous sandbars and shoals during low water tide greatly influences the spatial distribution of the wave propagation.

The intensive transport shipping and unloading at offshore construction sites such as wind farms in the German Bight requires an improvement in forecast accuracy. Fig. 2 illustrates the intensity of ship traffic in the German Bight and around construction areas at offshore wind farms. A wave height <1.3 m is required for ships to be able to dock at offshore construction sites. The users (e.g. shipping companies) have requested an improvement of sea state prediction in the significant wave height H_S domain of 0.5–2 m. In case H_S exceeds 1.2 m, disembarking is too hazardous for crew members and the transport ship must return to the harbor. Such operations are planned in advance and inaccurate predictions cause high additional costs.

The wave models of the third generation have been developed and used for sea state prediction, e.g. the WAM model (WAve Model) used by forecast services in Europe such as ECMWF (European Center of Medium range Weather Forecast), the German Weather Service (DWD, http://www.dwd.de), and the Danish Meteorological Institute (DMI, www.dmi.dk), which are a part of the global marine weather and warning systems. In the open sea (deep water) the wave models are already capable of producing a