SEA STATE PARAMETERS IN HIGHLY VARIABLE ENVIRONMENT OF BALTIC SEA FROM SATELLITE RADAR IMAGES

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ABSTRACT

In this work, remote sensing Synthetic Aperture Radar (SAR) data from TerraSAR-X and Tandem-X (TS-X and TD-X) satellites have been used to estimate total significant wave height and surface wind speed in various areas in the Eastern Baltic Sea to further improve empirical XWAVE_C algorithm and to investigate the wave behaviour and local variability. In total, 91 TS-X StripMap scenes between 2012 and 2016 were processed and analysed. The wave height results from SAR images were compared with collocated *in situ* buoy measurements from different timeframe and locations. The analysed data include both high and low wind sea. New corrections using local wind speed, simultaneously estimated from the same subscene, were introduced to further improve XWAVE_C wave height estimation for short wave systems dominate in the Baltic Sea. The comparison of SAR-based wave height with measured wave height showed high agreement with correlation *r* of 0.89.

Keywords – SAR, sea state, surface wind, Baltic Sea, coastal processes.

1. INTRODUCTION

The algorithms to estimate surface wind fields and wave parameters from Synthetic Aperture Radar (SAR) imagery has seen significant evolution in recent years [1–6]. The spaceborne SAR is a unique sensor in ocean applications, being weather and daylight independent, having high resolution and global coverage, the surface wave parameters can be estimated with high accuracy over sufficiently large area [1].

The current work focuses on the wave height estimation from TerraSAR-X (TS-X) and Tandem-X (TD-X) imagery in the Eastern Baltic Sea, specifically in Gulf of Finland (GoF), Gulf of Riga (GoR), and Northern Baltic Proper (NBP), using empirical algorithm XWAVE_C (C = coastal) which was developed for coastal areas and validated in southern North Sea [6]. So far TS-X and TD-X data is used for the Baltic Sea in [7] although, only for acquiring peak wavelength and peak propagation direction. The Baltic Sea, with the absence of prominent swell waves longer than 200m, a complex coast line, archipelago sea, and the significant wave height remaining mostly in the domain of 0–2m (rarely exceeds 5 meters) [8], is a challenging location to validate XWAVE_C algorithm. In TS-X SAR imagery short waves with peak wavelength Lp<50m are either invisible while producing image clutter, or are barely visible (50m<Lp<100m), while producing non-linear distortions in the form of defocused streaks in SAR flight direction. Therefore, in the Baltic Sea, the contributions of such ‘‘unstructured” short waves with a significant wave height of 0–2m significantly increase importance of improvements.

2. DATA

For the validation, a series of TS-X and TD-X Multi-Look Ground Range Detected (MGD) StripMap products were acquired in the Eastern Baltic Sea over buoy locations and coastal areas for sea state parameters estimation. The data was provided by German Aerospace Center (DLR) via the EOWEB® interface. An individual StripMap image with pixel resolution of 1.25m covers 30km×50km. The satellite images were acquired between 2012 and 2016 in HH and VV polarisations. The meteo-marine parameters were estimated based on statistics of subscenes of 1024×1024 pixels that covers an area of 1280m×1280m for spatially enhanced TS-X StripMap images used for this study.

The extracted wave height from SAR imagery was compared with collocated *in situ* buoy measurements.

Three different types of buoys were available to use – ADCP, wave rider, and pressure sensor. Fig.1 shows an overview of total 91 available TS-X scenes and buoys utilised for validations. For wave height comparison, 89 data pairs were available.

Wind speed comparisons between the estimations and *in situ* data from 6 measurement stations from Estonian Weather Service (Fig.1) results in 66 collocation pairs.

Fig.1. Overview of Estonian coast and measurement locations overlaid on Google Earth ® image.

3. METHOD AND RESULTS

For image processing empirical XWAVE_C algorithm introduced in [6] was used. The algorithm has been designed for North Sea with focus on Wadden Sea with shallow water and tidal effects. The method 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 analysed subscene to estimate wave height. 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 signatures similar to clutter, can be accurately estimated. XWAVE_C was implemented into the Sea Sate Processor (SSP) for fully automatic processing for near-real-time (NRT) services (Fig.2) at DLR ground Station Network. The SSP includes XWAVE_C, a pre-filtering procedure for removing image contaminations 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 method works for all SAR images and subscenes in full automatic mode.

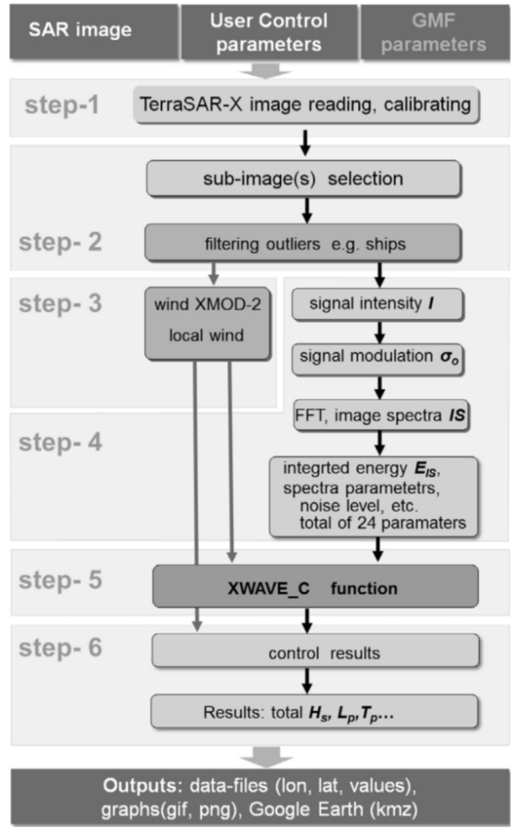

Fig.2. Flow chart of Sea State Processor (SST) designed for NRT services [6].

The basic equation for wave height estimation in the XWAVE_C function is [6]:

$$H_s^{XWAVE\_C} = a_1\sqrt{B_1 E_{IS}\tan(\theta)} + a_2 B_2 + a_2 B_3 + a_4 B_4 + a_5 B_5 \quad (1)$$

where E_{IS} is the integrated spectral energy, θ is local incidence angle, a_1–a_5 are coefficients (constants), and B_1–B_5 are functions of spectral parameters. More information can be found in [6].

Sea state is strongly dependent on local wind input which the TS-X is capable of providing by analysing the same subscene used for wave height estimations by measuring the roughness of the sea surface [9]. The nonlinear algorithm XMOD-2 that takes into account the full nonlinear physical model function was used to estimate local wind speed of the subscene.

The comparison of 89 collocated data pairs has shown the original XWAVE_C algorithm applied in Baltic Sea reproduces measured wave height. The improvements however could be applied for sea state system combinations special for the Baltic Sea, which has not been observed by TS-X acquisitions before.

It was found out, parameter a_5B_5, specially developed for German Bight, which is the correction for long structures on SAR-image, e.g. dry sandbanks etc., is also meaningful in the estuary Baltic Sea. Applying this correction, the correlation between measured wave height and XWAVE_C wave height was r = 0.87, Root Mean Square Error (RMSE) = 0.29m, and Mean Error (ME) = 0.04m for total significant wave height, although the distance D_S (S = subscene) between measurements and analyzed subscene for some comparisons was slightly more than 10km (to increase the number of collocations, the TS-X scenes acquired not directly over buoys were also used).

The local measurements, especially in the coastal area, where numerous islands (e.g. thousands in Gulf of Finland) themselves and disordered complex short sea state produced by them, cause the SAR-image distortions that in turn cause underestimation of wave height.

The improvement has been developed using local wind information from the same subscene analysed. By comparison with *in-situ* collocated data set, a reason for underestimations was found to be connected to the insufficiency in the sea state signal in the coastal areas with wind shadowing. A minimal wave height calculated based on JONSWAP spectrum using wind speed results from XMOD-2 algorithm that was correctly estimated from the same subscene. This theoretical wave height for short wind sea was then used for below 1m wave height range.

The second correction is related to the distance between the measurement buoy location and the selected SAR sub-scene used for comparisons. A factor F_D (D = distance) was estimated based on the distance D_S and applied to XWAVE_C result to gain the resulting wave height:

$$H_s = F_D H_s^{XWAVE\_C} \quad (2)$$

Using of this correction is limited by physics and is practically applicable up to 10km.

Fig.3 shows the comparison between *in situ* buoy measurements and estimated wave height from TS-X sensor using the XWAVE_C method with all correction procedures discussed above are shown. The reached Pearson correlation coefficient was r = 0.89, with the RMSE = 27 cm. This is a significant improvement of the accuracy for sea state estimated using original XWAVE_C. The advances are mostly visible in low sea state conditions in coastal areas.

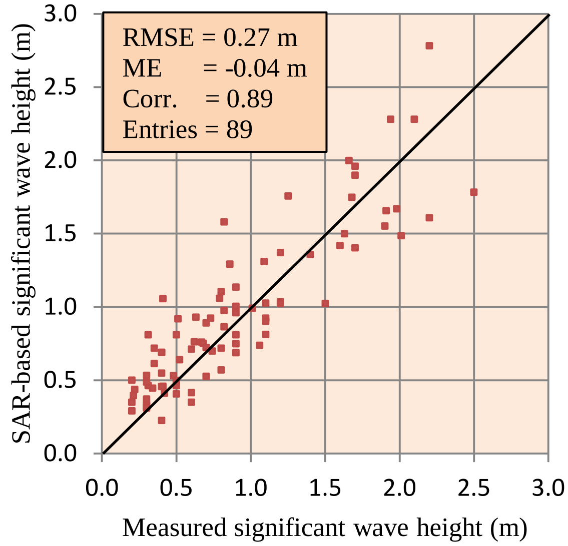

Fig.3. The comparison of the total significant wave height from all data acquired over the study area in 2012–2016 including various weather conditions.

The comparison between XMOD-2 wind speed and measured wind speed show high correlation as well with r of 0.76, RMSE of $3.38 m \cdot s^{-1}$, and ME $0.78 m \cdot s^{-1}$ (Fig.4).

The wind measurements stations are usually not within the SAR image coverage, except Tallinna Madal station (Fig.1); thus the statistics for wind comparison has lower correlation due to longer distance D_S (up to 20km). Furthermore, since most of the measurement stations are at coast or already inland where wind speeds differ from open sea, the slightly deteriorated results can be explained.

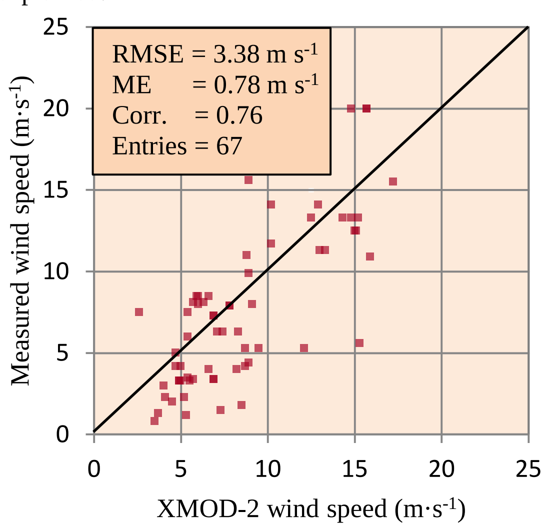

Fig.4. The comparison between SAR-based wind speed and measured wind speed.

4. SUMMARY AND OUTLOOK

XWAVE_C algorithm was successfully validated using the Baltic Sea dataset with high statistical results. Significant wave height estimated from SAR imagery correlated with measured values with correlation coefficient of *r* of 0.89. Wind speed comparison showed slightly deteriorated, yet still significant correlation coefficient *r* of 0.76.

Two new correction parameters were introduced that help to estimate wave height even more accurately. Firstly, a minimum wave height estimated from JONSWAP spectra based on local wind speed was introduced. The correction helps to improve significant wave height estimation from SAR imagery in the range of 0–1m and is affecting mostly coastal areas with wind shadowing effects. The second correction takes into account the distance between measurement station and SAR sub-scene from which the wind and wave parameters are calculated.

The further steps of this work are to acquire new images in coastal areas with different weather situations to assure the workability of the new suggestions and eventually implement the corrections to NRT process.

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