Sea State from High Resolution Satellite-borne Synthetic Aperture Radar Imagery

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SUMMARY

The Sea Sate Processor (SSP) was developed for fully automatic processing of high resolution Synthetic Aperture Radar (SAR) data from TerraSAR-X (TS-X) satellites and implemented into the processing chain for Near Real Time (NRT) services in the DLR Ground Station "Neustrelitz". The NRT chain was organised and tested to provide the processed data to the German Weather Service (DWD) in order to validate the new coastal forecast model CWAM (Coastal WAve Model) in the German Bight of the North Sea with 900m horizontal resolution. The NRT test-runs, wherein the processed TS-X data were transferred to DWD and then incorporated into forecast products reach the best performance about 10min for delivery of processed TS-X data to DWD server after scene acquisition.

To do this, a new empirical algorithm XWAVE_C (C=coastal) for estimation of significant wave height from X-band satellite-borne SAR data has been designed for coastal applications. The algorithm is based on the spectral analysis of subscenes and the empirical model function yields an estimation of integrated sea state parameters directly from SAR image spectra without transformation into wave spectra. To provide the raster coverage analysis, the SSP intends three steps of recognizing and removing the influence of non-sea-state-produced signals in the Wadden Sea areas such as ships, buoys, dry sandbars as well as nonlinear SAR image distortions produced by e.g. short and breaking waves.

For the validation, more than 150 TS-X StripMap scene sequences with a coverage of ~30km×300km across the German Bight since 2013 were analysed and compared with *in-situ* Buoy measurements from 6 different locations. On this basis, the SSP autonomous processing of TS-X Stripmap images has been confirmed to have a high accuracy with an error RMSE=25cm for the total significant wave height.

1. INTRODUCTION

The estimation of marine and meteorological parameters is an important task for operational oceanographic services. In comparison to *in-situ* buoy measurements at a location, remote sensing allows to cover large areas and to estimate the spatial distribution of investigated parameters. The spatial validation of forecast data, e.g. sea state and surface wind, by remote sensing can significantly improve the forecast quality and help explain natural phenomena beyond ordinary circumstances such as storm front propagation, local wind gusts and occurrence of wave groups with extreme wave height (Pleskachevsky et at., 2012).

Dependent on resolution and coverage, the remote sensing data are applied in three ways:

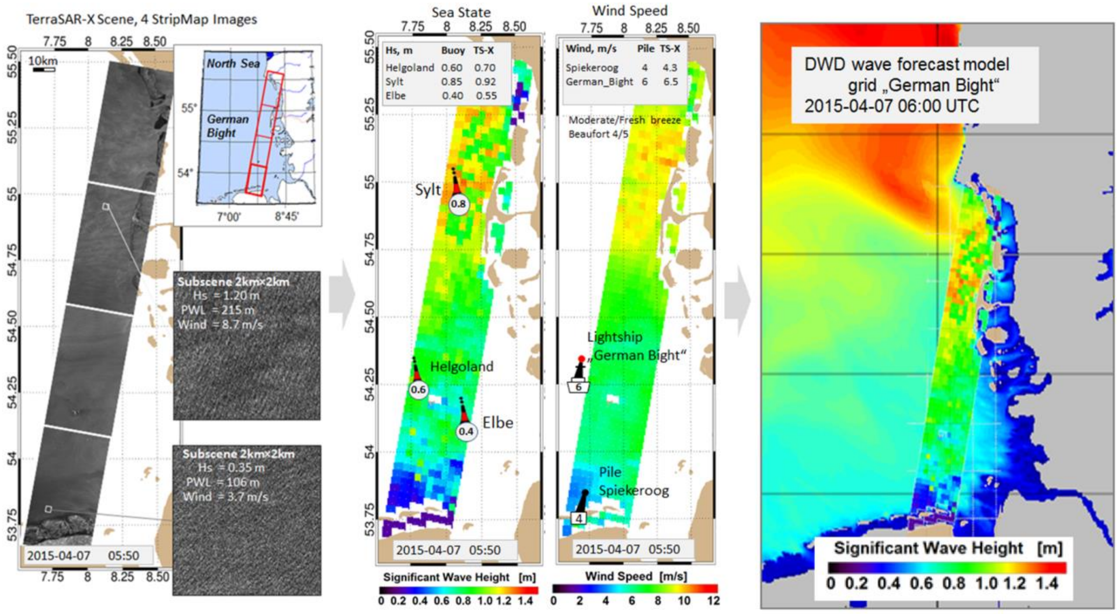
(1) Comparison with already simulated processes (hindcast) to study different weather conditions (e.g. storms) in order to improve the model physics and parametrization.

(2) Forecast validation: the remote sensing data are processed in Near Real Time (NRT), immediately transferred to weather services to be displayed together with the actual forecast (e.g. sea state) for a comparison.

(3) Assimilation of the data in the model runs: e.g. wave forecast model input is modified using the remote sensing data.

The intensive traffic for construction and maintenance at offshore facility sites such as wind farms in the German Bight requires an improvement in forecast accuracy. A wave height H_S of less than 1.3m is required for ships to be able to dock at offshore construction sites. In case H_S exceeds 1.3m, disembarking can be too hazardous and the transport ship has to return to the harbour. Such operations are planned in advance and inaccurate predictions cause high additional costs. For this reason, users (e.g. shipping companies) request an improvement of sea state prediction in the significant wave height H_S in range of 0.5m-2m.

In order to improve the forecast in coastal areas of the German coast, the 900m high resolution Coastal Wave Model (CWAM) for the German Bight and the western Baltic Sea has been developed by DWD and BSH (German Maritime and Hydrographic Agency) (Kieser et al., 2013).



Subscene 2km×2km
Hs = 1.20 m
PWL = 215 m
Wind = 8.7 m/s

Subscene 2km×2km
Hs = 0.35 m
PWL = 106 m
Wind = 3.7 m/s

Hs, m	Buoy	TS-X
Helgoland	0.60	0.70
Sylt	0.85	0.92
Elbe	0.40	0.55

Wind, m/s	Pile	TS-X
Spiekeroog	4	4.3
German_Bight	6	6.5

Figure 1: An example of TerraSAR-X scene processing and implementation for forecast validations: Meteo-marine parameters (Total Significant Wave Height H_S and surface wind speed U_{10}) processed with 3km×3km posting using Sea State Processor from TS-X StripMap scene acquired over the German Bight of the North Sea on 07.04.2015. Local wind speed is estimated using the XMOD-2 algorithm for the same subscenes analysed. The collocated measurements represent the H_S in meter for wave rider buoys and the wind speed U_{10} in m·s^{-1} for lightships and piles are also shown. The local variabilities in wave field are observed by overlaid of TS-X derived H_S over CWAM (Coastal Wave Model) model results of DWD.

CWAM is based on the Wave Model (WAM) and complements the series of wave models consisting of the Global Wave Model (GWAM) and the European Wave Model (EWAM) which are operated by the DWD. The wave CWAM model was coupled to the circulation model of the BSH which uses the same bathymetry grid. The purpose of this modification was to improve the forecast quality especially near the coasts, where the bathymetry varies greatly in space.

The objective of this paper is to develop an algorithm and processor to estimate meteo-marine parameters from satellite-borne SAR data allowing for strict distinction of waves in H_S domain of 0m-2m with decimetre accuracy for highly variable coastal environments. The processed data are transferred to DWD and incorporated for CWAM model validation. The development includes three tasks:

(1) Designing an empirical algorithm-function XWAVE_C (C=coastal) using the approach of a direct estimation of integrated sea state parameters from SAR image spectra without transformation into wave spectra. This approach was chosen because of the need for robust rapid data processing which does not involve the time for sophisticated and long mathematical iterations for the transformation and must work for all cases (swell, short wind sea, their combinations). As the model-function estimates the wave height correctly when the analysed scene includes the “pure” sea state, a series of filtering procedures should be included to consider artefacts such as ships, seamarks, currents fronts, etc.: before analysis, function terms and post-processing check of results.

(2) Integrating the XWAVE_C model function, wind estimation algorithms, filtering and checking procedures into a Sea State Processor (SSP) for automatic raster processing software. The SSP was installed in the NRT processing chain at the satellite ground station “Neustrelitz”. It includes also a parameter-based user interface and sequentially performs stable raster analysis of multiple TS-X images.

(3) Organization and testing the NRT chain “from acquisition to validation”, wherein the TS-X data were automatic processed, transferred to DWD and then incorporated into forecast products. Ordering, collecting and processing the data; analysis of results, verifications.

2. DATA SOURCES

For sea state processing the X-band data from TS-X and its twin TD-X were used. TS-X (launched in 2007) TD-X (launched in 2009) operate from 514km height at a sun-synchronous orbit with a ground speed of $7\text{km}\cdot\text{s}^{-1}$ (15orbits per day). They operate with a wavelength of 31mm and a frequency of 9.6GHz. The repeat-cycle is 11 days, but the same region can be imaged by different incidence angles after three days, dependent on scene latitude. The TS-X data used for this study are Multi-Look Ground Range Detected (MGD) standard products with pixel spacing of 1.25m for StripMap mode (resolution of 3m). The collected and analyzed data consist of more than 150 scenes acquired over German Bight. Fig.2. presents concept for the TS-X data ordering in German Bight in domain of DWD CWAM wave forecast model domain and collocated with 6 available measurement stations.

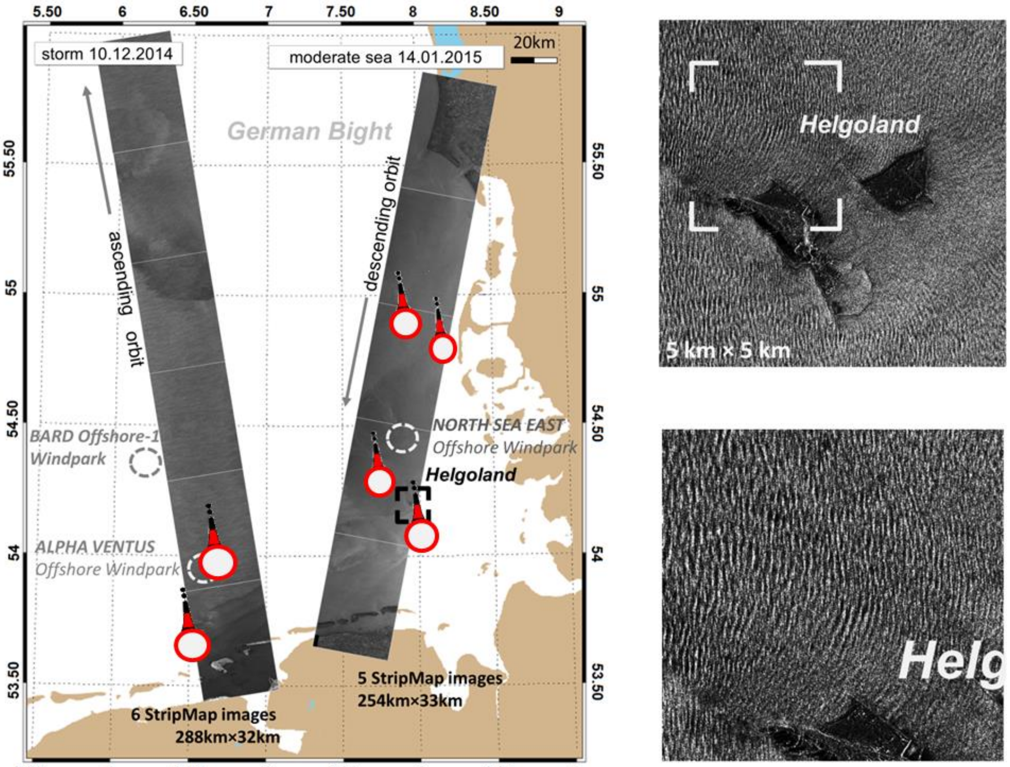


Figure 2: The concept for TerraSAR-X scene ordering in the German Bight with two examples: typical ascending (~17:00 UTC) and descending (~06:00 UTC) overflights collocated with 6 available buoys; each scene consists of 3-6 StripMap images.

3. SEA STATE ESTIMATION FROM TERRASAR-X IMAGES

It is known from statistics that the wave height in range of 0-2m in the German Bight is presented mostly by local short windsea with wavelengths <100m. These waves are often well spread in frequency and direction and do not represent ordered long wave crests like swell. In StripMap TS-X SAR images such waves are either invisible (wavelength L<~50m), producing image noise, or barely visible (~50<L<~100), producing non-linear distortions in form of defocusing streaks. The contribution of such “unstructured” waves for total significant wave height is in the order of 0-1.5m and is usually neglected for global ocean applications where mainly long waves are investigated. For coastal application, especially these short-crest waves and their contribution and their SAR imaging are investigated and considered in the model function in order to achieve the required accuracy.

For deep water, an empirical XWAVE model function for obtaining integrated wave parameters has already been developed for X-band data (Bruck, 2015). XWAVE was based on the analysis of image spectra and uses parameters fitted with collocated buoy data and information on spectral peak direction and incidence angle. The main parameter is the integrated value of the directional wave number Image Spectrum (*IS*) E_{IS}.

$$E_{IS} = \int_{k_x^{\min}}^{k_x^{\max}} \int_{k_y^{\min}}^{k_y^{\max}} IS(k_x, k_y)\, dk_y\, dk_x \qquad \textbf{(1)}$$

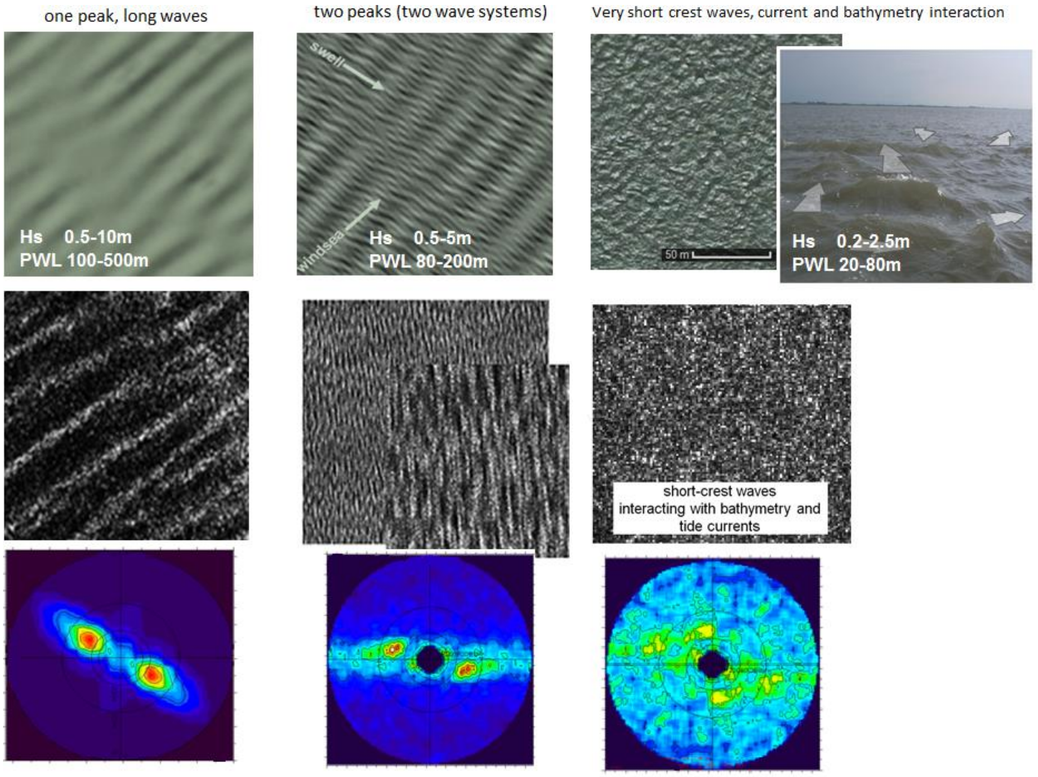


Figure 3: Example for imaging the different sea states by TerraSAR-X (first row - random surface simulation from wave spectra and a cut form Google Earth image over German Bight). Well imaged long waves (low wind), the shape of image spectra approaching the form of wave spectra (left). Windsea covers the long waves by amount of short-crest waves: defocusing structures from short and fast moving targets covers swell (middle). Typical short sea state in coastal area of German Bight (right): Very short wave crests present a large number of small, nonstable, fast and chaotically moving targets. Such a sea state in range of 0-1.5m H_S is typically imaged as a noise with a hardly recognized wave pattern. However, the noise properties are connected to wave crests amplitudes and speed.

where $IS(k_x,k_y)$ is the Image Power Spectrum in wavenumber domain (y=satellite flight direction, x=to-satellite direction) with $k^{MAX}=\pi/(\text{subscene\_size})$. $IS(k_x,k_y)$ is obtained by using FFT on a subscene of the radiometrically calibrated TS-X/TD-X intensity image. The integration domain is limited by the maximal wavelength L_{max}=600m corresponds to k_{min}=0.01 in order to avoid the effects of wind streaks signal produced by turbulent boundary layers (1) and by minimal wavelength L_{min}=30m correspond to k_{max}=0.2 to avoid SAR image distortions from short sea surface waves and wave breaking streaks entering the domain 0-30m (2).

The XWAVE algorithm was tuned using data acquired over NOAA buoys in open oceans worldwide and in the northern part of the North Sea where measurements near oil platforms (e.g. EKOFISK) are available. XWAVE is capable to estimate integrated wave parameters with Scatter Index $SI_{Hs}^{XWAVE/BUOY}$=21% for waves in the range about 2m-15m wave height with a mean value of 3.6m (averaging over times of acquisitions) and $SI_{L}^{XWAVE/BUOY}$=13% for wavelengths in the range 80m-600m with a mean value of 240m (Bruck 2015). These results are more than satisfactory for open seas and for a global analysis. However, applied for short and steep sea state in the German Bight, the algorithm results in strong overestimation of wave height by a series of signals unknown to the algorithm for moderate conditions with H_S in the range of 0.2-3m in coastal shallow waters (Wadden Sea).

The original XWAVE approach has been extensively validated and adopted for coastal sea state. The connections of errors with spectral parameters have been established and explained. The parameters which turned out to be the most important are: U_{10} - local wind speed using XMOD-2 (Li and Lehner 2013) algorithms; the ratio $R^{in/out} = N_S^{in}/N_S^{out}$ that indicates the character of non-linearity of the imaging mechanism and the ratio $R_E^{30/E400} = E^{30}/E^{400}$ indicates the relation of energy from real long waves (80m-400m) to noise energy produced by streak-structures (30m-80m) in case of appearing non-linear effects (the local wind speed U_{10} helps to separate them from local short windsea). An explanation for $R^{in/out}$ is illustrated in Fig.4 where an example for three similar sea states traveling in different directions (peak wavelength PWL ~70m-100m) is shown.

E^{30} integrated energy of a spectrum annulus corresponds to wavelength 30m-80m.
E^{400} integrated energy of a spectrum annulus corresponds to wavelength 80m-400m.
N_S^{in} spectrum noise in domain inside of so-called azimuthal *cut-off* wave number.
N_S^{out} spectrum noise in domain outside of so-called azimuthal *cut-off* wave number.

The retuned and extended XWAVE_C function for coastal application is presented by the equation:

$$Hs^{XWAVE\_C} = a_1\sqrt{B_1 E_{IS} \tan(\theta)} + a_2 B_2 + a_3 B_3 + a_4 B_4 + a_5 B_5 \qquad \textbf{(2)}$$

where a_1-a_5 are coefficients (constants) and B_1-B_5 are functions of spectral parameters. The first two terms represent positive contributions in wave height (spectral energy due to long waves and wind offset due to short wind waves not visible by SAR) and the last three are negative deductions for the elimination of different kinds of outliers. B_1 represents noise scaling of the total energy E_{IS} (short wind waves and their breakings produce an additional noise that influences resulting energy, $B_1 = x_0 R^{in/out}$ with x_0 tuned using collocated buoy data). The second term a_2B_2 represents wind impact with $B_2 = U_{10}$. However, a_2 is found to be not a unique constant; for strong wind $U_{10} > 19\text{m}\cdot\text{s}^{-1}$ a_2 is modified to express the transition of wave regime into strong breaking and flying water particle targets (Beaufort 9). The terms a_3B_3 and a_4B_4 are corrections for eliminating the impact of short (e.g. wave breaking induced) and long wavelength (e.g. wind streaks) structures in the SAR image, respectively. These structures result in spectral peaks and diffused spectra energy not directly connected to the sea state: $B_3 = R^{E30/E400}$ and $B_4 = E^{600}$. The last term a_5B_5 with $B_5 = E_K$ is a correction for outliers produced by extra-large structures like sandbanks or ship wakes which have not been pre-filtered.

The TS-X scenes were processed with 3km×3km posting (~10×15=~150 subscenes per image). The collocations were considered within a time window of +/- 10min for comparison with model data and +/-20min for buoys (slightly varying recording period). The local comparison of the TS-X estimated wave height with *in-situ* buoy measurements was conducted for 6 stations in the German Bight (Fig.6). The scatter index $SI^{TSX/BUOY} = 20\%$ was obtained for all collected data (for tuning data until 12.2014 and as well for residual data verification).

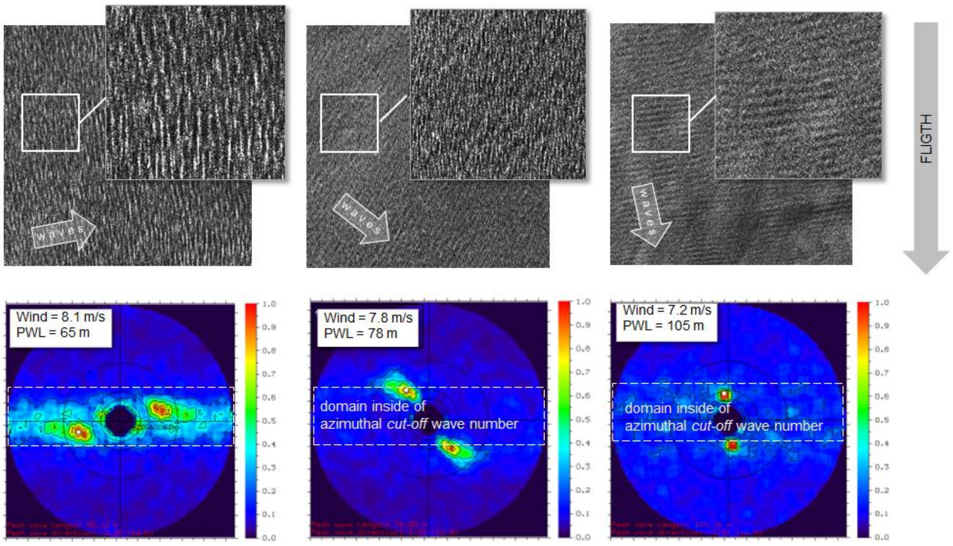
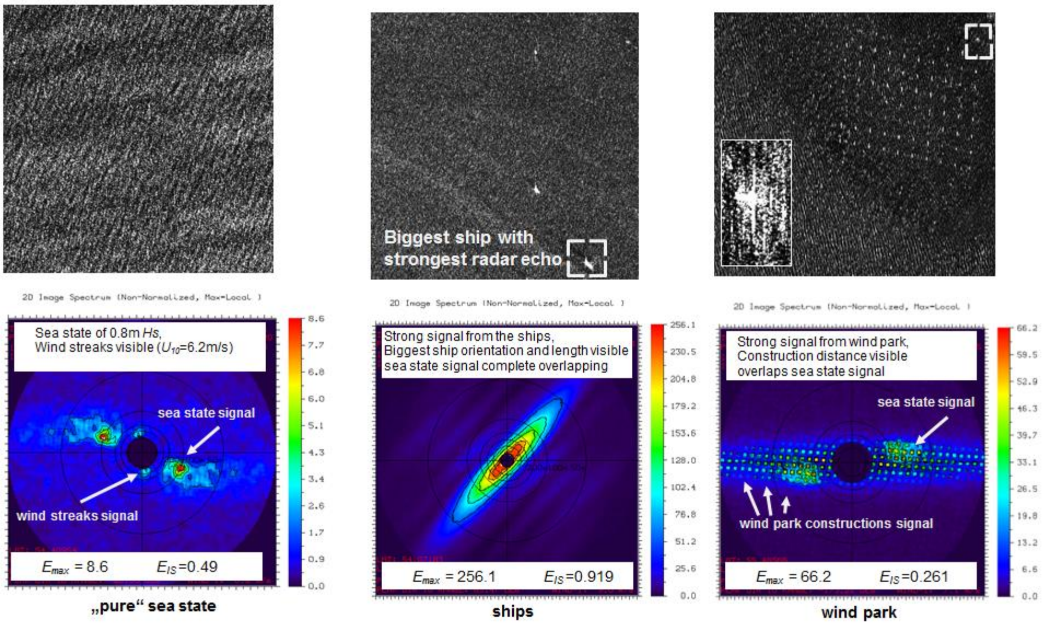


Figure 4: Example for imaging for similar sea state traveling in different directions (peak wavelength PWL ~70m-100m) by TerraSAR-X StripMap: azimuth traveling (right), range traveling (left) and intermediate situation. The wind speed is ~7-8m·s-1for all subscenes. For ~range traveling waves, the distortions dominate (ratio $R^{in/out}$ ~4), for ~45° traveling waves the non-linear distortions are visible (ratio $R^{in/out}$ ~2), the near-azimuth traveling waves are minimally distorted by non-linear effects (ratio $R^{in/out}$ ~1) and the shape of image spectra approaches shape of wave spectra.



„pure“ sea state ships wind park

Figure 5: Artefacts for sea state estimation in TerraSAR-X subscenes (top) and corresponding image spectra (bottom): ships (left) and wind park (middle). The “pure” sea state suitable for conventional estimations is shown for comparison (left). The treatment are applied in three stages: removing outliers before FFT analysis, a function term based on determined spectral *k*-bin, and a control of results based on statistics of the whole scene processed.

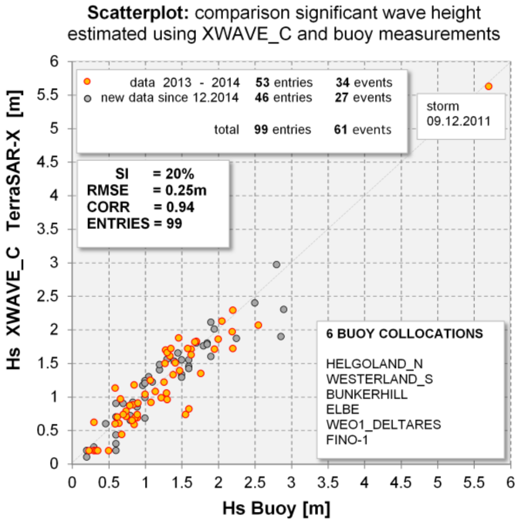


Figure 6: Total comparison of all available data acquired over the German Bight in 2013-2015 including a storm on 09.12.2011: 61 TerraSAR-X Scenes (overflights/events/days) with 201 StripMap images and 99 buoy collocations (collocation around 30min and up to 5km spatially).

4. SEA STATE PROCESSOR FOR PRACTICAL USE

All operations are integrated into the Sea State Processor (SSP) developed for both HH and VV polarisation. The SSP is developed in C++ code and performs the following steps (Fig.7):

- Step-1: reading and calibrating the SAR image, reading User Control parameters and GMF parameters,
- Step-2: selection of a subscene and pre-filtering (removing image intensity artefacts like ships, buoys etc. based on local intensity statistics),
- Step-3: calculation of XMOD-2 wind,
- Step-4: spectral analysis of the subscene (FFT, integration and spectral parameters),
- Step-5: wave height estimation using XWAVE_C GMF (SSP core),
- Step-6: control of results using wind speed and integrated spectral parameters (e.g. long structures like sand banks produce high spectral values in domain $k<0.01$ and can be separated) and generating outputs.

The SSP was installed at the Ground Station “Neustrelitz” (Pleskachevsky et al., 2015, Schwarz et al., 2015) to provide an operational service and has been tested. The delivery of NRT products from “Neustrelitz” to the user (e.g. DWD) occurs by E-mail and by FTP transfer. For the common users, a file with the data (lon, lat, H_S), the Google Earth file (.kmz) to preview the image file (.jpg) with color-coded wave heights are provided. For example, a TS-X StripMap acquired over the German Bight on 15.07.2015 at 05:51 UTC was NRT processed in the ground station “Neustrelitz” using the installed SSP. At 07:04 UTC, the results (file includes geo-coordinates with H_S values) had been transferred to DWD and automatically overlaid on their CWAM forecast wave height map of 06:00 UTC. This validation shows the local variation and differences in sea state in comparison to predictions, e.g. a long Scharhörnplate-sandbar near Scharhörn-island was partially dry (no waves) while in the model prediction the bar was wet with H_S~0.5m.

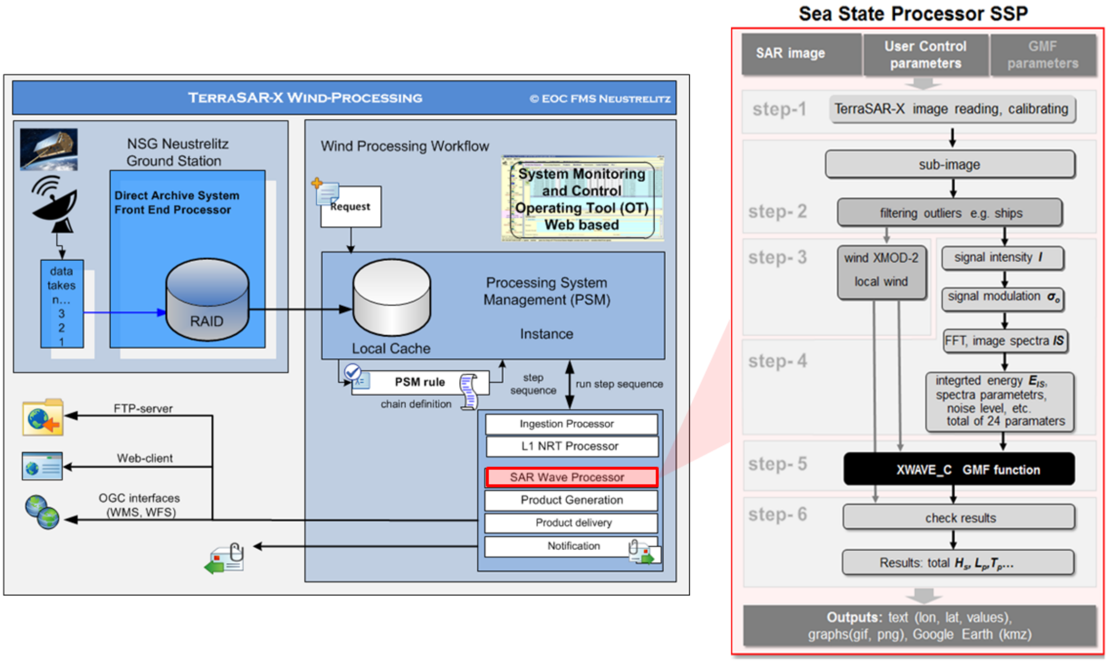


Figure 7: NRT-processing chain for TerraSAR-X data in DLR ground station Neustrelitz. The Sea State Processor was integrated into the chain (marked in red).

5. SUMMARY

The XWAVE_C algorithm to derive meteo-marine parameters from X-band SAR data was developed for coastal applications particularly by taking into account the short wave sea state with a non-conventional imaging mechanism. It was found that the parameters of short wave sea states with a hardly visible imaged wave pattern can be estimated based on a combination of local wind information and the properties of image spectrum noise. An NRT version of the Sea State Processor was made operational (Pleskachevsky et al., 2016, Schwarz et al., 2015) and processed data were provided in a test mode for the validation of forecast Wave Model CWAM of the German Weather Service in the German Bight in order to support and improve the predictions in coastal areas and at offshore constructions. The SSP processor is now extended for SENTINEL S-1 C-band data and has been tuned for the worldwide application to estimate sea state from VV S-1 IW-mode images.

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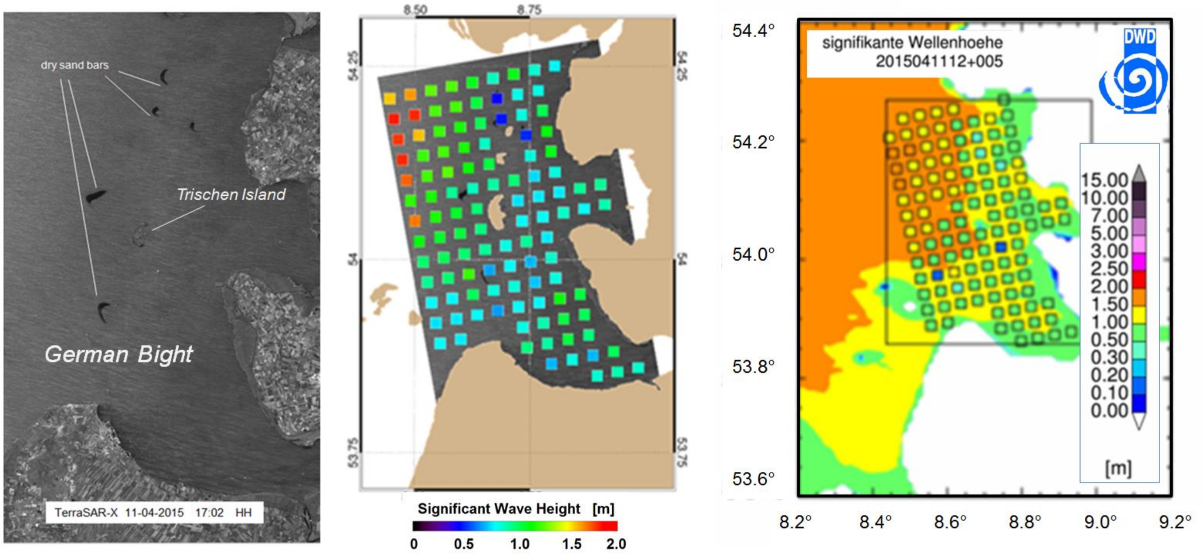

Figure 8: Validation Example. TerraSAR-X StripMap image acquired on11.04.2015 at 17:02 UTC (left) processed (top right) and plot by DWD with overlaying with CWAM model results (bottom right). Interesting to note that the sand bars apparently dry by TerraSAR-X are wet in the model with sea state H_S ~1-1.5m. In TerraSAR-X the waves are damped around the bars with H_S ~ 0.3-0.8m.

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