Sea State from Sentinel-1 SAR Wave Mode Imagery for Maritime Situation Awareness

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Abstract

An empirical algorithm was developed for estimation of wide spectrum of integrated sea state parameters from Sentinel-1 Wave Mode imagery including total significant wave height H_s, swell wave height, height of windsea, first moment wave period T_{m1}, second moment wave period T_{m2}, and mean wave period T_m. The algorithm was tuned and cross-validated using two different global wave models and buoy measurements. The accuracy of the estimated H_s reached against the models $RMSE_{swh}$=0.35 m and against NDBC buoys $RMSE_{buoy}$=0.44 m. The period's accuracies evaluated by the models are $RMSE_{Tm1}$=0.52 s, $RMSE_{Tm2}$=0.48 s, $RMSE_{Tmean}$=0.63 s and the accuracy of partial integrated parameters are $RMSE_{swh-swell}$=0.42 m, $RMSE_{swh-windsea}$=0.42 m, $RMSE_{Twindsea}$=0.63 s.

Introduction

The rapid development of satellite techniques, SAR sensors, SAR processors, algorithms, ground infrastructures and significant improvement of transfer and processing of large amount of data made possible a series of oceanographic applications in NRT in recent years [1,2,3]. Several minutes after the image acquisition, the derived products can be transferred to weather services to validate forecasting model results or directly to ship bridges in order to optimize the ship routing [2]. The different products such as significant wave height, surface wind speed, ice coverage, oil spills, etc., can be processed in parallel for the same satellite image or from different satellites and combined for supporting Maritime Situational Awareness (MSA). Under MSA one understands a system for the fusion of various data in order to improve maritime safety and security. This includes different kinds of information on the maritime environment based on remote sensing, *in-situ* measurements, forecast modelling and communication. The oceanographic parameters were also implemented for SAR processing of man-made connected features. E.g. a ship detectability model connects the probability of detection in dependency to wind speed and significant wave height [4,5].
An essential data source for MSA are high resolution weather and sea state information. This paper introduces an algorithm for meteo-marine parameter estimation from Sentinel-1 (S1) Wave Mode imagery (WV), called CWAVE_EX (EX for extended). The algorithm will become a new part of DLR's Sea State Processor (SSP) developed for Near-Real-Time (NRT) processing of TerraSAR-X and S1 Wide Swath Mode (IW) imagery.

Data and Method

CWAVE_EX was trained for calibrated S1 WV SLC products for an adoption into the SSP framework. The idea was to reuse the widely known CWAVE approach [6] already applied for S1 WV [7]. On this way, the core of the method remains a linear regression model function. However, the request was to reach higher accuracy not only for H_s but also for wave periods. Also estimation of partial integrated parameters like swell and windsea wave heights was purposed.
In order to extend the possibilities of original CWAVE method based on using normalized image variance and products of image spectra with orthonormal functions, a series of feature extraction procedures and additional parameters were introduced.
In the classic way, the estimation is based on NRCS sub-scenes analysis and FFT image spectra in wave number space. However, to get more stable results, each vignette 20 km×20 km was processed several times in sub-images using a sliding window cover ~4.6 km×4.6 km (FFT-1024) to get averaged values for each estimated feature. Actually, five feature types were involved for training of the model function:

- type-1: NRCS and NRCS statistics (variance, skewness, kurtosis, etc.).
- type-2: geophysical parameters (wind speed using CMOD algorithms).
- type-3: Grey Level Co-occurrence Matrix (GLCM) parameters (entropy, correlation, homogeneity, contrast, dissimilarity, energy, etc.).
- type-4: Spectral parameters based on image spectrum integration of different

wavelength domains (0-30m, 30-100m, 100-400m, 400-2500m) and spectral width parameters (Longuet-Higgins, Goda-parameter).

type-5: Spectral parameters of ISP defined in [4] using orthonormal functions and cut-off wavelength estimated using autocorrelation function (ACF).

The model function was tuned and validated using two independent data sources for ground truth: CMEMS model results with spatial resolution of 1/12 deg. [8] and WW3 model of NOAA with resolution of ½ degree (spatially interpolated). Both model's outputs are provided in a 3h-interval and were therefore also temporally interpolated. The stationary NOAA buoys [9] (typical hourly measurements) were used for validation and also temporally interpolated. The buoy measurements were no taken for validation in case the measurement time gap exceeded a 3h threshold. The estimated scattering between CMEMS and WW3 reach an RMSE=0.23 m. The scattering between collocated CMEMS and buoy measurements correspond to RMSE=0.28 m.

42 S1 WV relative orbits collocated with 41 NOAA buoys were found, for a defined maximum collocation distance under 50 km. (25 relative orbits by Alaska and Hawaii, 17 relative orbits in Atlantic). Each orbit includes 30-170 vignettes and is acquired around four times per month. These collocated orbits for 2017 and 2018 build the main part of the data pool. ~500 passes over worldwide storms were additionally selected. Totally, around a quarter million model collocations were analysed.

For the estimations, filtering of the S1 data was carried out:

- -60° <latitude<60° to avoid ice coverage.
- normalized variance $1.0<nv<2.0$ for wv1 and $1.0<nv<1.4$ for wv2 [7]).
- at least one model grid point must disconnect the S1 vignette location from land (zero value in model results).

Totally ~ 8% of the S1 WV vignettes get lost due to these conditions.

The potential distribution of the mentioned buoy collocation distance is as follows:

- 2 collocated orbit <2 km
- 15 collocated orbit <2 0km
- 73 collocated orbit <50 km

For an ideal case, when each orbit is acquired ~2-3 times per month, ~2000 collocations are possible every year. However, in reality only ~2250 measurements have been pooled for buoy validation over the two years 2017 and 2018. There are three sources of loss of collocations:

1. time gap between measurements above 3h (or a buoy has failed for months). Some buoys were taken out of service (e.g. NDBC-43010 since 2018).
2. collocations lost due to normalized variance *nv* filtering.
3. S1 orbits were not completely acquired. This concerns mostly the long ascending orbits with more than 140 vignettes starting in Antarctic and collocating with buoys at the Aleutian Islands (e.g. ascending orbit No.151 with 128 vignettes, collocated with NDBC-43010 (wv2 vignette No. 94 with ~7 km distance) and with NDBC-46036 (wv2 vignette 120 with ~40 km distance)).

Results

For the processing, monthly S1 WV data sets with ~ 6000/6000 model collocations for wv1/wv2 were created from the orbits described above. The model function was tuned multiple times using first one processed month (~6.000 collocations), later two month (~12.000 collocations) and further always adding of each next processed month. On this way, the stability of the function was studied by considering of influence of new data on resulting RMSE. After including ~30.000/30.000 (wv1/wv2, corresponding to ~6 months) collocated data pairs the resulting RMSE was stable in order of mm, and adding the random month-collocation data did no more change the results. The validation was carried out using the rest of the data with ~ 70.000/70.000 collocations (corresponds to ~1.5 year).

For the H_s a cross validation was carried out. After the model function was tuned independently using CMEMS and WW3 data, the coefficients were swapped. The CMEMS tuned coefficients were validated with WW3, and vice versa WW3 tuned coefficients were tuned with CMEMS. Additionally, a mix data set was created and used for tuning and validation using both CMEMS and WW3 collocations. All three versions were validated against the buoys. **Table 1** presents the results of the cross validation. As can be seen, the optimal RMSE ~ 43cm by buoy comparison results using only CMEMS model what might be a consequence of the better spatial model resolution in comparison to WW3.

Table 1 Cross validation of total significant wave height H_s using different data sources. RMSE in meter is given for wv1/wv2

Tuning data	Validation data		
	CMEMS	WW3	BUOYS
CMEMS	0.33/0.38	0.35/0.40	0.42/ 0.44
WW3	0.34/0.39	0.34 / 0.39	0.44/ 0.46
CMEMS&WW3	0.34/ 0.39		0.43/ 0.45

The model function is designed uniformly and allows estimation of series of integrated sea state parameters from input features, while only the respective function coefficients have to be exchanged for different SAR sensors and acquisition modes. **Table 2** presents the actual state of the training with two groups of estimated parameters: total and partially integrated.

Table 2 Accuracy of sea state integrated parameter estimated from Sentinel Wave Mode imagery.

Parameter		RMSE wv1/wv2	Integ-ration
symbol	**Description**		
H_s	significant wave height	0.34/0.38 m	total
Tm_1	first moment wave period	0.51/0.56 s	total
Tm_2	sec. moment wave period	0.46/0.51 s	total
Tm	Mean wave period	0.46/0.51 s	total
H_s^{swell}	sig. wave height swell	0.40/0.45 m	partial
H_s^{wind}	sig. wave height windsea	0.40/0.46 m	partial
T^{wind}	Mean period wind sea	0.62/0.67 s	partial

Summary and outlook

For all data the mean RMSE (averaged wv1 and wv2 cases) for H_s is ~0.35 m. The averaged scatter index for Hs is SI=~14% (mean value ~2.52 m), bias~-0.001 m. However, for different sea state domains the accuracy is not constant:

H_s<2.5 m RMSE~0.28 m,
2.5 m<H_s<5.5 m RMSE~0.41 m,
5.5 m<H_s RMSE~0.92 m.

The complication for the proof function training is the natural distribution of wave height acquired (see **Figure 1**). For example, only in ~5% of cases H_s is higher than 5.0 m and high storm conditions with H_s>8.0 m only occur in ~1% of all cases. Thus, the method under continuous improvement. In fact, not all possibilities to reach higher accuracy, especially for higher sea state, were exhaust. For a stable model function, more than 30.000 data pairs are needed, after entering more data for 2019 (or more orbits for the past), it will be possible to divide the data in several domains for more fine tuning.

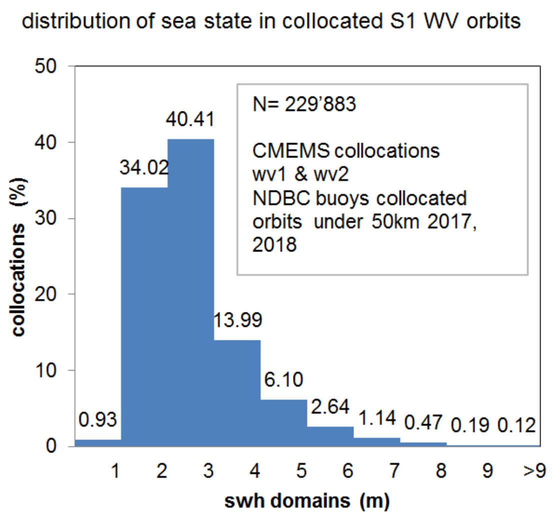

Figure 1 Distribution of significant wave height H_s in acquired S1 WV scenes.

The method was developed in order to be integrated into the NRT processing chain of DLR's ground stations. This means the method is not only optimized for fast and robust processing, but also has been designed in a modular architecture for smooth maintenance and updatability. The DLR Ground Station Neustrelitz applies SSP as part of a near real-time demonstrator service which involves daily provision of surface wind and sea state parameters estimating fully automatically from S1 IW images of North and Baltic Sea.

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