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Accurate estimation of significant wave height with Support Vector Regression algorithms and marine radar images

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A B S T R A C T

Significant wave height (H_s) is a basic parameter in wave characterization, important for different problems in marine activities such as the design and management of vessels, marine structures, and wave energy converters. H_s is usually estimated using in-situ sensors, mainly buoys, that record time series of wave elevation information. In this paper we propose a method for H_s estimation based on a Support Vector Regression algorithm over non-coherent X-band marine radar images. Results for three different platforms (Fino 1, Ekofisk and Glas Dowr) at different locations of the North Sea and South Africa are presented, showing that the SVR obtains a better result than the existing standard method in H_s prediction, within different sea states observed at each location.

1. Introduction

The availability and accuracy of wave data play a crucial role in the better understanding of numerical (The WAMDI group, 1988; Tolman, 2009) and statistical wave models (Casas-Prat et al., 2014; Durrant et al., 2013), wave forecasting for safe ship navigation, design and operation of wave energy converters (López et al., 2013), and the design of vessels and marine structures: oil platforms, breakwaters (Comola et al., 2014; Kim and Suh, 2014), wave overtopping volumes (Nørgaard et al., 2014), ports and harbors, etc. Thus, the topic has a clear impact on human safety, economics and clean energy production. One of the most important parameters to define the severity of a given ocean wave field is the significant wave height, H_s. H_s is usually estimated using in-situ sensors, such as buoys, recording time series of wave elevation information. Buoys provide reliable sea state information that characterizes wave field in a fixed position (i.e. the mooring point). In addition, as buoys are anchored in a hostile media (the ocean), the probability that measuring problems (and therefore missing data) that occur in situations of severe weather is very high (Rao and Mandal, 2005).

Complementary to the punctual information that buoys' measurements represent, an alternative way to estimate H_s (and therefore a useful tool to reconstruct missing data from ocean buoys) consists of using remote sensing imaging methods, such as air and space borne Synthetic Aperture Radar (SAR) images (Alpers and Hasselmann, 1982), on- and off-shore coherent radars (Nwogu and Lyzenga, 2005; Plant et al., 2008; Seemann et al., 2013) or conventional X-band marine radars (Hessner et al., 2001; Izquierdo et al., 2005; Reichert et al., 2005), which are broadly installed in every moving ship, and off- and on-shore platforms.

The analysis of the marine radar images of the sea surface is capable of estimating wave field and surface current information in real time for oceanographic monitoring purposes (Chen et al., 2012; Izquierdo et al., 2005; Nieto-Borge and Guedes-Soares, 2000; Reichert et al., 2005; Senet et al., 2001; Young et al., 1985). Radar images of the ocean surface are produced by the backscattering phenomenon of the electromagnetic waves due to the roughness of the sea surface (Alpers and Hasselmann, 1982; Plant et al., 2008). These radar images are then analyzed to obtain estimations of wave spectra in different spectral domains (Izquierdo et al., 2005; Reichert et al., 2005), which allow calculating typical sea state parameters, such as characteristic wave periods, wave lengths, and wave propagation directions (Hessner et al., 2001; Hessner et al., 2014). Estimating H_s from the wave spectrum derived from the X-band marine radar analysis is not straightforward, since the physics of the imaging mechanisms has complex dependencies on environmental conditions, including both wave conditions and other environmental factors such as wind. The wave spectral estimations derived from the radar images are not properly scaled in the sense that their integral cannot provide values of the standard deviation of the wave elevation field, and therefore, a direct estimation of H_s is not possible.

Some approaches to estimate H_s from marine radars take into account the geometrical shadowing effect of the lower waves by the higher waves to the radar antenna illumination (Buckley and Aler,

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1998; Buckley et al., 1994; Salcedo-Sanz et al., 2015). An alternative approach to estimate H_s from X-band marine radar considers that H_s depends linearly with the squared root of the signal-to-noise ratio *SNR*, where the signal is the spectral energy of the un-scaled wave spectrum, and the noise is related to the spectral energy of the speckle noise within the radar image (Nieto-Borge et al., 2008). This technique is an extension of the methodology initially proposed by (Alpers and Hasselmann, 1982) to derive H_s from synthetic aperture radar (SAR) images of the sea surface. The *SNR*-based method is more robust, from the operational point of view, than the shadowing-based method and it is widely used for the standard applications of wave monitoring activities using conventional X-band marine radars (Chen et al., 2012; Hessner et al., 2001). Thus, the *SNR*-based method is used as a standard technique for H_s estimation. Note that the *SNR*-based method needs a calibration campaign with an in-situ sensor, such as a buoy, to calibrate the marine radar. This calibration is not necessary in the method that analyzes the shadowing effect (Salcedo-Sanz et al., 2015). Although the *SNR*-based method to estimate H_s is used all over the world, there are some limitations where this technique does not provide reliable values for H_s, giving some indications that the H_s estimation depends on more parameters than only *SNR* (Vicen-Bueno et al., 2012).

In this paper an extension to the *SNR*-based method is proposed. This proposed extension uses Support Vector Regression (SVR) to estimate H_s. The method takes into account additional sea state parameters than only *SNR*. All those parameters are derived from the standard analysis of wave fields by using X-band marine radars. The work analyzes the relevant sea state parameters to estimate H_s and compare the obtained results with the results derived from the Standard Method (SM), based only on the estimation of *SNR*. For that purpose, a set of marine radar data in combination with H_s values measured by buoys have been used. The data were recorded in three different geographical locations under different oceanographic conditions: the German basin and the Norwegian sector, both in the North Sea, and the Sable Field in South Africa.

The rest of the paper is structured as follows: Section 2 deals with the basics of the wave field analysis by using X-band marine radar data sets, including the H_s estimation by the standard method (SM), and its limitations. Section 3 describes the geographical locations and the oceanographic conditions of the X-band radar and buoy data used in this work. The following Section 4 introduces the SVR algorithms used to improve the H_s estimation by SM. Section 5 shows the achieved results after applying the SVR algorithms to the used data. Finally, Section 6 summarizes the conclusions of the work.

2. Analysis of the sea surface from X-band radar

As mentioned before, the analysis of wave fields from X-band marine radars is based on the acquisition of consecutive radar images of the sea surface. Hence, the data sets are time series of radar images where the spatio-temporal (x,y,t) evolution of the sea surface can be analyzed. From these data sets, applying a three-dimensional Fourier decomposition the so-called image spectrum $\mathcal{I}(k,\omega)$ is obtained, where $\boldsymbol{k}=(k_x,k_y)$ is the wave number vector and ω is the angular frequency. In practice, $I(\boldsymbol{k},\omega)$ is estimated by using a three-dimensional FFT-based algorithm, therefore the $(\boldsymbol{k},\omega)$ values are defined in a discrete domain, where the sampling wave numbers $(\Delta k_x,\Delta k_y)$ depend on the spatial size of the radar images and their spatial resolutions given by the range and azimuthal resolutions of the radar system. The angular frequency resolution $\Delta\omega$ depends on the number of images in the radar image time series and its sampling time (i.e. the radar antenna rotation period). Hence, the spectral components are located within the spectra domain $\Omega_{\boldsymbol{k},\omega}$ defined as

$$\Omega_{\boldsymbol{k},\omega} \overset{\text{def}}{=} [-k_{x_c},k_{x_c}) \times [-k_{y_c},k_{y_c}) \times [0,\omega_c], \tag{1}$$

where k_{x_c}, k_{y_c}, and ω_c are the respective Nyquist limits in wave numbers and angular frequency given by the spatio-temporal resolution of the radar image time series. For the estimation of H_s, the relevant spectral components $(\boldsymbol{k},\omega)\in\Omega_{\boldsymbol{k},\omega}$ of the three-dimensional image spectrum $I(\boldsymbol{k},\omega)$ are classified in the following contributions (see the example illustrated in Fig. 1):

- Static patterns caused by the long range dependence of the radar backscatter intensity due to the radar equation (Skolnik, 2002). As this dependence is not on the time domain, the spectral components of this contribution of the image spectrum $\mathcal{I}(k,\omega)$ correspond to those wave numbers $\boldsymbol{k}$, where $\omega\approx 0$ (Young et al., 1985). To avoid the static pattern components, the spectral domain $\Omega_{\boldsymbol{k},\omega}$ defined in Expression (1) includes only those frequencies higher than a threshold value, $\omega\geq\omega_{th}$ (Nieto-Borge et al., 2004). For practical applications (Nieto-Borge et al., 2008), typical value of the threshold frequency is $f_{th}=0.04$ Hz (i.e. $\omega_{th}=2\pi f_{th}$).
- Wave components that hold the dispersion relation of linear gravity waves. These spectral $(\boldsymbol{k},\omega)$-components are located in the surface $\Lambda_{\omega(\boldsymbol{k})}\subset\Omega_{\boldsymbol{k},\omega}$ defined by the dispersion relation

$$\Lambda_{\omega\boldsymbol{k}} \overset{\text{def}}{=} \left\{(\boldsymbol{k},\omega)\in\Omega_{\boldsymbol{k},\omega} \mid \omega=\sqrt{\text{gk}\tanh(\text{kd})}+\boldsymbol{k}\cdot\boldsymbol{U}\right\}, \tag{2}$$

where $k=\|\boldsymbol{k}\|$, g is the acceleration of the gravity, d is the water depth and $\boldsymbol{U}=(U_x,U_y)$ is the so-called current of encounter (Senet et al., 2001) responsible of the Doppler shift in frequency given by the dot product $\boldsymbol{k}\cdot\boldsymbol{U}$. As in the case of the domain $\Omega_{\boldsymbol{k},\omega}$, $\Lambda_{\omega(\boldsymbol{k})}$ includes the frequencies that hold the condition $\omega\geq\omega_{th}$. In practice, the domain $\Lambda_{\omega(\boldsymbol{k})}$ is sampled with the spectral resolutions $(\Delta k_x,\Delta k_y,\Delta\omega)$ given by the FFT algorithm. This sampled $\Lambda_{\omega(\boldsymbol{k})}$ domain is commonly known in the analysis of ocean waves by using marine radars as dispersion shell (Young et al., 1985).
- Background noise: This spectral noise is caused by speckle noise due to the roughness of the sea surface induce by the local wind. The spectral noise appears in the image spectra of different radar systems under different polarization and incidence conditions, such as Synthetic Aperture Radar (SAR) (Alpers and Hasselmann, 1982), or, like in this case, in X-band marine radar images acquired at grazing incidence conditions (Nieto-Borge et al., 2008).
Taking into account these different spectral contributions to $I(\boldsymbol{k},\omega)$, it is possible to retrieve sea state information by applying inversion modeling techniques (Nieto-Borge and Guedes-Soares, 2000; Nieto-Borge et al., 2004; Seemann et al., 1997; Young et al., 1985). The sea state information provided by the inversion modeling techniques are the current of encounter $\boldsymbol{U}$ (Hessner et al., 2014; Senet

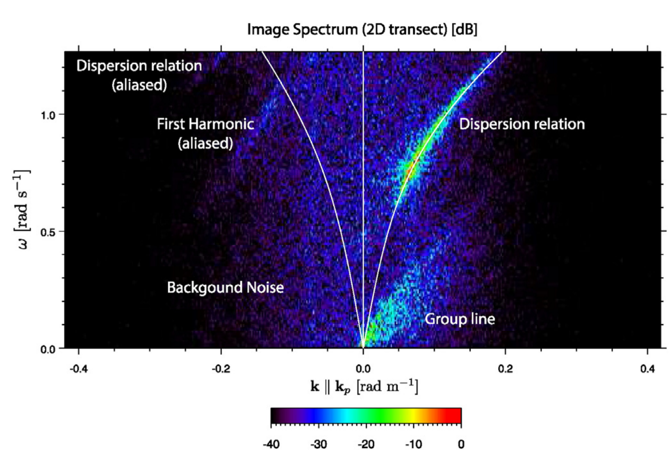

Fig. 1. Estimation of the image spectrum $I(\boldsymbol{k},\omega)$ of a radar image time series. The plot corresponds to a transect in the spectral domain $\Omega_{\boldsymbol{k},\omega}$ along the peak wave direction, $\boldsymbol{k}\|\boldsymbol{k}_p$, where $\boldsymbol{k}_p$ denotes the peak wave wave number vector.