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# ESTIMATION OF OCEAN WAVE HEIGHTS FROM TEMPORAL SEQUENCES OF X-BAND MARINE RADAR IMAGES

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## ABSTRACT

Marine radars scan the water surface at grazing incidence with HH polarization. Unlike other remote sensing systems, marine radars cover smaller areas, but these sensors are able to obtain short-term temporal information about wave fields using consecutive antenna rotations.

This work deals with a method to estimate the significant wave height from sea clutter image time series. This method is based on similar techniques developed for Synthetic Aperture Radar (SAR) systems. The basic idea is the significant wave height is linearly dependent on the root square of the signal-noise ratio, where the signal is assumed as the radar analysis estimation of the wave spectral energy and the noise is computed as the energy due to the sea surface roughness.

## 1. INTRODUCTION

The measurement of ocean waves with marine radars is based on the spatial and temporal structure analysis of the sea surface radar images. These radar images are due to the interaction of the electromagnetic waves with the sea surface ripples caused by the local wind [14, 15, 12, 6, 9]. This interaction produces a backscatter of the electromagnetic fields and, therefore, an image pattern in the radar display unit. This image pattern is commonly known by sailors as sea clutter. Using temporal sequences of sea clutter images, the spatial and temporal variability of the sea surface is analyzed to extract the unambiguous directional wave spectrum, as well as the related sea state parameters, such as the peak wave periods, the mean wave propagation direction, etc.

This work investigates a technique to estimate the significant wave height from sea clutter image time series. The method is based on a similar technique developed for spaceborne Synthetic Aperture Radar (SAR) systems. The main idea behind is the significant wave height is linearly dependent on the root square of the signal/noise ratio, where the signal is assumed as the radar analysis estimation of the wave spectral energy and the noise is computed as the energy due to the sea surface roughness.

The paper is structured as follows: Section 2 introduces the basic ideas of the wave measurement technique by using marine radars. Section 3 describes the stochastic ocean wave theory used in this investigation. The following section, 4, deals with an overview of the wave measuring system. Section 5 describes the inversion modeling technique to extract wave information from temporal sequences of sea clutter images. Furthermore, the proposed method to analyze ocean wave heights is described in section 6, and the obtained results appear in section 7. Finally the conclusions of this investigation are summarized in section 8.

## 2. BASICS OF THE WAVE MEASUREMENT THEORY BY USING X-BAND MARINE RADARS

Ordinary X-Band marine radars working in HH-polarization are suitable to be used as an oceanographic microwave remote sensing device to analyse different phenomena related to the sea surface features, such as ocean waves, local wind fields, ocean currents, etc. The measurement of sea states using marine radars is based on backscatter of the electromagnetic waves by the ripples and the roughness of the free sea surface due to the local wind. Hence the presence of a wind blowing over the sea is necessary to obtain wave information from radar images. This pattern of returned electromagnetic energy is modulated by the larger structures, such as swell and wind sea waves. Figure 1 shows an example of sea clutter image taken by a marine radar on board a moving vessel in the North Sea.

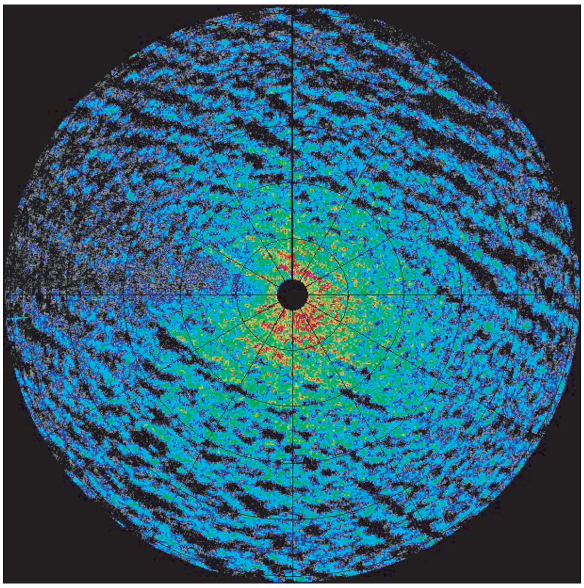

Figure 1: Digitized sea clutter image showing the backscatter phenomenon due to an ocean wave field.

Compared to other air and spaceborne remote sensing systems, navigation radar images cover smaller areas but

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they obtain the temporal information of the sea surface. Different phenomena appear in the nautical radar imaging. Those are the main responsible of the final sea clutter shown by the radar screen.

- Range dependence [2].
- Azimuthal dependence with the wind direction [4].
- Wind speed dependence [4].
- Azimuthal dependence with the wave propagation direction [11].
- Wave tilt modulation [15, 6].
- Shadowing modulation, whch occurs when the higher waves hide the lower waves [6, 12].
- Wave hydrodynamic and orbital modulation due to the motion of the water particles [1].

Analyzing radar data sets it can be realized that all of these phenomena contribute to additional spectral components in the image spectrum (e.g. the power spectral density of a sea clutter data set) which do not belong to the wave field. For example, the range dependence leads to a static pattern in the sea clutter temporal sequence causing a high spectral energy in the low frequency domain and the tilt and the shadowing modulation introduce additional energy in high wave numbers and frequencies.

## 3. STOCHASTIC DESCRIPTION OF SEA STATES

Ocean waves are oscillations of the sea surface generated by the wind strength. Those waves present typical periods between 1 s to 20 s (frequencies $f$ beetwen 1 Hz to 0.05 Hz) and wavelengths between 1 m to 600 m. The wave elevation $\eta$ for a specific position $\vec{r} = (x,y)$ at time $t$ are usually described through the concept of sea state. Sea states are wave fields with invariant statistical homogeneity in the spatial dependence and stationary in their temporal evolution. Under these assumptions, the free surface elevation $\eta(\vec{r},t)$ has the following spectral representation

$$\eta(\vec{r},t) = \int_{\Omega_{\vec{k},\omega}} e^{i\left(\vec{k}\cdot\vec{r}-\omega t\right)} dZ(\vec{k},\omega) \tag{1}$$

where $\vec{k} = (k_x, k_y)$ is the two dimensional wave number vector and $\omega = 2\pi f$ is the angular frequency of the ocean wave field. The integration domain $\Omega_{\vec{k},\omega}$ is defined as: $\Omega_{\vec{k},\omega} \equiv [-k_{x_c}, k_{x_c}) \times [-k_{y_c}, k_{y_c}) \times [-\omega_c, \omega_c)$, being $k_{x_c}$, $k_{y_c}$ and $\omega_c$ the Nyquist cut-off limits for each spectral variable. The spectral random measures $dZ(\vec{k},\omega)$ are complex amplitudes that are usually considered as circular Gaussian random variables, statistically uncorrelated for different wave components $(\vec{k},\omega)$. Under these assumptions, the sea surface elevation $\eta$ can be regarded as a linear, homogeneous and stationary zero-mean stochastic process. This stochastic process defined by Equation 1 is usually described by the so-called three-dimensional wave spectrum

$$F^{(3)}(\vec{k},\omega)d^2k d\omega = \mathbf{E}\left[dZ(\vec{k},\omega)dZ^*(\vec{k},\omega)\right] \tag{2}$$

where $\mathbf{E}$ is the expectation operator and the asterisk indicates the complex conjugate. It is known [5] that ocean waves are dispersive showing a dependence between $\vec{k}$ and $\omega$. For linear waves the dispersion relation is given by $\omega = \varpi(\vec{k}) = \sqrt{gk\tanh(kd)} + \vec{k}\cdot\vec{U}$, where $d$ is the water depth, $k = |\vec{k}|$ and $\vec{U} = (U_x, U_y)$ is the surface ocean current. Hence, for linear ocean waves, only those wave spectral components for those frequencies $\omega$ and wave numbers $\vec{k}$ which hold the dispersion relation are possible within the spectral domain $\Omega_{\vec{k},\omega}$ in Equation 1.

## 4. MEASURING SYSTEM DESCRIPTION

The procedure to analyze wave fields using a nautical radar consists of measuring time series of $N_t$ consecutive sea clutter images (see Figure 2). The sampling time of this temporal sequence of images corresponds to the antenna rotation period. The spatial resolution of each image depends on the azimuthal and the range resolution of the radar antenna. To measure and store the radar data sets an A/D converter, *WaMoS II* [15, 3, 8], specific for this purpose is used. *WaMoS II* is an operational Wave Monitoring System that was developed at the German *GKSS Research Center Geesthacht*. The system consists of a conventional navigation radar, a high speed video digitizing and storage device and standard computer (see Figure 3). The analog radar video signal is read out and transferred to the computer where an analysis software carries out the computation of the sea state parameters in real time. The data can be accessed directly, via removable media, or on-line via modem or Internet.

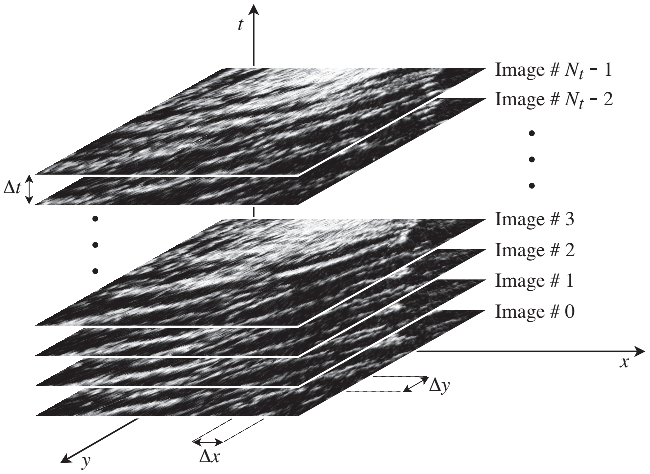

Figure 2: Scheme showing a temporal sequence of radar subimages needed to analyze ocean wave fields.

## 5. ANALYSIS OF TEMPORAL SEQUENCES OF NAUTICAL RADAR IMAGES

The sampled sea clutter time series $\Xi$ can be considered as a spatial and temporal sampled stochastic process $\Xi \equiv \left\{\xi(x_j, y_l, t_q)/0 \leq j < N_x; 0 \leq l < N_y; 0 \leq q < N_t\right\}$, where $\xi$ is the grey level value provided by the *WaMoS II* digitalization. $\xi$ depends on each sampled position and time step. The indexes $j$, $l$ and $q$ cover the number of pixels of the time series $\Xi$ ($N_x$, $N_y$ and $N_t$ samplings in $x$, $y$ and time axis respectively). The estimation of the wave spectrum is obtained by applying an inverse modeling technique. The wave spectrum inversion method has the following steps:

1. Image normalization: This technique is performed by subtracting the mean intensity and reducing the spatial trends of the sea clutter time series $\Xi$ to decrease the main

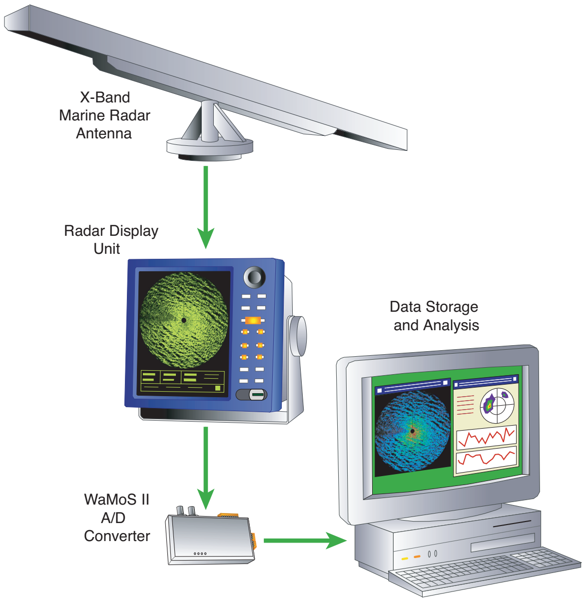

Figure 3: Scheme of an installation needed for ocean wave measurement.

contribution of the static patterns in wave numbers and frequencies [7].

2. Spectral estimation: Application of a three-dimensional Discrete Fourier Transform to obtain the estimation of the so-called image spectrum, $F_{\Xi}^{(3)}(k_{x_m},k_{y_n},\omega_p)$, where $m=0,\dots N_x-1$; $n=0,\dots N_y-1$ and $p=0,\dots N_t/2$. There are three main contributions to the total spectral energy in the function $F_{\Xi}^{(3)}$:
   - Wave field components [14].
   - Higher harmonics of the wave components due to nonlinear mechanisms in the nautical radar imaging [6, 12, 7].
   - Background noise spectral energy (BGN) due to the roughness of the sea surface [12].
3. Calculation of the surface current $\vec{U}$: This parameter is obtained by analyzing the location of the wave and the higher harmonic components $(\vec{k},\omega)$ of the image spectrum $F_{\Xi}^{(3)}$ inside the spectral domain $\Omega_{\vec{k},\omega}$ [13].
4. Filtering of the image spectrum to take off all the $(\vec{k},\omega)$ components of the image spectrum which do not belong to the wave field. Therefore the dispersion relation for ocean waves is applied to the image spectrum

$$F_f^{(3)}(k_{x_m},k_{y_n},\omega_p)=\begin{cases} F_{\Xi}^{(3)}(k_{x_m},k_{y_n},\omega_p) & \text{if } p\in\Omega_p^{mn} \\ 0 & \text{otherwise}\end{cases} \tag{3}$$

   where $\Omega_p^{mn}\equiv\left\{p/|\vec{k}(\omega_{p-1})|\leq|(\vec{k}_{x_m},\vec{k}_{y_n})|\leq|\vec{k}(\omega_{p+1})|\right\}$.
5. Application of the Modulation Transfer Function: This function $(\mathscr{T}_{\mathscr{M}})$ is applied to the filtered spectrum $F_f^{(3)}$ (see Equation 3) in order to correct the effects introduced by the shadowing and the tilt modulation [10]. $\mathscr{T}_{\mathscr{M}}$ follows a power decay law on the wave number, where the exponent is obtained empirically [15, 6, 9], $\mathscr{T}_{\mathscr{M}}(k)\sim k^{-\beta}$, with $1\leq\beta\leq1.4$. Comparisons between numerical simulations and real measurements from a buoy and a nautical radar [9] have shown a good empirical approach for the exponent $\beta$ is 1.2.

## 6. SIGNIFICANT WAVE HEIGHT ESTIMATION

Significant wave height, $H_s$ is well known parameter used by oceanographers an ocean engineers to characterize the wave height of a wave field. $H_s$ is the average of the one-third of the highest wave heights of the wave record. Assuming a Gaussian wave field, $H_s$ can be derived from the wave spectrum [7] as

$$H_s=4\cdot\sqrt{\int_{\Omega_{\vec{k},\omega}}F^{(3)}(\vec{k},\omega)d^2kd\omega} \tag{4}$$

The ocean wave measurement with X-band marine radars has the particularity that the spectral densities obtained after the inversion method described above have values related to the scale of grey levels $\xi(x_j,y_l,t_q)$ in the sea clutter time series $\Xi(\vec{r},t)$, rather than the wave elevation $\eta(\vec{r},t)$. Furthermore, the values of these grey levels depend on how the electromagnetic fields are backscattered by the sea surface and how their power is received and amplified by the radar equipment and they do not depend directly of how high the wave are. Therefore $\Xi$ only contains the relative information about the energy distribution of the wave field. Hence, these non scaled spectra do not provide directly the wave height estimations. Taking into account similar problems which occur with the ocean wave detection with spaceborne SAR systems [1] and due to the existence of the background noise due to speckle within the image spectrum, a method is proposed to estimate the significant wave height from sea clutter temporal sequences. Following this idea [7], $H_s$ can be estimated as

$$H_s=c_0+c_1\sqrt{\text{SNR}} \tag{5}$$

where $c_0$ and $c_1$ are calibration constants, which depend on each specific installation (e.g. platform height, angle of incidence, etc.), and $SNR$ is the signal-noise ratio. A proper definition of $SNR$ must be consistent in the sense that no wave spectral components should be considered as speckle background noise components (see Figure 4), on the other hand any background noise contribution should not be considered as wave energy.

The proposed definition of $SNR$ takes into account the main features applied to the inversion modelling technique described above. The following definition of ”SNR” uses the wave number spectrum $F^{(2)}(\vec{k})$ resulting of the frequency integration of the filtered spectrum $F_f^{(3)}$ and the application of the modulation transfer function $\mathscr{T}_{\mathscr{M}}$

$$F^{(2)}(\vec{k})=2\mathscr{T}_{\mathscr{M}}(k)\cdot\left[\int_{\omega_{th}}^{\omega_c}F_f^{(3)}(\vec{k},\omega)d\omega\right] \tag{6}$$

where $\omega_{th}$ is a frequency threshold to avoid the spectral energy of the static patterns.

$$\text{SNR}=\frac{\displaystyle\int_{\Omega_{\vec{k}}^{\alpha}}F^{(2)}(\vec{k})\,d^2k}{\displaystyle\int_{\Omega_{BGN}}F_{\Xi}^{(3)}(\vec{k},\omega)\,d^2k\,d\omega} \tag{7}$$

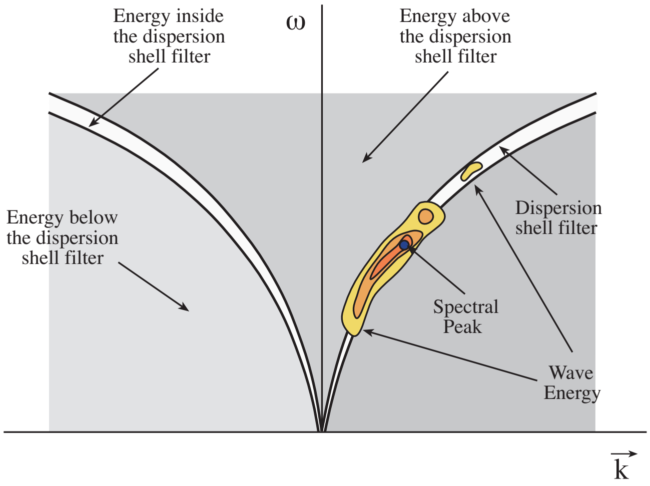

Figure 4: Scheme showing the different spectral components in the image spectrum used to estimate the significant wave height.

where the integration domains are

$$\Omega_{BGN} \equiv \left\{(\vec{k},\omega)\in\Omega_{\vec{k},\omega}/\omega<\varpi(\vec{k})-\Delta\omega\right\}\cup \left\{(\vec{k},\omega)\in\Omega_{\vec{k},\omega}\;/\;\omega>\varpi(\vec{k})+\Delta\omega\right\} \qquad (8)$$

and

$$\Omega^{\alpha}_{\vec{k}} \equiv \left\{\vec{k}\in[-k_{x_c},k_{x_c})\times[-k_{y_c},k_{y_c})/ F^{(2)}(\vec{k})\geq\alpha\cdot\max[F^{(2)}];\,0\leq\alpha\leq 1\right\} \qquad (9)$$

The parameter $\alpha$ is a constant to avoid the contribution of the background noise within the dispersion shell filter.

Figure 5 shows an example of background noise depending on the wave number vector $\vec{k}=(k_x,k_y)$ for a fixed value of the wave frequency $\omega$. The horizontal axis correspond to the azimuthal coordinate and the vertical axis with the range. A transect in the two dimensional spectrum shown in Figure 5 appears in Figure 6. It can be seen the wave number $k$ dependence if the one-dimensional structure of the spectrum due to the speckle by the sea surface roughness, which is called in this work background noise. Furthermore, it can be seen that for high wave numbers the spectral density shown in this Figure 6 present a constant value. Following similar results derived from the sea surface detection using spaceborne SAR systems [1], this constant value of the speckle noise can be identified as the thermal noise of the sensor system.

## 7. TEST OF THE PROPOSED METHOD USING IN-SITU DATA

To test the proposed method, a data set of in-situ data recorded by a oceanographic buoy has been used. these records are composed by sets of wave elevation time series. From these data sets the significant wave height values are derived. These data were acquired by the Floating Production and Storage Offshore (FPSO) *Norne* in the northern North Sea from November 1997 till January 1998. During this measuring 1517 marine radar data sets and 6890 buoy measurements were taken. The radar measured every three hours for a period of half an hour continuously, where as the buoy delivered data every 10 minutes. Figure 7 shows the comparison between $\sqrt{\mathrm{SNR}}$ computed from Equation 7 using the marine radar data sets and values of $H_s$ derived from the buoy records. It can be seen that the correlation coefficient $r$ is 0.89 and the proposed linear model given by Equation 5 fits quite properly with the obtained results.

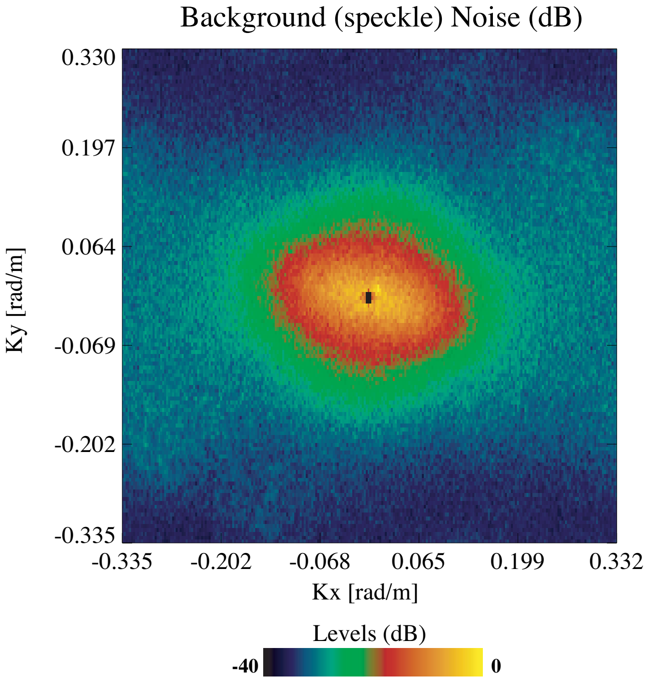

Figure 5: Two-dimensional speckle background spectrum depending on the wave number for a given frequency plane.

It order to discuss properly the comparison between the radar data and the buoy data, it should be pointed that buoys measure wave properties in the temporal domain (e.g. time series) at a fixed ocean location, the mooring point. On the other hand, radars scan areas of the ocean and, for the specific case of the marine radar, deliver time series of images. Thus, the radar data are defined in both the spatial and the temporal domain. Hence any comparison between punctual and spatial measurements should take into account the typical decorrelation of wave fields in in the spatial domain. Taken this concept into account, the obtained correlation coefficien ($r=0.89$) present a similar values than the correlation coefficient between two boys moored at two kilometers apart, which corresponds to the radar subimage size. So the wave field parameters derived from buoy records are time averaged and space and time averaged for the marine radar case.

## 8. CONCLUSIONS AND OUTLOOK

Ordinary marine X-band radars are a suitable tool to scan the sea surface and derive the related sea state parameters. Hence these systems are able to provide estimations of the significant wave heights $H_s$ of a given wave field. The $H_s$ estimation is obtained analyzing the signal-noise ratio in a similar way than methods proposed for Synthetic Aperture Radars (SAR) systems. A correlation coefficient of 0.89 between the in-situ

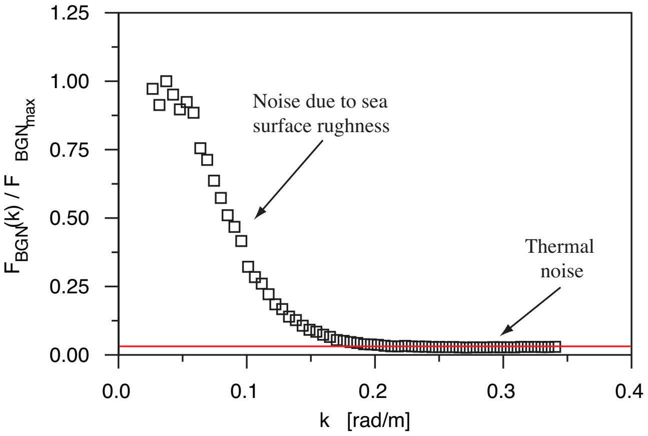

Figure 6: One-dimesnional speckle background spectrum depending on the wave number for a given frequency plane.

data and radar measurements can be reached using the background noise power spectral density, located within the wave number and frequency domain, and the total amount of wave energy within the dispersion shell. For that purpose, the application of an inversion modeling technique is applied to the thre-dimensional image spectrum.

The existence of this background spectral energy, which depends on the roughness of the sea surface, outside the wave dispersion shell is an additional tool to extract more oceanographic information from sea clutter images than the significant wave height $H_s$. Hence, A parameterization of the background spectral density as a function of the wave numbers and geophysical parameters will permit to derive additional meteorological information, such as wind velocity and direction, from the three-dimensional spectra derived from temporal sequences of sea clutter radar images.

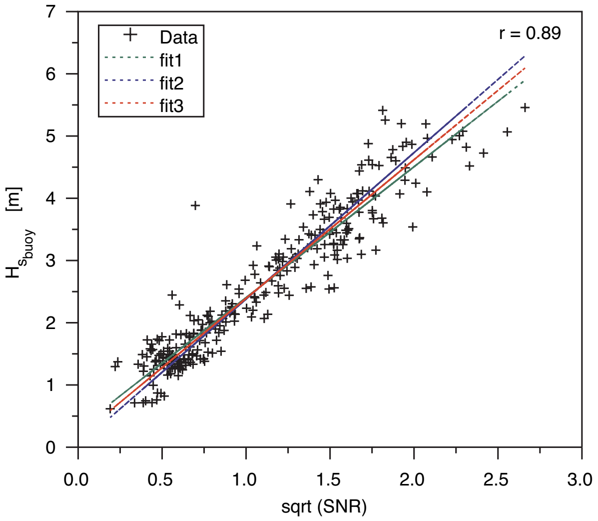

Figure 7: Scatter plot of marine radar $\sqrt{\mathrm{SNR}}$ values verus significant wave height $H_s$ measurements derived from oceanographic buoy records. Labels indicate the least square fits on horizontal (fit 1) and vertical (fit 2) minimization and their mean value (fit 3).

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