NUMERICAL PSEUDO – RANDOM SIMULATION OF SAR SEA AND WIND RESPONSE

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ABSTRACT

Wind and wave data from SAR imagery over the oceans have been routinely employed for many years, and the techniques to extract such data are a well established field of research. The paper presents a different method, based the well established two wavelength models, whereby the surface slope is simulated by numerically generating the instantaneous water height. The numerical approach seems to offer a greater flexibility granting a much greater freedom to introduce fully non linear and non spectral effects in the short wavelength.

1 INTRODUCTION

Most if not all the techniques used for extracting sea surface with active sensors are based upon analytical forms of the sea wave spectrum. This has the obvious advantage of providing a closed form for the function which relates the sensor response to the physical parameters of interest, but it also poses a strong constraint on the complexity of physical effects which can be taken into account.

In order to provide some insight on the image formation mechanism, an alternative approach is proposed here, whereby numerical simulation of the sea state is carried out by pseudo randomly generating the water surface according to any given spectrum. Just like any other two (or three) wavelength model, this supplies all the information about surface tilt, while backscattering characteristics – which depend on smaller scale phenomena such as capillary waves and whitecapping – must be separately specified. There is a difference, though, in that numerical simulation allows a much greater freedom in specifying and testing non linear hypotheses on the backscattering functions; another advantage is that it poses no limits to the shape of the spectrum.

2 PSEUDO – RANDOM SIMULATION OF SEA SURFACE

The basic idea - i.e. to simulate a great number of sea surface realisations and to evaluate the scattering coefficient by ensemble averaging the statistics of surface tilt an other parameters -is of course not new in principle: it dates back to 1990 (Bruening et al.) and was used also to investigate into wave radio altimeter data (Della Rocca & Pugliese Carratelli, 2001 a,b). Unlike Bruening’s classical work, however, the simulations shown in this paper are extended down to wave lengths of the order of one meter, well under SAR pixel size, thus allowing a numerical rather than parametric representation of sub resolution phenomena.

The actual implementation of the procedure presented here is based on the large experience of wave synthesis techniques which have been developed in the past: a Random Phase Double Summation technique was employed, as described for example by Miles and Funke (1987) and Goda (1989) and the phase locking effect was limited by adopting a rather high number of spectral components as in (Giarrusso & al., 2001).

An instantaneous water height field realisation \( \eta(X,Y,t) \) can be generated by assuming a discrete directional spectrum form \( f_d(\omega_j,\theta_j) \), and by setting \( A_{i,j} = \sqrt{2 \cdot f_d(\omega_j,\theta_j)} \frac{d\omega}{df} \). By pseudo-randomly setting the phase parameters \( \varepsilon_{i,j} \):

\[
\eta(X,Y,t) = \sum_j \sum_i A_{i,j} \cos(k_j(X \cdot \sin \theta_j + Y \cdot \cos \theta_j) - \omega_j t + \varepsilon_{i,j})
\]

(a cosine form of the transformation is assumed here).
The most obvious choice for \( Sd(\omega_i, \theta_j) \) would be a JONSWAP spectrum with a directional spreading function, but of course any shape can be easily taken into account. Different spectral parameters lead to different wave field realizations (Fig. 1).

3 SAR AND WIND RESPONSE

Once a satisfactory description of the sea surface is obtained, the simulated image depends on the local scattering coefficients \( \sigma_l \) Here “local” refers to the spatial resolution of the simulation, which is smaller than the typical gravity wavelength. Assuming a Valenzuela-style backscattering function (Eqs. 2 - 3 and Fig. 2):

\[
\sigma_j = \beta \cdot \cos^4 \vartheta \quad \text{(HH polarization)}
\]

\[
\sigma_j = \beta \cdot \cos^4 \vartheta \cdot \left( \frac{\varepsilon^2 \cdot (1 + \sin^2 \vartheta)}{(\varepsilon \cdot \cos \vartheta + \sqrt{\varepsilon})^2} \right)^2 \quad \text{(VV polarization)}
\]

The local \( \sigma_l/\beta \) is known, and simulating a RAR (Real Aperture Radar) image is simply a question of taking into account the local slope, a simple derivative of the sea elevation \( \eta(X, Y, t) \). The actual \( \beta \) will depend on the local surface conditions (Bragg resonant capillary waves, whitecaps, etc). The slope is thus a very important parameter: (Fig 3) shows its computed frequency distributions for different significant wave heights and wind directions.

In order to reconstruct the simulated image from the SAR signal orbital velocity values are also necessary to evaluate Doppler – related effects: following the same approach the time varying local velocity is given by the sum of the surface velocities of each spectral and directional component: so, for example, the X velocity component will be (Eq. 4):

\[
V_x(X, Y, t) = \sum_{j} \sum_{i} gA_{ij} \omega_i^{-1} k_i \cos (\omega_i t - k_i (X \cdot \cos \theta_j + Y \cdot \sin \theta_j) + \varepsilon_{ij})
\]

RAR and SAR cross section for various values of parameters such as wave height, spreading function parameter and peak spectral period for both horizontal and vertical polarization can thus be computed just like in any analytical model, but non-spectral and non linear information such as different distribution of the capillary – Bragg resonant water waves on the two sides (windward and leeward) of the long waves can easily be added.
The influence of such parameters as geometrical and sea-state parameters can easily be taken into account. Fig 4 thus shows the $\sigma_1$ distributions for the same wind direction and significant wave height $H_s$ assuming VV polarization.

![Fig. 3. Frequency distributions of local incidence angles for different significant wave heights and wind directions.](image)

![Fig. 4. Frequency distributions of local $\sigma_1$ / $\beta$ for different significant wave heights and wind directions.](image)

![Fig. 5. Values of $\sigma_0$ for different wind directions and speed values (CMOD).](image)
The following pictures show the effect of assuming different backscattering properties along the wave, (Fig. 6) such as may derive from asymmetrical distribution of capillary waves or whitecapping; radar section frequency distribution is shown for $\beta = 1.2$ on the wind side of the waves and $\beta = 0.8$ on the lee side and compared with the $\beta = 1$ results. (Fig. 7 and 8).

While the assumption is admittedly sharp and unrealistic, the results still it suggests that spatial roughness distribution over a wavelength might be relevant and can be simulated. Such a possibility appears to be particularly interesting since new results are now available on the spatial distribution of small scale roughness over sea waves, mostly to the work by Kudryavtsev et al.(1999,2002).

The phenomena deriving from larger scale wave formation and transformation such as shoaling and current interaction can then be taken into account by making use of the widely tested model such as WAM or SWAN (Giarrusso et al 2004, Pugliese Carratelli et al 2005).

**Fig. 6.** Different values of parameter $\beta$ along the wave.

**Fig. 7.** Frequency distributions of local backscattering for wind direction $= 188.5^\circ$.

**Fig. 8.** Frequency distributions of local backscattering for wind direction $= 278.5^\circ$. 
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REFERENCES

1. Bruening, C., Alpers W. and Hasselmann K. “Monte Carlo Simulation studies of the nonlinear imaging of a two dimensional surface wave field by a synthetic aperture radar” Int. Journal of remote Sensing 11, 1990


