PROCEEDINGS OF JOINT

3^{rd} INTERNATIONAL CONFERENCE ON ELECTROMAGNETICS IN AEROSPACE APPLICATIONS

and

7^{th} EUROPEAN ELECTROMAGNETIC STRUCTURES CONFERENCE

SEPTEMBER 14-17, 1993 - POLITECNICO DI TORINO, ITALY

A SAR OCEAN RAW SIGNAL SIMULATOR

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Abstract - Scope of this paper is to outline an efficient SAR (Synthetic Aperture Radar) raw signal simulator for ocean scenes, based on a sound physical model. Electromagnetic radar return is modelled in terms of the Bragg-resonant backscattering extended to the bi-dimensional case. Ocean dynamics and statistics are taken into account.

1 Motivations

The Seasat launch in 1978 clearly showed the possibility to perform a continuos and global ocean environment surveillance. Principal features revealed by SAR imagery regarded surface waves structures, as well as internal waves, bottom bathymetry and ship wakes. Such a spectacular and partly unexpected Seasat SAR imagery promoted a great scientific effort in order to correctly interpret such a large amount of data. In order to develop inversion techniques different models for SAR image formation have been formulated [1]. These are generally quite involved due to the dynamic nature of the features under survey and the radar echo acquisition process [1]. As well known, SAR data acquisition is achieved via two different mechanisms for along-track (azimuth) and across-track (range) scanning: the latter is performed at one half the speed of light, hence instantaneously, whereas azimuth scanning is done at the sensibly lower speed, i.e. at the platform velocity [2]. Such a different time-scale scanning affects the SAR imagery of time-varying features and is at the base of some peculiar problems encountered in the inversion schemes applied to the ocean [1,2]. First attempts to recover pertinent information from SAR image were based on linear models and provided limited results; some non-linear inversion schemes have been more recently employed. Among different and interesting applications we underline the great relevance of the SAR to be sensitive to the directional ocean wave spectra and therefore the chance to estimate them by means of an appropriate model. Within such a framework a SAR raw signal simulator may be of valuable aid.

2 General framework

In this paper a general SAR raw signal simulator scheme is given, in accordance with the distributed surface (DS) model [1,3].

Before proceeding further some preliminary facets of the problem at hand are pointed out.

First of all, we recall that an imaging radar can be simply (but effectively) defined as a system whose main task is to estimate the scene reflectivity. A SAR imaging system is based upon two different data acquisition for along-track (azimuth), and across-track (range) scanning. Such an estimator is not perfect: in particular, its ability to spatially resolve two points on the image plane is not arbitrarily fine: resolution is the quantity used to measure such a limitation [2]. The generated image (i.e., the backscattering reflectivity estimate) is affected by a multiplicative noise which arises from the interference of the elementary returns within each resolution cell [2,4], because SAR is a coherent system.

From the oceanographic point of view, the scene dynamics impact on image formation is of fundamental and remarkable interest. We note that, even in presence of an ideal SAR system (e.g., unlimited fine resolution), a non-linear time-space mapping is accomplished when time-varying scene are in order [1,2]; this aspect of the problem is of great relevance and it is strictly related to the ocean dynamic model. As a matter of fact, the scene reflectivity is time-dependent whereas its estimate (i.e., the SAR image) is time-averaged [1,3]. Therefore, in the following we mainly focus our attention on ocean dynamics and their effect on SAR raw signal formation.

The SAR raw signal $s(\cdot)$, i.e., the signal received on board, can be written as follows [3]:

$$s(x',r') = \iint dx dr\, \gamma(x,r,t) g(x'-x, r'-r) \exp[2j\eta_o r] \quad , \tag{1}$$

wherein $g(\cdot)$ is the system transfer function, $\gamma(\cdot)$ represents the time-varying backscattering function. (x',x) are azimuth coordinates, (r',r) range ones, (see Fig.1), and η_o a system parameter. Dimensionless variables are used throughout.

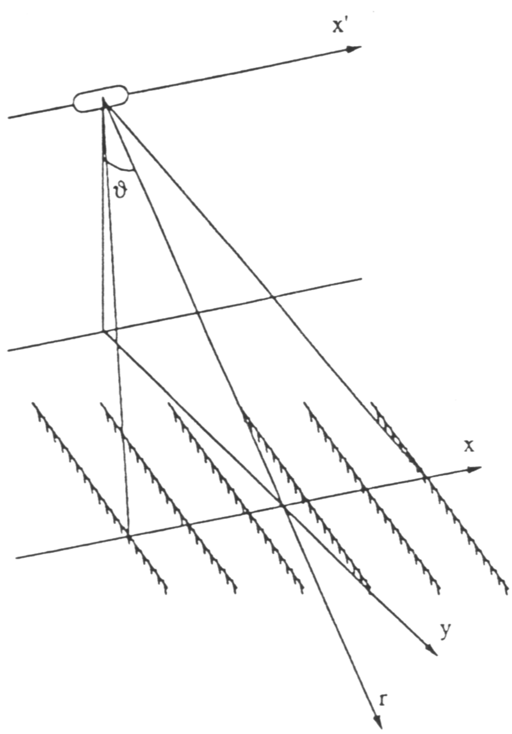

Fig.1: Relevant to the geometry of the problem.

Eq.(1) does not show a desirable functional convolutional dependence as in the case of static scene [2]. In order to circumvent this limitation it is convenient to note that:

$$s(x',r') = \mathfrak{s}(x',r',t'=x') \quad ,$$

where:

$$\mathfrak{s}(x',r',t') = \iiint dx dr dt \{g(x'-x, r'-r)\delta(t'-t)\} \cdot \cdot \gamma(x,r,t)\exp[2j\eta_o r] \quad , \tag{2}$$

which is now recognised to be a (three-dimensional) convolution. Accordingly:

$$\mathfrak{s}(x',r',t') = \frac{1}{(2\pi)^3} \iiint d\xi\, d\eta\, d\omega\, G(\xi,\eta) \cdot \cdot \hat{\Gamma}(\xi, \eta-2\eta_o, \omega)\, \exp[j(\xi x' + \eta r' + \omega t')] \quad , \tag{3}$$

wherein ξ, η, ω are the Fourier mates of x',r',t', respectively; capital letter means space-wavenumber spectra of the corresponding low case function, and the caret implies the time-frequency transformation. For the three-dimensional spectrum $\hat{\Gamma}(\xi, \eta-2\eta_o, \omega)$ we have the following intermediate step:

$$\Gamma_t(\xi,\eta,t) = \iint dx dr\, \gamma(x,r,t) \exp[-j(\xi x + \eta r)] \quad ; \tag{4}$$

we assume,

$$\Gamma_t(\xi,\eta,t) = \Gamma(\xi,\eta)\exp[-j\sigma(\xi,\eta)t] \quad , \tag{5}$$

wherein:

$$\Gamma(\xi,\eta) = \iint \gamma(x,r,0)\exp[-j(\xi x + \eta r)] \quad ; \tag{6}$$

accordingly:

$$\hat{\Gamma}(\xi,\eta,\omega) = \int \Gamma_t(\xi,\eta,t)\exp(-j\omega t)dt = = 2\pi\,\Gamma(\xi,\eta)\delta[\omega - \sigma(\xi,\eta)] \quad . \tag{7}$$

Assumption (5) implies that the spatial wave components of $\gamma(x,r,t)$ propagate with different speed velocities described by the function $\sigma(\xi,\eta)$. Furthermore, $\omega=\sigma(\xi,\eta)$ is the ocean wave wavenumber-frequency dispersion equation. Substituting eq.(7) in eq.(3) we get:

$$\mathfrak{s}(x',r',t') = \frac{1}{(2\pi)^2} \iint d\xi d\eta\, G(\xi,\eta)\,\Gamma(\xi,\eta-2\eta_o) \cdot \cdot \exp\{j[\xi x' + \eta r' + \sigma(\xi,\eta-2\eta_o)t']\} \quad . \tag{8}$$

When a Taylor expansion to the first order of the normalized dispersion relation is applicable, eq.(8) leads to a very compact expression:

$$s(x',r') = \frac{1}{(2\pi)^2}\exp(j\bar{\sigma}x')\iint d\xi d\eta\, G(\xi,\eta)\cdot$$
$$\Gamma(\xi,\eta-2\eta_o)\exp\{j\xi[x'(1+\sigma_\xi)]\}\exp\{j\eta[r'+x'\sigma_\eta]\} \quad , \tag{9}$$

wherein σ_o is the zero-order expansion term, $\sigma_\xi = \partial\sigma/\partial\xi$, $\sigma_\eta = \partial\sigma/\partial\eta$, and $\bar{\sigma}$ is a function of these previous three terms. Eq.(9) shows that the raw signal comes out naturally in the deformed output system $\bar{x},\bar{r}$:

$$\begin{cases}\bar{x} = x'(1+\sigma_\xi) \\ \bar{r} = r' + x'\sigma_\eta\end{cases} \quad , \tag{10}$$

and therefore the desired raw signal $s(x',r')$ can be obtained through the available $s(\bar{x},\bar{r})$ data by means of interpolation.

Finally, no-linear hydrodynamic modulation must be included in a complete physical model [3]. Such a theory, only available in the case of interaction of a single gravity wave with a short-wave spectrum, can be applied in a limited number of cases. Furthermore, we note that according to DS model no velocity bunching effect is recognised although the particle motion is taken into account [3].

Hereafter, in Fig.2, to conclude we sketch a block diagram depicting the general framework just examined and illustrated.

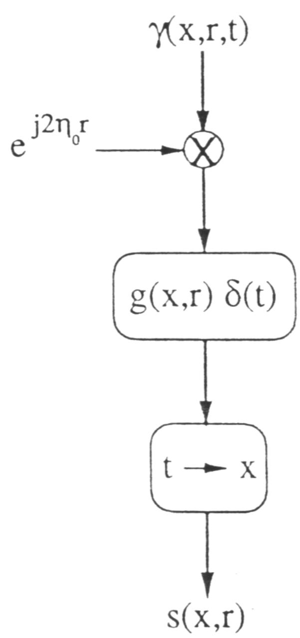

Fig.2: Block diagram relevant to the general framework of the problem.

3 Electromagnetic modelling

Electromagnetic backscattering at microwave frequencies of ocean surface wave structure, at least for intermediate incidence angles and moderate sea-state, is dominated by the Bragg resonance of short waves over the long one [5-7]. In the simplest one dimensional case, the scattering resonant short wave is the one whose wavenumber ζ is related to the electromagnetic wavenumber k and at the incident angle θ by the relation:

$$\zeta = 2k \sin\theta \quad . \tag{11}$$

Generalization of Bragg-resonant backscattering must be considered in order to suitably incorporate it in a SAR raw signal simulator scheme. Such a model must extend eq.(11) to oblique incidence, and should exhibit a physical dependence on sea state parameters and its random nature. Such statements are crucial in a physical simulation scheme and are mandatory to exploit such a tool in any inversion procedures.

Eq.(1) does not exhibit desirable polarimetric properties, which can be included by an appropriate matrix generalization, $\underline{\underline{\gamma}}(\cdot)$, of the backscattering pattern. It has been shown in Ref.[8] that :

$$\underline{\underline{\gamma}} = \underline{\underline{S}}\cdot D(\cdot) \quad , \tag{12}$$

wherein the matrix $\underline{\underline{S}}$ takes into account the (macroscopic) polarimetric behaviour relevant to the long wave and $D(\cdot)$ describes the (microscopic) behaviour of elementary scattering facet. Furthermore we note that eq.(12) includes the so-called tilting effect [7,8]. An explicit $D(\cdot)$ expression can be obtained inserting the short wave modification over the facet, in terms of a single capillary wave, that is:

$$D(\cdot) = \sum_p J_p\left(\frac{4\pi}{\lambda}B(\xi,\zeta)\cos\theta\right)\cdot$$
$$\frac{\sin\left[\frac{4\pi^2}{\lambda\xi}N\delta_x\cos\theta\right]}{\sin\left[\frac{4\pi^2}{\lambda\xi}\delta_x\cos\theta\right]}\;\frac{\sin\left[\frac{4\pi^2}{\lambda\zeta}M(\sin\theta+\delta_y\cos\theta)\right]}{\sin\left[\frac{4\pi^2}{\lambda\zeta}(\sin\theta+\delta_y\cos\theta)\right]}\cdot$$
$$\mathrm{sinc}\left[\frac{8\pi^2}{\lambda\zeta}(\sin\theta+\delta_y\cos\theta)-2\pi p\right]\cdot \tag{13}$$
$$\mathrm{sinc}\left[\frac{8\pi^2}{\lambda\xi}\delta_x\cos\theta-2\pi p\right]\exp[jp\Theta(\xi,\zeta)] \quad ,$$

wherein N and M are the ripple crest numbers along x and y axes, δ_x, δ_y the facet's slopes according x and y axes, and $B(\cdot)$, $\Theta(\cdot)$ the amplitude and phase of the ripple.

Resonance may occur whenever:

$$\begin{cases} \xi = \dfrac{4\pi}{p\lambda}\delta_x \, cos\theta \\ \zeta = \dfrac{4\pi}{p\lambda}(sin\theta + \delta_y \, cos\theta) \quad , \end{cases} \qquad p = 1,2,.... \qquad (14)$$

and eq.(13) reduces to:

$$D(\cdot) = \sum_p J_p\left(\frac{4\pi}{\lambda} B(\xi,\zeta)\cos\theta\right) NM \exp\left[jp\Theta(\xi,\zeta)\right] \quad , \qquad (15)$$

which shows that the Bragg-resonant contribute is weighted by the ripple amplitude. In particular, eq.(14) specifies the resonant wavenumber of the short wave modification over the long wave structure; eq.(15) accounts for this contribution in terms of its associated amplitude and phase.

Some comments are now in order.

Results (14) and (15) are relative to a single sinusoidal ripple over the long wave. In the real case, the short wave spectrum is not monochromatic and its spectrum should be considered. However, condition (14) shows that only a discrete set of resonant spatial frequencies contribute to the ocean backscattering and this could be the starting point to select those ripple frequencies that are mainly responsible of the ocean backscattering. As a matter of fact, Bragg-resonant theory (to the first-order) accounts for a linear model [5,6]; in effect, the electromagnetic field acts as a delta function in the wavenumber space picking out of the two-dimensional surface wave spectrum [9,10] those waves that meet the condition of Bragg resonance, see eq.(14).

Finally, we note that the long ocean structure modulates the Bragg scattering due to the short waves [3,5,6,8]. In order to model the long wave structure an appropriate ocean surface simulation must be performed [11]. A general answer to this problem cannot be given. Fortunately, whenever a gaussian ocean model is in order it is possible to get the latter from the sole power spectra knowledge [9]. Alternatively, some other ocean surface characterizations, as for instance the bispectrum, are needed [10,11].

4 Summary and concluding remarks

In this work we outlined a sound physical electromagnetic and computationally efficient synthetic aperture radar raw signal simulator for ocean surface waves.

The reflectivity function has been modelled by means of a two-scale rough surface and it contains sea height information. In particular, no-linear hydrodynamic modulation is taken into account.

The synthetic aperture radar raw signal is a transformation of this reflectivity function. Such a transformation depends on the ocean dynamics and we considered the distributed-surface approach.

As last remark, we note that the model described here validates the idea of SAR ocean monitoring for features detection and measurement, and shows the possibility to exploit a SAR simulator as a training tool in order to effectively depict an inversion scheme to unveil such a features.

5 References

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This work was supported in part by the Italian Ministry of Scientific Research and Technology (M.U.R.S.T.) under M.U.R.S.T.40% "Telerilevamento dell'Ambiente. Sensori a microonde ed integrazione dei dati" contract.