Simulation Model for Sea Clutter in Airborne Radars

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***Abstract*— This paper presents the architecture and the methods used to dynamically simulate the sea backscatter of an airborne radar operating in a medium repetition frequency mode (MPRF). It offers a method of generating a sea backscatter signal which fulfills the intensity statistics of real clutter in time domain, spatial correlation and local Doppler spectrum of real data. Three antenna channels (sum, guard and difference) and their cross-correlation properties are simulated. The objective of this clutter generator is to serve as the signal source for the simulation of complex airborne pulsed radar signal processors.**

I. Introduction

In the design of a radar signal processor it is necessary to have a signal simulation source which generates realistic signals. Concretely, to design CFAR detectors and clutter suppression algorithms a realistic simulation method for clutter is necessary. In the case of airborne radar some models have been proposed, which consider principally local stationary clutter [1] [2] [3] [4] but not Doppler spectra due to internal clutter motion. Under this assumption the signal is generated at the output of a bank of Doppler filters with a Doppler dispersion due only to platform movement. This model is appropriate for stationary clutter (e.g. ground clutter) but not for sea clutter. Also, these models do not consider the existence of three processing channels (sum, guard and difference) whose clutter is correlated. The objective of the work is to present a sea clutter simulation model which solves these deficiencies.

A complete simulation model of the sea backscatter received by an airborne radar is described. The main properties of the model are listed below:

- It simulates 3 antenna channels (sum, difference and guard) and the dependences given among them are considered.
- The coherent clutter corresponding to the backscatter of a coherent burst is simulated.
- The gross sea surface is represented by a correlated bidimensional Gaussian process. The coherence of the surface is kept during different coherent bursts.
- The fine sea surface movement is modelled through the Doppler spectrum of a resolution cell. The spectrum of the surface cells is composed of the sum of two components: Bragg events, caused by capillary waves, and the Whitecap, related to the ripple caused when waves break [5].
- K distribution has been used to model the reflectivity of the sea surface. K model appears as the most physical applicable to the amplitude statistics of sea clutter [6] [7].

The paper is structured as follows: section II presents the general architecture of the simulation model and section III describes the mapping procedure to sample surface radar cells. The computation of the mean reflectivity is explained in section IV, whereas the method to generate the coherent echo of each radar resolution cell is presented in section V. Finally, a section with results is included.

II. General Architecture

The clutter generator block diagram is presented in figure 1. It starts with the acquisition of external parameters related to the radar, bursts, etc which are necessary for the simulation. The surface around the radar is divided in range-azimuth patches with homogeneous widths ΔR and $\Delta\theta$, so that their joint scattering return can be simulated dynamically. Next a mean clutter reflectivity map is created as described in section IV depending on the clutter characteristics, wind direction and wind speed. The TSC model is used in our computation but other models can be also used for the surface reflectivity [6].

As the sea backscatter is considered to be K-distributed [7], it is formed by the product of two components: the texture and the speckle. The texture is Gamma distributed and represents the backscatter from the capillary waves, while the speckle follows a Rayleigh distribution and is caused by the small ripples of the waves.

The texture apart from being Gamma distributed, also presents spatial correlation and a two-component-spectrum, as mentioned before. Since the correlation is directly related with the dynamics of the sea surface height, a synthetic Gaussian height field has been generated using a typical model for the sea surface (e.g. Pierson-Moskowitz) in order to simulate its spatial correlation. The Gaussian process can be easily transformed to a correlated Gamma process with a practically equal autocorrelation function [8] by means of a memory less non-linear transformation (MNLT).

The echo is generated in the frequency domain (the spectrogram of the coherent echo) to obtain the temporal response by the inverse FFT. The Doppler spectrogram of the texture and speckle are simulated separately and multiplied afterwards. The averaged reflected power and spatial correlation is imposed on to the two-component spectrum (Bragg and Whitecap [5]) of the texture, as described in section V. The power of the speckle, on the other hand, is normalized to unity.

The gains corresponding to each reception channel are applied to each spectrogram. Afterwards the three spectrograms are folded in frequency and the contributions of all the cells at the same range and frequency sample summed.

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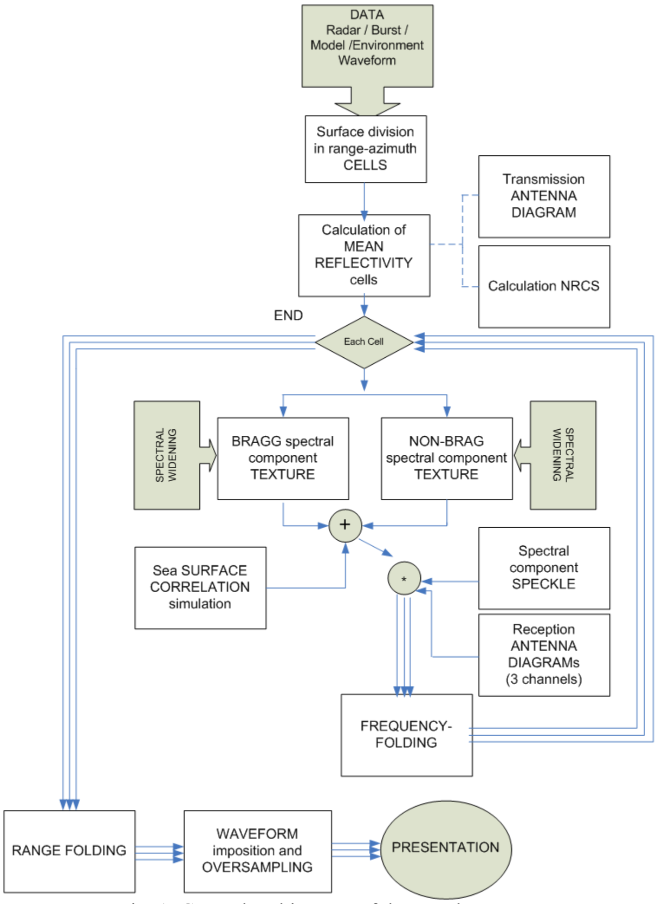

Fig. 1: General architecture of the sea clutter generator

The temporal signal is obtained through the inverse FFT in the azimuth direction. Finally range-folding is applied in the time domain and impose the transmitted waveform, by convolving it with the ambiguous range-pulses matrix in the direction of range and summing final transient of a pulse to the beginning of the following one.

III. MAPPING PROCEDURE

The surface of the sea is divided in resolution cells and all the scatterers within each cell are modelled as a single point scatterer located in its centre with amplitude described by the K distribution and a given spatial and time correlation. A rectangular sampling grid in distance and azimuth with the following sampling criteria is proposed:

A. Sampling in Distance

This criterion is the most demanding in terms of computational load when a suitable reproduction of the interference due to the sidelobes of the pulse compression waveform is aimed [1]. A cell resolution half the size of the radar range resolution may be a good trade-off solution.

B. Sampling in Azimuth

Uniform sampling in azimuth is preferred to isodoppler contours. It is very simple to impose the presence of a sample at the maximum Doppler frequency of the sea clutter with azimuth samples, which avoids undesirable power losses, unlike with isodoppler contours. The uniform sampling in azimuth justifies the assumption of a stationary Doppler spectrum due to sea surface movement. The second aspect that must be taken into account in respect to sampling in azimuth is the correct simulation among the three channels: sum, difference and guard. Due to the fact that antenna diagrams of sum and difference channel are practically orthogonal; the sampling rate must be high enough with respect to the antenna beamwidth. Simulations with four samples per antenna bandwidth (3dB) give satisfactory results.

C. Doppler Condition

A minimum condition in the azimuth sampling is imposed so that there is at least the contribution of one azimuth-cell in each Doppler bank filter. In order to reduce the computational load, it is possible to divide the surface in to two regions [1]: "sidelobe" where the surface clutter entering antenna through sidelobes are important and the "mainlobe" where clutter power entering antenna sidelobes are negligible. In the sidelobe region only three ambiguous ranges have been simulated, while in the mainlobe region all ranges up to the horizon have been considered.

Once the surface is divided in patches, the discrete spectrum for each patch is simulated separately and summed in the non-ambiguous frequency range to form the clutter map, which consists of another rectangular grid with distance and frequency samples. The distance sampling criterion is the same used at the surface's division.

D. Sampling in Frequency

Two samples per frequency cell have been used in order to obtain enough samples in time to simulate transitional pulses and the effects of windowing in the time domain. The width of the frequency cell is determined by the quotient of the PRF and the number of pulses processed in a coherent burst.

IV. MEAN REFLECTIVITY

The RF power returned by a surface cell of incremental area *dA* is given by the two-way radar equation:

$$\mathrm{dC} = \frac{P_T \lambda^2 G^2(\theta,\phi)\sigma_0(\theta,\phi)dA}{(4\pi)^3 L R^4} \qquad (1)$$

where P_T (W) is the transmitted RF power, $\lambda(m)$ the wavelength of the transmitted signal, G the one-way power gain of the antenna, σ_0 (m^2/m^2) the normalized cross section of the incremental area, L the factor of system losses, $R(m)$ the distance from the radar to the centre of the cell and θ and φ the azimuth and elevation in the antenna coordinate system.

As the distance to the cell is much larger than the resolution of the cell, R, G and σ_0 can be considered constant within the cell (values will be taken at its centre).

A. Normalised clutter radar cross-section (NRCS)

We use the model TSC (Technology Service Corporation) [6] to describe the mean reflected clutter power for low and medium grazing angles. Furthermore, a specular component [1] for high grazing angles has been added, which corresponds to the altitude line echo. The TSC model offers several advantages over other models such as GIT or SIT: it is also valid for grazing angles closed to 90º (of special relevance with airborne radar) and includes anomalous propagation data. It considers the variation of the reflectivity with the relative angle of line of sight and the wind as well.

B. Coordinate System Transformations

The radiation pattern of the antenna is usually given as function of the azimuth and elevation in respect to its central point, while mean reflectivity depends on the elevation angle of the cell respect to the radar. That is why cell coordinates (R, azimuth) should be transformed into radar elevation and antenna coordinates.

V. K DISTRIBUTION

There are various models to describe the sea backscatter probability function, e.g. Weibull or Log-normal, but the compound K distribution [6] [5] has become perhaps the most popular one since higher spatial resolution radars have been used. Not only has it been proven to fit real sea data, but is also held by an underlying physical scattering model.

$$\mathrm{K} = speckle \cdot \sqrt{texture} \tag{2}$$

$$\mathrm{f}_{\text{text}}(x) = \frac{b^{\nu}}{\Gamma(\nu)} x^{\nu-1}.\exp(-bx) \qquad 0 \le x \le \infty \tag{3}$$

$$\mathrm{f}_{\text{spec}}\left(E \big/ x = 1\right) = \frac{2E}{x}.\exp\left(-E^2 / x\right) \qquad 0 \le E \le \infty \tag{4}$$

The K-distribution is defined by the product of two components: the speckle and the texture. The sea texture can be modelled as a space-correlated Gamma distributed variable, with two spectral components and the mean power given by the reflectivity map.

A. Texture Generation

The spatial correlation of the texture depends on the physical correlation of the sea surface height. Due to that fact a statistical dynamical model has been used to generate sea surface height. Good models of the height of the sea surface for different environments exist, such as, Pierson-Moskowitz or Phillips spectra among others. These models consider the surface as a Gaussian bidimensional correlated process whose aspect depends on the direction and velocity of the wind. Since the texture consists of the returns coming from the capillary waves, it is expected to fit to the surface's correlation.

Therefore the method to simulate the correlated texture is based on the generation of a Gaussian bidimensional time-variant process with zero mean and unit variance and space autocorrelation given by the movement of the sea surface. This process is then filtered through a MNLT, which transforms the distribution density of the process from Gaussian to Gamma without significant changes on its autocorrelation. The relation of the input and output correlations of the filter is almost linear [8] and the correlations of the surface and the texture can be considered the same with $\nu > 1$.

Due to computational efficiency, only a small area of the sea surface is generated and repeated in space to complete the area covered by the airborne radar. The repetition distance of the small area should not be a multiple of the PRF to preclude the artificial creation of discontinuities when they are joined.

The Gamma distribution of the texture has two parameters: the shape parameter (ν) and the scale parameter (b). The shape parameter can be determined by the empirical model described in [9]:

$$\log_{10}(\nu) = \frac{2}{3}\log_{10}(\varphi_g) + \frac{5}{8}\log_{10}(A_c) - k_{pol} - \frac{1}{3}\cos(2\theta) \tag{5}$$

where φ_g is the grazing angle, A_c the cross resolution in distance, θ the angle between the antenna mainlobe and the wind direction and k_{pol} takes the value 1.39 for vertical polarization and 2.09 for horizontal.

The scale parameter can be expressed as a function of the shape parameter and the mean reflectivity calculated in the previous section:

$$b = \frac{\nu}{dC} \tag{6}$$

B. Doppler Spectrum

The movement of the waves causes the widening of the clutter spectrum inside a resolution patch. There are three reflection mechanisms [5] which contribute to the spectrum return and are called: Bragg, Burst and Whitecap.

Bragg events are the result of gravity-capillary waves caused when the wind blows over the surface. Burst events appear when waves are about to break in the look direction of the radar, whereas Whitecap matches the ripple generated after waves break.

As Burst events are dispersed impulses which can be simulated separately as punctual clutter randomly distributed, a two component spectrum model, such as the suggested in [9], can be adequate for sea clutter. This model is compounded by 2 Gaussian functions combined in the following way:

$$S(f) = x\frac{a\hat{S}(f,\sigma_0,f_0) + x\hat{S}(f,\sigma_1,f_1)}{a+x} \tag{7}$$

where $\hat{S}(f,\sigma_0,f_0)$ is the Bragg component and $\hat{S}(f,\sigma_1,f_1)$ the Whitecap. The parameter a has been adjusted to the mean of the Gamma variable of the cell $a=E\{x\}=\nu/b$ and x the correlated Gamma variable. The spectrum is normalized so that its integration equals the power of the texture x.

This model has the advantage of associating local spectrum width with the echo amplitude. Measurements have demonstrated that the sea clutter spectrum has no spatial constant width and that this width is related to local clutter amplitude (cells with more amplitude have a wider spectrum) [7].

If the Doppler shift corresponding to the geometry of the patch with the airborne platform is added to the Doppler shift of the Bragg and Whitecap components given by [5], each spectral component can be defined as:

$$\hat{S}(f,\sigma,\Omega)=\frac{\exp\left(-\left(f-\Omega\cos\theta_v-f_D\right)^2/2\sigma^2\right)}{\sqrt{2\pi\sigma^2}} \qquad (8)$$

where θ_v is the angle between the moving direction of the radar and the wind on the horizontal plane, f_D the Doppler shift of the patch due to platform movement, σ^2 the variance and Ω the frequency shift of the component (f_0 or f_1).

References [5] and [9] give estimations of the parameters Ω and σ^2 of the Doppler components. Because of the similarity in the application field, results in [9], which were collected from an airborne platform, have been considered. Nevertheless, the spectra widths should be broadened by the Doppler spectrum of the moving antenna pattern:

$$\sigma_T^{\,2}=\sigma_0^{\,2}+\sigma_{\exp}^{\,2} \qquad (9)$$

$$\sigma_{\exp}^{\,2}=\frac{\log(2)}{2\cdot\left(\pi.\dfrac{\Delta\theta_a}{v_{\exp}}\right)^2} \qquad (10)$$

where $\Delta\theta_a$ is the radar resolution in azimuth in º and v_a the scan velocity of the antenna in º/s.

VI. Range and Doppler Ambiguities

A sea clutter simulator of a MPRF mode must be able to enforce both range and frequency ambiguities. Due to memory limitations and in order to avoid the use of long frequency vectors, the frequency folding is applied directly to the spectra of individual patches. Afterwards the spectral contributions of all the patches at the same range and non-ambiguous frequency samples are summed.

The next step consists of the application of the range-folding. Since the ambiguous echo has been generated in the frequency domain, the echo is first transformed into the time domain through an IFFT in the Doppler coordinate and range-folding is then applied.

VII. Results

As an example, the results of a simulation for the sum, guard and difference channels (figures 2, 3 and 4) have been presented. The platform height is 3000 m and has a velocity of 46 m/s. The antenna is pointing to the horizon and the PRF is around 8 KHz.

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References

[1] R. L. Mitchell, "Radar Signal Simulation," Artech House, 1976.

[2] A. L. Friedlander, L. J. Greenstein. "A generalized clutter computation procedure for airborne pulse doppler radars". IEEE Transact. AES. January 1970.

[3] P. E. Laurence, A. P. Szabo. "Clutter Simulation in Maritime Environments". IEEE Radar conference, 2003.

[4] A. P. Szabo. "Clutter Simulation for Airborne Pulse-Doppler Radar". IEEE Radar conference, 2003

[5] D. Walker, "Experimentally motivated model for low grazing angle radar Doppler spectra of the sea surface," IEE Proc. Radar, Sonar and Navigation, vol. 147, pp. 114-120, 2000.

[6] I. Antipov. "Simulation of Sea Clutter Returns". DSTO-TR-0679 report, 1998.

[7] K. D. Ward, R. J. A. Tough, S. Watts, "Sea clutter: Scattering, the K Distribution and Radar Performance," Institution for Engineering and Technology, 2006.

[8] R. J. A. Tough, K. D. Ward. "The correlation properties of gamma and other non-Gaussian processes generated by memoryless nonlinear transformation".J. Phys. D: Appl. Phys. 32 (1999).

[9] L. Rosenberg, N. J. Stacy, "Analysis of Medium Grazing Angle X-band Sea-clutter Doppler Spectra," IEEE Radar Conference, 2008, RADAR '08, pp. 1-6.

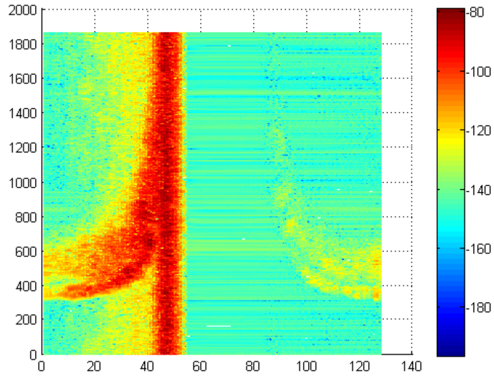

Fig. 2 Ambiguous Doppler-RangeMatrix of Sum Channel

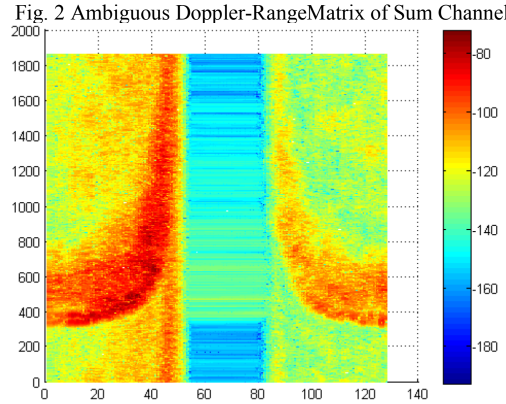

Fig. 3 Ambiguous Doppler-Range Matrix of Guard Channel

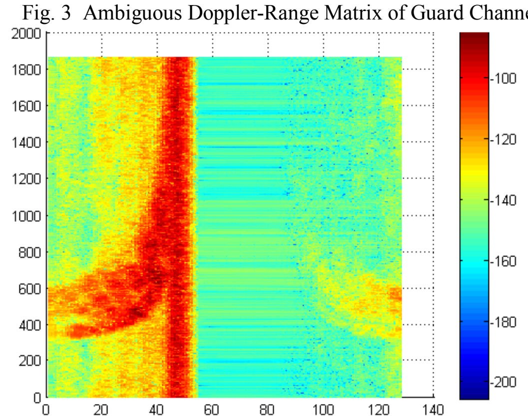

Fig 4. Ambiguous Doppler-Range Matrix of Difference Channel