THE DETERMINATION OF THE SEA SURFACE NRCS WHEN CORRUGATED BY BLOWING WIND AND RAINFALL: AN APPLICATION TO RAINFALL RATE MEASUREMENTS OVER SEA

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ABSTRACT

The prediction of the power backscattered by the sea surface in the presence of rainfall is the object of this paper. An electromagnetic (e.m.) model predicting Normalised Radar Cross Section (NRCS) of such surface, must conveniently account for both a large scale roughness roughness due to wind and a small scale roughness due to raindrop splashes. While several models are available in the literature for wind-induced roughness, only few experimental results or theoretical studies concerning additional rainfall-induced roughness are available. Here we describe an e.m. model that accounts for the effects of the raindrop splashes, and discuss some related results. An improved algorithm is then proposed here for retrieving rainfall rate profiles by means of spaceborne rain radars, which utilises the relationship between sea NRCS and rainfall rate.

INTRODUCTION

Knowledge of global precipitation is essential for understanding Earth's climate and its changes. Observation of rainfall over the sea/ocean surface is of great importance for such purpose: for this reason, remote sensing methods for improving rainfall rate estimates over ocean surface are becoming of increasing interest. Determining the backscattering properties of the sea surface accounting for additional perturbation due to rainfall is useful for improving techniques so far proposed in the literature for estimating rainfall intensity over the sea surface when using a spaceborne rain radar. For such an objective, suitable e.m. models to represent and evaluate effects of rain perturbation on the NRCS of sea surface are needed.

Signals backscattered from the sea surface are random processes depending on several physical phenomena, but mainly on wind and rainfall induced corrugation. While the influence of wind on sea NRCS has been investigated in depth, the same did not happen for the effects of rainfall; though, it was shown by Bliven et al. (1)-(2) that the influence of rainfall on the backscattering coefficient is not negligible. Therefore, in principle, once a suitable analytical model (possibly taking advantage of specific experimental results) is available to predict NRCS of the water surface in the presence of rainfall, then rainfall intensity could be retrieved simply by estimating the sea surface NRCS. Furthermore, such model may also help to improve inversion algorithms based on radar measurements and aimed at retrieving rainfall profiles, and to resolve interference between volumetric effects due to rainfall (backscatter and attenuation) and sea surface backscatter effects due to the same rainfall.

In this paper we first discuss the applicability of two different e.m. models for computation of such NRCS under the simplified hypothesis of saline water surface roughened by rainfall only. The chosen models are the Full Wave Model (FWM) by Bahar (3) and the Integral Equation Model (IEM) by Fung et al. (4), utilised jointly with the experimentally derived sea roughness frequency spectrum by Bliven et al. (2). The excellent agreement between the two models is shown by a compared analysis of the two models' results in Capolino et al (5).

FWM is the model utilised for the electromagnetic characterisation of the sea surface whean corrugated by both rainfall and blowing wind, under three simplifying hypotheses, i.e. that the total corrugation is the linear combination of that induced by rainfall and that due to the blowing wind; that the two corrugations are statistically independent; that the correlation length of the rainfall corrugation is much shorter than the wind corrugation.

As an applicative example, we present some results concerning rainfall rate retrieval in the proximity of the sea surface. Rainfall rates are estimated by comparing radar returns of two adjacent range cells (those closest to the sea surface). We show that a good guess of the sea NRCS can be profitably exploited for improving such estimates based on spaceborne rainfall radar measurements.

PHYSICAL CHARACTERISATION OF THE SEA SURFACE

Let us consider a sea surface corrugated by wind and by the effects of raindrop splashes. It has been shown that the crown and stalks phases, following raindrop splashes, are important features to be considered for analysing backscattering near grazing incidence angle, while ring waves are important for backscattering at incidence angles near nadir (see Bliven et al. (1)). Here we consider only ring waves, and model them as a random process with characteristics similar to those of waves generated by wind.

Surface roughness induced by rain

The roughness of the water surface is modeled through a Gaussian height distribution, with variance $h_R^2(rms)$. Suppose then that the kinetic energy of the falling drops is transferred in its greatest part to the water surface to generate ringwaves. An approximate relationship between the variance $h_R^2(rms)$ and the rainfall rate, can thus be obtained referring to experimental results carried out with artificial rain reborted by Bliven et al. (1). In such experiments, a fixed raindrops size (2.8 mm diameter) was used with drops falling from 1 meter above the water surface, thus hitting the water surface with a lower velocity then the terminal velocity of real rain. Trying to extrapolate in some manner such results to the real case of raindrops falling with their true terminal velocity, we resorted to some energetic considerations based on the assumption that a linear proportionality relationship exists between the kinetic energy and the mean square height of the surface, and that it is independent on the type of rainfall. In order to obtain a relationship between the rms height of the water surface and rainfall intensity accounting for terminal velocity of raindrops, we considered two models of Drop Size Distribution (DSD):

a) a Dirac delta-shaped DSD centred on a fixed diameter of 2.1mm, which is close to the average real DSD maximum (see Bliven et al. (1))
b) a Marshall-Palmer DSD.

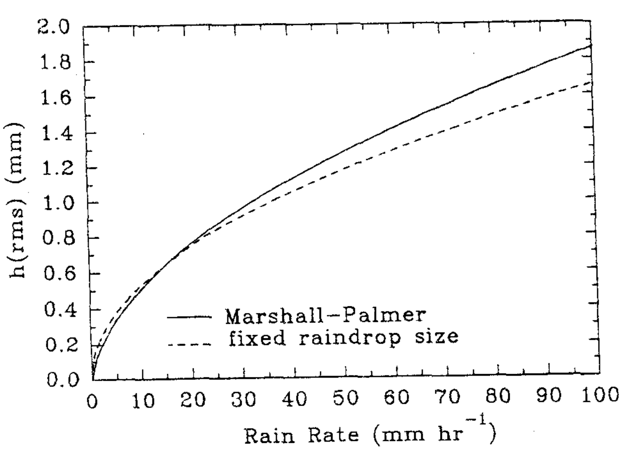

Fig. 1. Rainfall rate versus root mean square height $h_R(rms)$ of the water surface roughness. Continuos curve refers to a Marshall-Palmer DSD model, dashed curve to rainfall with costant diameter raindrops.

It is reasonably believed that the above simplifying assumptions hold for 'normal' rainfall rates (R <100 mm/h): Fig. 1 reports the rms height h(rms) versus rainfall rate obtained according to the aforementioned hypotheses. Examining Fig. 1 it can be concluded that both DSDs considered lead to quite similar results, and that the rainfall intensity-rms height relationship obtained as above is not very sensitive to the adopted DSD model.

In order to provide a complete characterisation of the water surface, intrinsically able to relate surface physical parameters to NRCS, we adopted the ring wave frequency spectrum described by Bliven et al. (2), converting it to the ring wave wavenumber spectrum - more suitable for e.m. models.

Surface roughness induced by wind

The contribution of blowing wind to total roughness is modelled as a zero mean Gaussian height distribution process. Two different wavenumber spectra were then considered: an approximated Pierson-Moscowitz spectrum as reported by Brown (6) and those reported in the more recent paper by Apel (7). The distribution of the local surface slope has also been assumed as zero mean Gaussian distribution with variance calculated as in the papers by Bahar (3) and Bahar and Kubik (8), integrating the wavenumber spectrum.

E.M. MODELING OF THE SEA SURFACE

Being our objective an accurate and complete polarimetric description of the sea echo when the surface is corrugated by two statistically independent phenomena (wind and rain), we considered the e.m. model described by Bahar (3). We assumed that roughness derives from the superposition of two statistically independent random processes induced by rainfall and wind. Roughness contribution due to wind and rainfall will be hereafter referred to as the large and small scale process, respectively.

The height standard deviation $h_R(rms)$ for the small scale process is of the order of a few millimeters, and its correlation length of the order of a few centimeters. Considering the values for the wind roughness given by Bahar (3) and Apel (7), it can be easily verified that the average radius of curvature of the rain roughness is much larger than that of the wind roughness. If L_R and L_W are the correlation lengths of the roughness due to rain and to the wind, respectively, we have $L_W >> L_R$. Under these hypotheses, the small scale process 'rides' the large scale process.

As shown by Bahar and Kubik (8), when the mean slope is low, height distribution and slope distribution can be considered independent, which leads to a simplified formula for the NRCS. This is then calculated by means of a statistical average over the slopes and over the heights. The total NRCS σ is then written as in Capolino et al. (9):

$$\sigma^{pq} = \int_{\bar{n}} A(\bar{n}^f, \bar{n}^i, n) Q(\bar{n}^f, \bar{n}^i, n) p(\bar{n}) d\bar{n} \quad (1)$$

where

$$Q(\bar{n}^f, \bar{n}^i, \bar{n}) = \left|\chi^R(\bar{v}\cdot\bar{n})\right|^2 Q_W(\bar{n}^f, \bar{n}^i) + \\ + (\bar{n}\cdot\bar{a}_y) Q_R(\bar{n}^f, \bar{n}^i, \bar{n}) \quad (2)$$

The symbol pq reresents the arbitrary polarisation of incident and radiated waves (H,V) and the symbols we adopted are those defined by Bahar (3). The term $A^{pq}(n^f, n^i, n)$ includes the Fresnel reflection coefficients. The terms $\left|\chi^R(\bar{v}\cdot\bar{n})\right|$ and $Q_{W,R}$ account for the statistics of the phase of the e.m. wave determined by the height distribution of the rough surface induced by wind and rain corrugations, respectively. Their expression are reported by Bahar (3). The integration with respect to $\bar{n}$ means that the result is averaged along the slopes of the large scale surface due to the wind ($\bar{n}$ is the local normal to the large scale surface, and $p(\bar{n})$ is the Gaussian pdf of slopes). Notice that $Q_R(n^f, n^i, n)$ is weighted by the slope of the large scale surface while Q_W is not because, as mentioned above, it is assumed that the small scale corrugation rides the large scale corrugation. This corresponds to computing the ring waves contribution by means of a statistical average over the slopes of the wind roughened surface. Shadowing effects were not considered, since they are not relevant for observation angles close to nadir.

SEA SURFACE NRCS BEHAVIOUR

In order to verify in first place the applicability of the FWM to the case of interest and, secondarily, the validity of the physical characterization of the sea surface, we compared the NRCS obtained by the FWM with that obtained by the Integral Equation Model (IEM) by Fung et al. (4) and by Capolino et al. (5) in the case of corrugation induced by rainfall only, and with experimental results in the case of corrugation induced by wind only. In the first case, considering only ring waves, the sea surface NRCS predicted by FWM is in a very good agreement with that predicted by IEM for several rms heights $h_{R(rms)}$ and incidence angles that have been considered. In the second case (wind corrugation only) we compared the predicted NRCS with the experimental results from Schroeder et al. (10) referring to 13.9 GHz (Fig. 2). Indeed, measurements values are taken from the regression line in Scroeder et al. (8). The curves relative to nadir incidence for some wind speeds refer to the two wavenumber spectra considered, namely the approximated Pierson-Moskowitz and that reported by Apel (7). The measurements have been carried out in two distinct experiments. As expected, the Apel spectrum fits better the actual NRCS behaviour. Notice that the calculated NRCS is slighly greater than the measured one. Also Schroeder et al. (10) noted this effect by comparing their measurements with the SASS I model, and couldn't explain it. However, this difference is of the order of the uncertainity of the measurements, and could also be imputed to the Apel spectrum. The approximated Pierson-Moskowitz spectrum is not so accurate for nadir incidence, however we have found that, off from nadir, its prediction is in rather good agreement with the experimental results.

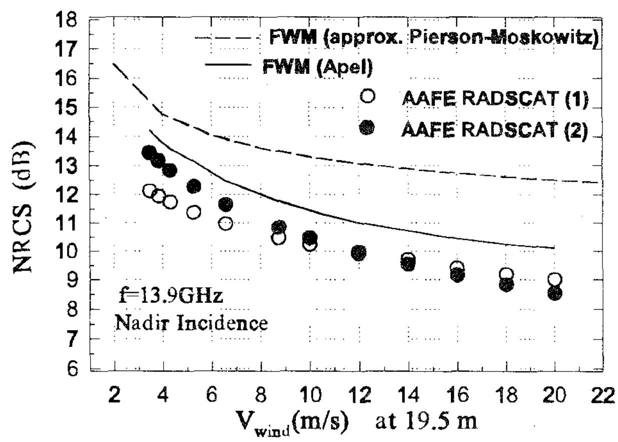

Fig. 2. NRCS versus wind velocity for nadir incidence: comparison between experimental data and the results obtained using models based on a Pierson-Moscowitz spectrum and on an Apel spectrum. Frequency: 13.75 GHz.

The following results refer to a frequency of 13.75 GHz, and to a wind speed of 4.3 m/s as in Bahar and Fitzwater (11). Surface corrugation due to rainfall is described in terms of standard deviation $h_{R(rms)}$. Indeed, h_R is related to the rainfall rate R through the approximated law plotted in Fig. 1. Nevertheless, an accurate description of such relationship is not available in the literature: for this reason, we have simply chosen h_R as the parameter describing sea roughness and rainfall intensity; one can obtain the NRCS as a function of h_R using Eqs. (1) and (2). In Fig. 3, the VV NRCS response is plotted versus incidence angle in the absence of rainfall, and in the case that additional perturbation due to rainfall is present, for different values of the surface roughness. When increasing rainfall intensity (increasing $h_R(rms)$), a decrease of the NRCS is correspondingly obtained for incidence angles close to nadir; this phenomenon can be observed for all incidence angles ranging from 0° to 10°. On the other hand, at incidence angles ranging from around 10° to 35 ° an opposite behaviour is evident, i.e. for increasing intensity a corresponding increase of the sea surface NRCS shows up, as also observed in the laboratory experiment described by Bliven et al. (1). At this frequency, NRCS is rather sensitive to rainfall intensity.

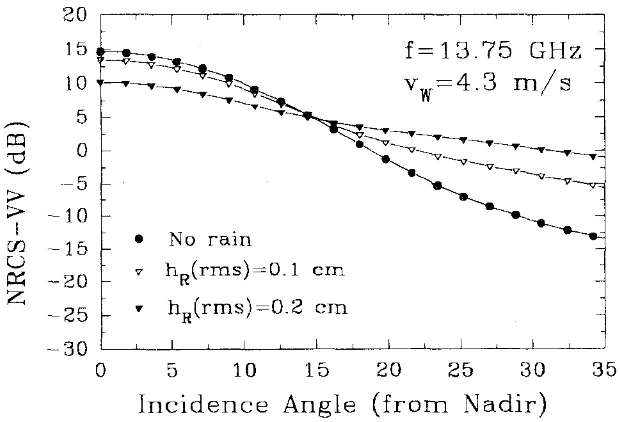

Fig. 3 VV NRCS response versus incidence angle, for some values of the rainfall induced corrugation

In Fig. 4 we report the sea surface NRCS versus rainfall rate *R* for some wind speeds and nadir incidence obtained using the more accurate spectrum described by Apel (7).

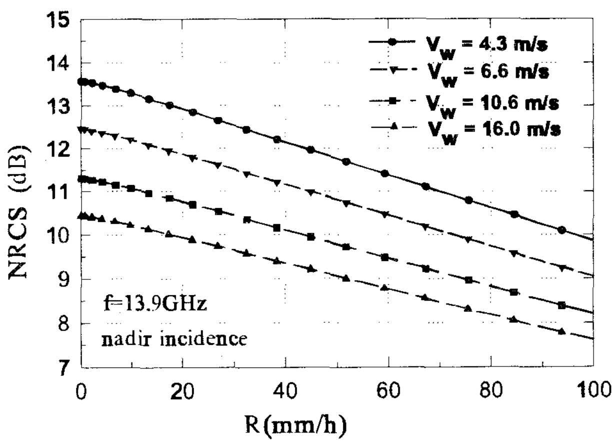

Fig. 4. NRCS copolar component, obtained based on an Apel spectrum, versus rainfall rate R for various wind velocities. Frequency: 13.75 GHz, nadir-incidence.

Notice that the variations ascribable to rainfall rate are of the same order of magnitude as those due to wind speed: this justifies the inclusion of rainfall induced corrugation in the e.m. model. We did not account for damping of sea waves that may become relevant in the presence of heavy rainfall, causing an increasing of the NRCS at nadir incidence (see Durden et al. (12)).The combined effects imputable to rainfall - damping of the sea wind waves and corrugation due to the impact of the raindrops on the surface - deserve further investigation for understanding backscattering behaviour under severe rainfall conditions.

THE "TWO-CELLS" METHOD

The dependence of the sea surface NRCS at nadir incidence on rainfall rate can be exploited in spaceborne rain radars to estimate rainfall rate at sea level by comparing power echoes from the first two contiguous radar range cells above the sea surface. Jointly with rainfall rate, also the value of sea surface can be obtained. Due to the powerful sea echo return, surface backscatter prevails in the first cell, while the second cell gives rise only to volumetric backscatter. If P_1 and P_2 are the mean echo powers from the first and second cell, respectively a simple relation is obtained providing sea NRCS under the hypothesis that rainfall rate R is the same in both cells:

$$\sigma_s(R) = \frac{P_1 C}{P_2 C_s} \alpha \cdot K(R)^{\beta} \cdot e^{0.46 \Delta r K(R)} \qquad (3)$$

where the dependence from rainfall rate is explicitly pointed out in $\sigma_S(R)$, and *K(R)* is the attenuation factor for propagation in rainfall. Assuming that the relationship $\sigma_S(R)$ is known, *R* can be computed by estimating P_1 and P_2. The key point of this inversion is that *K(R)* and $\sigma_S(R)$ exhibit opposite trends with respect to R. In Fig. 4 we report the result of a numerical simulation concerning the estimation of $\sigma_S(R)$ as a function of a simulated rainfall rate *R*.

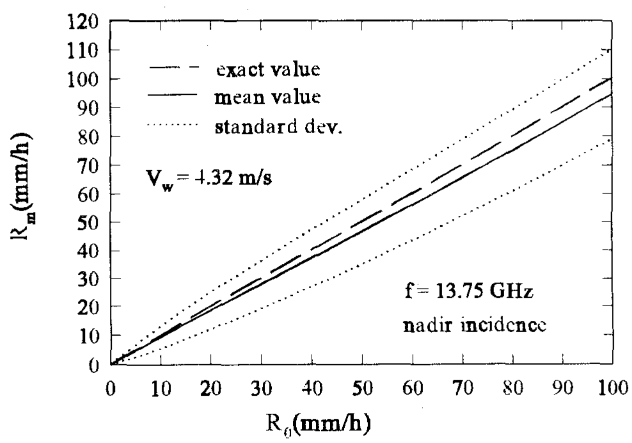

Fig. 5 Results of the "two cells" method: mean value and standard deviation of the statistics of the 'estimated' versus the 'true' rainfall rate at sea level.

The numerical simulation is performed by numerically solving Eq. (3) with respect to R, considering α as a random process and random errors in the relationships *K(R)* and $\sigma_S(R)$ as in Marzoug and Amayenc (12) with the mean value of the random process $\sigma_S(R)$ obtained by means of Eq. (1).
In Fig 5, the continuos and dashed lines represent the mean value and the standard deviation of 'estimated' rainfall rate at sea level, based on a statistical sample of 100 simulated estimates. Once the rainfall rate R has been estimated at sea level, it can be used as the starting value in the *k*ZS algorithm described in Marzoug and Amayenc (13), aiming at extracting the vertical rainfall profile.

CONCLUSIONS

By presenting a model that describes the effects of the additional roughness induced by rainfall over a sea surface with blowing wind, it has been shown that such effects on NRCS can not be considered as a side issue in the backscatter mechanisms. A full polarimetric description of the radar echo is thus possible, that can be utilised for rainfall rate retrieval at sea level or to overcome some of the inherent ambiguities associated with the algorithms designed for rainfall profile retrieval over the sea surface: one example has been given by means of a simple method that, exploiting two power measurements at nadir incidence, provides an estimate of rainfall rate at sea level. The same model and results could also be exploited to evaluate algorithms for scatterometer wind speed computation, in order to cancel the bias introduced by the rain roughness contribution.

Acknowledgments

This work has been partially supported by the Italian Ministry for University and Scientific and Technological Research, and by the Italian Space Agency.

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