Title

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Abstract -- The problem of improving estimates of rainfall intensity over the sea surface through spaceborne rain radars is addressed. The backscattered signal is composed of volumetric contribution due to rainfall and of the sea surface contribution. When trying to estimate the NRCS of the sea surface, one of the major difficulties is that different scale of roughness of the sea surface should be accounted for in the same e.m. model: the larger due to wind and the smaller due to the raindrop splashes. While in the first case several models are available in the literature, in the second case only a few experimental results or theoretical studies are at disposal. In this paper, a model which accounts for the additional roughness due to the effects of the raindrop splashes is analysed. Furthermore, an enhanced algorithm is proposed here for retrieving rainfall rate profiles, which utilises the relationship between sea NRCS and rainfall rate.

INTRODUCTION

Retrieval of rainfall intensity over sea surface by means of spaceborne rain radars is getting increasing importance for monitoring environmental parameters on a global scale. Let us consider a downward-looking spaceborne rain radar operating at attenuating frequency. One drawback of attenuation retrieval techniques is the heavy additional attenuation due to the possible presence of the melting layer, that is not easy at all to predict and model.

One of the most utilised class of algorithms considers the case of a single wavelength radar. It has been shown that surface the referenced technique (*k*ZS) performs generally better than other single frequency methods [1], but it is based on the knowledge of σ_S (Normalized Radar Cross Section, NRCS, of the sea surface), which is commonly predictable only very approximately. It becomes essential to determine the NRCS of the sea and how it is influenced by the surface corrugation induced by rain. In order to obtain an e.m. formulation to predict the NRCS that takes into account of both the roughness contribution induced by the effects of wind and raindrop splashes, the Full Wave Model (FWM) for rough surface is considered [2]. It will be shown that at C-band the additional effects of the rain are negligible respect to those of wind, thus the NRCS at C-band could be utilised to retrieve the corrugation parameters due to wind. It will be shown that the Ku-band is sensitive to the induced corrugation of the rain and its behaviour when varing the rainfall rate *R* is predicted and utilised in rain rate retrieval. Due to the strong sea return, the modified σ_S alone permits rainfall rate retrieval directly by means of differential echo measurements pertinent to the first two range cells above the sea surface. At nadir, for example, the first range cell is substantially affected only by the sea echo (that is much powerful than the volumetric one present in the same range cell), while the second range cell is affected only by the volumetric echo due to rainfall. The two power measurements relative to the two different cells show opposite behaviours with respect to the variation of the rainfall rate, thus allowing the estimation of rainfall rate at sea level directly by comparison.

E.M. MODELING OF 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 [3]. In our case, only ring waves have been considered, and been modeled as a random process with characteristics similar to those of the waves generated by wind. Since our purpose was an accurate and complete polarimetric description of the sea radar return when corrugated by two statistically independent phenomena (wind and rain), we considered the e.m. model described in [2],[4]. We assumed that roughness is due to the superposition of the two random processes due to rain and wind. The roughness due to wind and to rain will be referred to as large scale and small scale phenomenon, respectively.

As a preliminary example, for the sea surface roughened by wind we resorted to the Pierson-Moscowitz spectrum as in [2], with a zero mean Gaussian surface height distribution. The distribution of the local surface slope has also been assumed as zero mean Gaussian, like that used for the height of the surface roughened by rain, assumed as a random process with a wavenumber spectrum as that yielded from experimental results given in [5].

The height standard deviation h_R(rms) for roughness due to rain is of the order of a few millimeters, and its correlation length of the order of a few centimeters. Under these hypotheses, and considering the values for the wind roughness given in [2], it can be easily verified that the average radius of curvature of the rain roughness is much larger than that of the wind roughness. The NRCS has been calculated by means of a statistical average over the slopes and over the heights. Indicating with L_R and L_W the correlation lengths of the roughness due to rain and to the

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wind, respectively, we have $L_W >> L_R$. Assuming also the two random processes as statistically independent, we can write the total NRCS σ_S as the sum of two NRCS:

$$\sigma_S^{pq} = \sigma_W^{pq} + \sigma_R^{pq} \tag{1}$$

where

$$\sigma_W^{pq} = Q_W(\bar{n}^f, \bar{n}^i) \int_{\bar{n}} A^{pq}(\bar{n}^f, \bar{n}^i, \bar{n}) \cdot \left|\chi^R(\bar{v} \cdot \bar{n})\right|^2 p(\bar{n}) d\bar{n} \tag{2}$$

and

$$\sigma_R^{pq} = \int_{\bar{n}} A^{pq}(\bar{n}^f, \bar{n}^i, \bar{n}) \; (\bar{n} \cdot \bar{a}_y) \cdot Q_R(\bar{n}^f, \bar{n}^i, \bar{n}) p(\bar{n}) d\bar{n} \quad . \tag{3}$$

The term σ_R^{pq} is the NRCS contribution of the wind roughness perturbed by rainfall, σ_R^{pq} is the NRCS contribution due to rainfall, *pq* is the arbitrary polarisation of incident and radiated waves (H,V); the symbols we adopted are those defined in [4], in particular the term $A^{pq}(\bar{n}^f, \bar{n}^i, \bar{n})$ 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 and their expression are in [4]. The integration in the variable $d\bar{n}$ means that the result is averaged along the slopes of the large scale surface due to the wind. Notice It is important to note that the terms $Q_R(\bar{n}^f, \bar{n}^i, \bar{n})$ in the σ_R^{pq} component are weighted by the slope of the large scale surface. This corresponds to compute the NRCS component corresponding to the ring waves by means of a statistical average over the slopes of the surface roughened by the wind.

SEA NRCS BEHAVIOUR AT C- AND Ku-BAND

Some preliminary numerical results of the NRCS computations are discussed in the following for the frequencies of 5.6 and 13.75 GHz. Wind speed is supposed to be 4.3 m/s as in [2]. Surface roughness due to rainfall is described in terms of standard deviation h_R(rms). Indeed, h_R is related to the rainfall rate R, by the approximated law

$$h_R(\mathrm{mm}) = 0.1631\sqrt{R(\mathrm{mmh}^{-1})} \tag{4}$$

calculated through the graph in [3] obtained for an artificial rain falling from 1m height and using energetic consideration in order to find the relationship for raindrops falling at terminal velocity. Nevertheless, an accurate description of such relationship is not available in the literature, and 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 the formula (4).

In Fig. 1 the VV component of the NRCS at 5.6 GHz 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 h_R(rms) of the surface roughness. At this frequency, the NRCS of the sea is strongly dependent on sea wind conditions, while it is slightly dependent on rainfall intensity as shown by the Figure.

In Fig. 2 the VV component is plotted at a frequency of 13.75 GHz. 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 trend is present, i.e. for increasing intensity an increase of the sea surface NRCS shows up, as also observed in the laboratory experiment described in [3]. At this higher frequency, the NRCS is rather sensitive to rainfall intensity.

We point out that using the results for small incidence angles at C-band, it is possible to extract the component of the surface roughness only due to the wind. On the other hand, when the wind condition are known, at Ku band we can predict the roughness due to the corrugation induced by rain.

TWO-CELL ALGORITHM

The variation at nadir incidence of the NRCS of the sea surface can be utilised to compute the rainfall rate at sea level by comparing the first two contiguous range-cells above the sea surface. From that comparison the rain rate and the value of the NRCS of the sea surface can be obtained. Due to the powerful sea return, sea backscatter prevails in the first cell, while in the second cell only rainfall backscatter is present. If P_1 and P_2 are the powers of echoes referred to the first and second range cell, respectively, a simple relation is [6]:

$$\sigma_s(R) = \frac{P_1 C}{P_2 C_s} \alpha \cdot K(R)^{\beta} \cdot e^{0.46 \Delta r K(R)} \tag{5}$$

where *R* is the rainfall rate, $_s(R)$ is the NRCS of the sea surface depending on the rainfall rate and *K*(R) is the attenuation factor for propagation in rainfall. Knowing the dependence of the NRCS as a function of the rainfall rate, it is possible to compute *R* by means of the ratio between the two power measurements P_1 and P_2 . The key point of this inversion is that *K*(R) and $\sigma_s(R)$ have an opposite trend with respect to rainfall rate variations. In Fig. 3, a numerical simulation that rapresent the estimation of the $\sigma_s(R)$ as a function of a simulated rainfall rate *R* is reported. The numerical simulation is performed by finding the zeros of Eq. (5) considering: α as a random process and random errors in the relationships *K*(R) and $\sigma_s(R)$ as in [1] with the mean value of the random process $\sigma_s(R)$ obtained by means of Eq. (1). In Fig 3, the continuos and dashed lines represent the mean value and the standard deviation of the solution of expression (5), respectively. The corresponding rainfall rate is found through Eq. (4). When the rainfall rate R is available at sea level, it can be used as the starting value in the *k*ZS algorithm, aiming at extracting the rainfall rate height profile.

CONCLUSIONS

Several models are available in the literature that characterise the sea surface interaction with e.m. waves, when such surface is roughened by wind. In this paper, a model that takes into account the additional surface roughness due to rainfall is considered, in order to achieve a full polarimetric description of the radar return. Results can be utilised for rainfall rate retrieval or to overcome some of the inherent ambiguities associated with the retrieval algorithms. These first results can already be utilised for a more detailed characterisation of the sea surface return. 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. An algorithm for rain rate retrieval is proposed; it is shown how theoretical relationships between the sea NRCS $_s(R)$ and the rainfall rate R can be exploited. Such information can be directly used to retrieve the rainfall rate at sea level by direct comparison between the power echoes pertinent to the two first range cells above the sea surface. This technique is independent of possible ambiguities, like that induced by the melting layer of precipitation, or by the attenuation factor along the path from the second cell to the radar.

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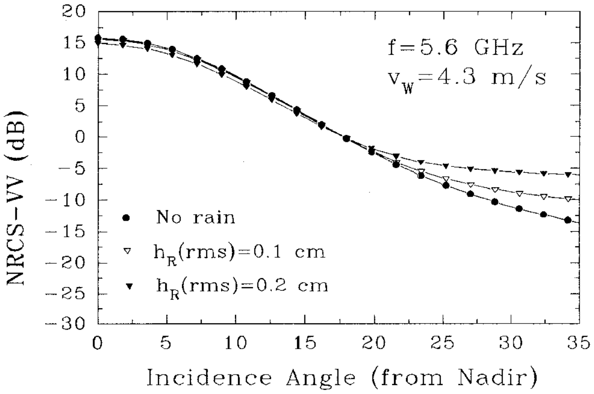

Fig. 1

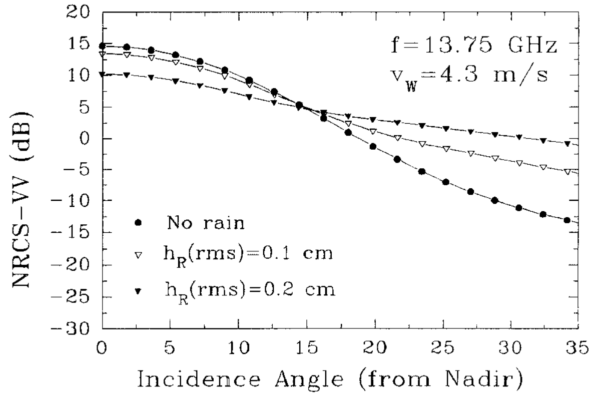

Fig 2

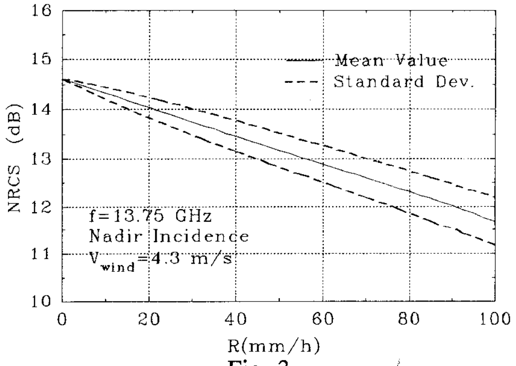

Fig. 3