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Authors

Capolino, F
Facheris, L
Giuli, D
et al.

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UTILIZATION OF RADAR BACKSCATTERING COEFFICIENT FROM SEA SURFACE IN RAINFALL RATE RETRIEVAL ALGORITHMS

F. Capolino^o, L. Facheris*, D. Giuli*, F. Sottili[†]

^oDipartimento di Ingegneria dell'Informazione, Università di Siena - Italy

*Dipartimento Ingegneria Elettronica, Università di Firenze - Italy

[†]Magnetek S.p.A. - Terranuova Bracciolini (Arezzo) - Italy

INTRODUCTION

Radar methods and data processing techniques for improving rainfall rate estimates over such surfaces are gaining increasing interest. Algorithms proposed for rainfall rate retrieval exploit backscatter or attenuation, as reported for instance by Iguchi and Meneghini (1). A fundamental drawback of attenuation-referenced techniques is the heavy and mostly unpredictable additional attenuation due to the possible - and likely - presence of the melting layer. Instead, surface-referenced techniques are generally more reliable, but they assume that the power backscattered by the sea surface is known with good approximation. Moreover, both kinds of techniques make use of relationships connecting specific attenuation to reflectivity: often such k - Z relationships are not fully representative of the real links among physical quantities involved.

A number of single frequency algorithms have been surveyed by Marzoug and Amayenc (2), each aiming to minimize the effects of some of the aforementioned errors. They showed that the surface-referenced algorithm referred to as kZS is potentially the most effective and stable, since it is not sensitive to calibration errors and to errors related to path integrated attenuation (PIA) above the rainfall top. Furthermore, when PIA increases, the errors' influence decreases. At low PIA values, the kZS algorithm becomes more sensitive to surface echo estimate (see also Marzoug and Amayenc (3)).

In this framework, it is reasonably expected that a well-grounded prediction of the backscattering behaviour of the sea surface when it is perturbed jointly by wind and rainfall can be usefully exploited to improve the kZS algorithm. To fulfil such prediction function, e.m. models are needed that suitably represent effects of rainfall on the NRCS (Normalised Radar Cross Section) of the sea surface. At this regard, it is opportune to mention that signals backscattered from the sea 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 effects of rainfall are not yet well assessed. However, Bliven et al. (4) showed that the influence of rainfall on the sea NRCS is not negligible.

In this paper, we first show that kZS performs at its best when uncertainty related to the sea surface NRCS is limited. Then, we suggest a possible kZS upgrade, based on the prediction of the NRCS of the water

surface roughened by both wind and rainfall. Such prediction relies on the Full Wave Model (FWM) by Bahar (5), which incidentally highlights the relevance of rainfall induced corrugation at the considered frequency (13.75 GHz). Results of numerical simulations - based on the same error model used in (3) - are finally presented, that confirm the potential of the upgraded algorithm.

THE KZS ALGORITHM

Consider a nadir looking spaceborne radar, operating at attenuating frequencies (between 5 and 40 GHz). The mean power of the rain echo from the volume centred at a distance r from the radar is proportional to the reflectivity factor $Z(r)$ and to the attenuation factor along the propagation path:

$$\overline{P(r)} = \frac{C}{r^2} Z(r) \exp \left[-0.46 \int_0^r k(s) ds \right] \quad (1)$$

where $Z(r)$ is the reflectivity factor, k (dB/Km) is the specific attenuation coefficient for propagation in rainfall and C is the radar constant accounting for system parameters. Analogously, the mean power backscattered by the sea surface ranging r_s is:

$$\overline{P_s(r_s)} = \frac{C_s}{r_s^2} \sigma_s(R) \exp \left[-0.46 \int_0^{r_s} k(s) ds \right] \quad (2)$$

where σ_s is the surface backscattering coefficient: notice that its dependence on rainfall rate R has been made explicit in Eq. (2). C_s plays the same role as C for the surface case (see (3)). In rainfall, Z and k are related by a standard empirical relationship:

$$Z = \alpha \cdot k^\beta \quad (3)$$

where α and β depend on frequency and Drop Size Distribution (DSD).

As suggested in (3), the kZS algorithm exploits the ratio $\overline{P(r)} / \overline{P_s(r_s)}$ to provide, through such standard reflectivity-attenuation relationship, the vertical profile of specific attenuation. The rainfall rate profile is in turn estimated by means of a frequency-dependent relationship of the kind $R(r) = a k(r)^b$. The power ratio instead of the absolute power is thus exploited, utilizing

the sea surface as the starting point in the integration of radar measurements that leads to the vertical attenuation profile estimate. This avoids bias errors such as those that could be brought by integrating power estimates from the melting layer, or absolute system calibration errors.

Simulations to validate the effectiveness of such rainfall profile retrieval algorithms need to account for

different errors and sources of uncertainty. Referring to the same error model described and utilized in (3), (in particular assuming β and α respectively constant and variable along the propagation path), we obtained the following final expression for the 'estimated' rainfall profile:

$$R_m(r) = R(r) \cdot \left[\left(\frac{1}{v(r)} \right)^{1-d} \cdot \frac{T(r) \cdot \exp \left(\frac{0.46}{\beta} \cdot F \cdot N_0^{1-d} \int_r^{r_s} [R(s)]^d ds \right)}{1 + \frac{0.46}{\beta} \cdot F \cdot N_0^{1-d} \int_r^{r_s} R(s)^d \cdot T(s) \cdot \exp \left(\frac{0.46}{\beta} \cdot F \cdot N_0^{1-d} \int_s^{r_s} [R(t)]^d dt \right) ds} \right]^{1/d} \quad (4)$$

with

$$T(r) = \left(\frac{\sigma_o \delta_r \sigma_l}{\sigma_s \delta_s \alpha_l} \right)^{1/\beta}$$

where v is a Gamma distributed variable with unitary mean value: it accounts for uncertainty in the N_0 parameter of a Marshall-Palmer DSD; $\alpha_l = v^{(1-\beta)}$; $F=0.228$, $d=1.156$; δ_r and δ_s are random variables accounting for finite integration of power echoes. The reader is referred to (3) for details concerning such parameters and random variables. Notice that in $T(r)$ we accounted for the difference between σ_s , the "true" sea surface NRCS and σ_o , its 'guess' value; more, with the random variable σ_l (Gamma distribution, unitary mean value, 0.5 standard deviation) we represented also possible uncertainties in the definition of the guess value. A guess value can be obtained, for instance, by measuring it over regions where rainfall is not present or by means of a sea surface model. Indeed, changes of sea surface NRCS due to raindrops impinging on the sea surface and to surface winds play a relevant role on the efficiency of the rainfall profile reconstruction. As shown in the following Section, such NRCS variations can be of the order of some dBs. Utilising a mean NRCS value for the sea surface could be the only solution when only rain radar measurements are available.

In (3) a guess value $\sigma_o=12$ dB was chosen at 13.75 GHz, since it is the mean value of sea NRCS when varying the wind speed in the absence of rainfall. Fig. 1 is an indicative example of the significant errors that can occur when σ_o fails to be a good guess, due to a significant bias error. The error is plotted as a function of altitude when the 'true' NRCS is 9 dB and rainfall rate is 20 mm/h (60 independent echoes are assumed). The results recalled in the next Section show that such a bias is perfectly consistent with the lack of information about surface wind and rainfall.

The purpose of the following exposition is in fact to present some results from a model able to predict the

surface NRCS as a function of rainfall rate and an algorithm capable to provide the rainfall rate at the surface level together with a good estimation of its NRCS.

Fig. 1. Mean value and standard deviation of 100 rainfall profiles reconstructed through the kZS algorithm. Rainfall rate over the surface: 20 mm/hr; wind velocity: 4.32 m/s at 19.5 m height.

NRCS OF THE SEA ROUGHENED BY WIND AND RAIN

The sea surface is supposed to be agitated by the joint action of wind and rainfall. Surface roughness is therefore the sum of this two random processes. The first is considered as a large-scale phenomenon, while the second as a small-scale phenomenon. The two processes are supposed to be zero-mean and statistically independent. We adopted the FWM (Full Wave Model) reported in (5), utilised as indicated by Capolino et al. (6)-(7): the reader is referred to the latter paper for

details and information concerning the wavenumber spectrum chosen. Fig. 2 shows the sea surface NRCS versus rain rate for some wind speeds and nadir incidence. Notice that variations due to rainfall rate are of the same order of magnitude as those due to wind speed: this justifies the inclusion of rain induced corrugation in the e.m. model. We did not account for the fact that heavy rainfall may damp sea waves causing an increase of the NRCS at nadir incidence as reported for instance by Durden et al. (8). The quantitative determination of the rainfall's joint effects of damping the sea wind waves and causing the additional corrugation by raindrops' impact is matter for further complex investigation.

Fig. 2. NRCS copolar component, (obtained through an Apel spectrum) versus rainfall rate R , for various wind velocities. Frequency: 13.75 GHz, nadir-incidence.

THE “TWO CELLS” METHOD

In order to predict jointly the sea NRCS and the rainfall rate over the sea surface, a simple method can be utilized. We will refer to it as to the “two cells” method, as it accounts only for echoes from a couple of adjacent radar range cells, namely the pair closest to the sea surface. We assume that no pulse compression is used, so that interference among contiguous range cells can be neglected.

The basic approximations required are:

- 1) the contribution of the sea surface to the first range cell echo is much more powerful than that due to the rainfall;
- 2) the same rainfall rate is present in both cells.

If Δr is the range resolution, $\overline{P}_s$ and $\overline{P}$ the mean powers from the first and the second cell, we have:

$$\frac{\overline{P}_s}{\overline{P}} = \frac{C_s \cdot \sigma_s(R) \cdot e^{-0.46 \frac{\Delta r}{\beta} k(R)}}{C \cdot Z(R)} \quad (5)$$

Exploiting Eq. (3), we get:

$$\left(\frac{\alpha \cdot \overline{P}_s \cdot C}{\overline{P} \cdot C_s} \right)^{1/\beta} = \frac{\sigma_s(R)^{1/\beta} \cdot e^{-0.46 \frac{\Delta r}{\beta} k(R)}}{k(R)} \quad (6)$$

Eq. (6) can be inverted with respect to R . On the other hand, being the “true” relationship $\sigma_s(R)$ unknown, a ‘guess’ law $\sigma_o(R)$ must be introduced, which approximates $\sigma_s(R)$ as closely as possible. For this purpose a theoretical model, like that recalled in the previous Section, could be employed.

Notice that one single solution can be found when inverting Eq. (6). In fact, $k(R)$ increases and $\sigma_o(R)$ decreases with R , respectively: thus the right hand term in (6) is a monotonic function of R .

The “two-cells” method can be utilised as a good starting point for algorithms, like kZS, aiming to reconstruct the rainfall precipitation profile and based on the sea surface NRCS. In fact, a better prediction of the NRCS to be utilised in the kZS algorithm can be provided by the joint use of the “two cells” method and of an e.m. like FWM: the former predicts rainfall rate based on two mean power estimates, the latter is able to predict such NRCS as a function of wind speed and rainfall rate.

In general, the following steps should be followed for an accurate estimation of the rainfall profile in the framework so far described:

- 1) Utilize a measured, estimated or predicted value of wind velocity over the sea surface.
- 2) For that wind velocity, select the theoretical relationship between rainfall rate R and surface NRCS.
- 3) Utilise the “two-cells” method, accounting for all possible errors, included all the approximations brought in to obtain the aforementioned relationship. The objective is to provide a rainfall rate estimate over the sea surface, jointly with the related NRCS estimate.
- 4) Utilise the NRCS estimate in the kZS algorithm for rainfall profile retrieval.

We present now the results of some simulations with the purpose to evaluate performance of the rainfall profile reconstruction based on the above scheme. The same error model described in Section 2 is assumed for the “two cells” method. For comparison purposes, all aforementioned relationships have been considered as deterministically valid ‘truth’ references in the simulations; in particular, we assumed $\sigma_s(R) = \sigma_o(R)$ provided by the e.m. model. The error model has been instead used to simulate uncertainties related to such relationships.

Concerning NRCS errors, in (3) Marzoug and Amayenc observed that “possible systematic changes of NRCS due to the effects of raindrops impinging on the ocean surface or to the effects of surface winds” were ignored. Consistently, we assumed a null bias error, since the e.m. model does accounts for rainfall-induced

corrugation. The random variable σ_l was given the same standard deviation value of 0.5 as in (3): though σ_l indeed should account for a residual percentage of error related to the approximations of the e.m. model, this choice may lead to quite pessimistic results when reliable wind estimates are available (in particular when obtain with good spatial and temporal resolution).

A given vertical profile of rainfall rate was assumed as the 'truth' reference. The rainfall rate R_m at the sea level was 'estimated' through the "two-cells" method by solving:

$$\frac{\delta_s \cdot \sigma_0(R) \cdot e^{-0.46 \Delta r FN_0^{1-d} R^d}}{\delta_r \cdot R^b} = \frac{\sigma_l \sigma_0(R_m) \cdot e^{-0.46 \Delta r FN_{0m}^{1-d} R_m^d}}{v^{1-b} R_m^b} \quad (7)$$

where $b=1.5$ (13.75 GHz). An independent 'estimation' of R_m was repeated 100 times, based on the same error statistics and on the same rainfall profile, and mean value and standard deviation of R_m were then estimated.

Fig. 3 reports the 'true' rainfall rate R over the sea surface versus the estimated rainfall rate R_m (two curves corresponding to the estimated standard deviation of R_m are also plotted. The dashed curve is $R_m=R$).

Fig. 3. "Estimated" rainfall rate R_m versus "true" rainfall rate R_o . Frequency: 13.75 GHz; wind velocity at 19.5 m height: 4.32 m/s. The mean value and the standard deviation curves are also plotted.

Fig. 4 refers to the reconstruction by means of the proposed scheme of a "true" rainfall profile with a constant rainfall rate up to 4.5 km altitude, then decreasing in such a way that reflectivity decreases with a rate of 5 dB/km. A rainfall rate of 10 mm/h at the sea level was considered, assuming the same wind velocity as before. Mean value and standard deviation of 100 independent reconstructions are plotted for the 32 range cells (range resolution= 250 m) between the surface and 8 Km altitude.

FINAL REMARKS

A direct use of the kZS algorithm with an excessively generic guess of the sea NRCS may easily lead to relevant errors in reconstructed rainfall profiles. A more accurate guess of such NRCS can be provided by an e.m. model like FWM: in any case, sea surface roughness induced by rainfall cannot be neglected by a model-based predictor. Through FWM we derived a relationship between surface NRCS and rainfall rate over such surface at nadir incidence, as a function of surface wind velocity. In spite of the intrinsic model approximations, such relationship confirms that rainfall remarkably modifies the NRCS value that would be predicted accounting for wind only.

Improved performance of the rainfall profile retrieval scheme proposed here has been demonstrated via simulations carried out at 13.75 GHz for different values of wind velocity, different rainfall rates over the sea surface and different rainfall profiles. All of them showed that the rainfall profile retrieval accuracy can greatly benefit from a more accurate prediction of NRCS. This implicitly assumes that wind velocity over the area of interest is available, provided by either measurements or models, or joint exploitation of both of them. Measurements should refer to the same or a contiguous area, provided by an independent sensor such a scatterometer. In another perspective, two frequency measurements could be exploited, one at C band (where sea NRCS is not affected by rainfall rate) and the other at Ku band. In summary, the scheme could be profitably exploited in all those contexts where additional information allows to overcome the bare hypothesis of a generic 'standard' average value of sea NRCS.

Fig. 4. Rainfall profile obtained through the proposed scheme. Rainfall rate on the surface: 10 mm/hr; wind velocity: 4.32 m/s at 19.5 m height. Mean value and standard deviation curves are also shown.

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