A model-based dual frequency method for rainfall profile retrieval over the sea surface by spaceborne rain radars

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ABSTRACT – A new dual frequency (C and K_u band) algorithm is presented for the retrieval of rainfall profiles over the sea surface. The algorithm is based on a simple iterative procedure that relies on nadir measurements, and on an electromagnetic (e.m.) model of the sea surface. Simulations are presented, indicating a good performance of the algorithm accompanied by a fast convergence rate.

INTRODUCTION

Several methods have been presented in the literature for the retrieval of rainfall rate profiles based on reflectivity data measured by spaceborne rain radars. In particular, apparent reflectivity is measured, since the radar apparatus operates at an attenuating wavelength (typically, in K_u band) for two important reasons: first, to reduce the weight of the payload; second, to limit the antenna beam footprint so that non uniform beam filling effects by the rain medium are minimized. Since rainfall rate cannot be derived directly from reflectivity measurements, it is obtained through inversion procedures that basically aim at estimating the specific attenuation profile, from which rainfall can be on turn estimated resorting to standard specific attenuation-rainfall rate relationships. This kind of profile retrieval is typically performed at (or very close to) nadir incidence.

In any case, single frequency inversion methods must face the problem of estimating the unknown total attenuation occuring between the radar antenna and the surface. For this purpose, surface referenced inversion methods assume that a NRCS estimate is given, from which the total attenuation can be inferred [1]. Such NRCS estimate can be more or less rough, depending on the way it is derived (measurements made in other areas, e.m. models, climatological averages). When radar measurements are performed over the sea surface, electromagnetic (e.m.) models can be profitably exploited to provide a more accurate NRCS estimate. However, the NRCS of the sea surface at K_u band is influenced not only by the surface wind but also by rainfall, decreasing with increasing rainfall rate at nadir incidence [2]. Recently, a new single frequency (K_u band) rainfall profile retrieval algorithm has been proposed based on the so-called kZS algorithm 'integrated' with a NRCS model of the sea surface [3]. For brevity, in this paper we refer to such algorithm as MI-kZS (Model Integrated kZS). This new approach requires a guess of the surface wind velocity referring to the same area that is being monitored or to a contiguous one: the related uncertainty does not affect the rainfall profile retrieval as heavily as a NRCS uncertainty in the original kZS algorithm.

In this paper, we introduce a new Dual Frequency Iterative Algorithm (DFIA) as the evolution of the previous work: DFIA exploits C and K_u band reflectivity measurements over the sea surface at nadir incidence to provide simultaneously the rainfall profiles and surface wind velocity estimates. The choice of the C band makes the surface NRCS estimates practically independent of rainfall induced corrugation; furthermore, total attenuation in rainfall at C band is smaller than in K_u band, therefore it does not heavily influence NRCS measurements. Nevertheless, such attenuation cannot be neglected, in particular when precipitation is intense. Thus, the DFIA corrects iteratively the C band NRCS estimate error through the total attenuation estimate made after the MI-kZS retrieval of the vertical rainfall profile.

THE DUAL FREQUENCY ITERATIVE ALGORITHM

As specified above, we consider a dual frequency spaceborne radar, operating in C and K_u band. The objective is to retrieve the rainfall profile over the sea surface, exploiting the two measurements and the sea surface e.m. model, based on the Full Wave Model approach, described in [2]. Due to the lack of space, the reader is referred to that paper; analogously, he/she is referred to [3] for the description of the MI-kZS method. It is sufficient to cite here that the e.m. model is able to provide - at both bands - the NRCS $\sigma_o(R_{surf}, V_w)$ as a function of the surface rainfall rate R_{surf} and the surface wind V_w. While V_w heavily influences the NRCS at both bands, in practice R_{surf} influences the K_u-band NRCS only. The DFIA thus proceeds as follows:

1) an arbitrary first guess wind velocity V_w^1 is utilized as input to the MI-kZS algorithm in order to obtain a first guess $R^1(r)$ (r being the radar range) of the vertical rainfall profile through the K_u-band power measurements.
2) Such estimate $R^1(r)$ is used to estimate, at C-band, the specific attenuation profile $k_c^1(r)$, from which the total path integrated attenuation (PIA) is then computed.
3) The C-band NRCS σ_{co} is estimated by correcting the radar measurements through the PIA estimate obtained at the previous step.
4) A first refinement of V_w is then obtained by inverting the NRCS relationship provided by the e.m. model at C-band.

5) The new wind velocity is utilized as before (steps 1-4).

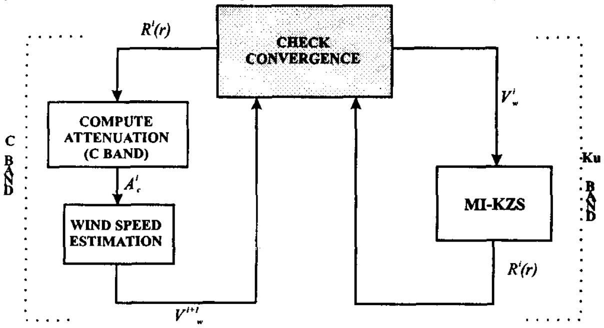

Fig. 1 – The DFIA scheme

The cyclical repetition of the above steps is shown in Fig. 1, where $R^i(r)$, A^i_c *and* V^i_w indicate respectively the vertical rainfall profile, the PIA and wind speed at the i-th iteration. The convergence condition is the following:

$$\left|V_w^n - V_w^{n-1}\right| < \varepsilon_w \qquad (1)$$

Obviously, ε_w influences the convergence speed. For the simulations presented here, $\varepsilon_w = 10^{-3}$.

THE SIMULATION

Simulations were carried out as in [4] and [3], with some extensions to the dual frequency case. The following uncertainties and model errors were accounted for:

- Random variations along the propagation path of the coefficient N_o of the exponential Drop Size Distribution model: N_o was modeled as a Gamma distributed random variable (rv) with a 0.5 ratio between the standard deviation and the mean value, assumed as $0.8 \cdot 10^{-7}$ m^{-4}.
- Random fluctuations of the received powers at both bands were modeled as independent random variables with pdf $p(x) = N_i^{N_i} x^{N_i - 1} exp(-N_i x)/(N_i - 1)!$, where N_i is the number of independent integrated samples.
- At both frequencies, the variability of N_0 was considered as the only source of uncertainty in the reflectivity-rain rate (*Z-R*) relationships, in the specific attenuation-rain rate ones (*k-R*) and in the reflectivity-specific attenuation (*Z-k*) ones. The following relationships were applied:

$$Z = EN_0^{1-b} R^b \qquad (2)$$

$$k = FN_0^{1-d} R^d \qquad (3)$$

$$Z = EF^{-\beta} N_0^{1-\beta} k^{\beta} \qquad (4)$$

  where *E*, *F*, *b*, *d* depend on frequency and $\beta = b/d$. Table 1 reports the values used in the simulations.
- E.m. model errors were accounted for by introducing an uncertainty factor σ_I and a bias σ_B, so that the 'true' NRCS $\sigma_s(R_{surf}, V_w)$ at both bands is modeled as follows:

$$\sigma_s(R, V_w) = \sigma_I \cdot \sigma_o(R, V_w) + \sigma_B \qquad (5)$$

At both bands, σ_I was modeled as a Gamma distributed rv with unit mean value and 0.5 standard deviation (a quite high uncertainty). In the following results, statistics of σ_I are not modified, while we refer to a variable percentage bias, that may account also for C-band calibration errors:

$$\varepsilon_\sigma \% = \frac{\sigma_B}{\sigma_o(R'_{surf}, V'_w)} \cdot 100 \qquad (6)$$

where R'_{surf} and V'_w are the true rain rate and wind speed.

	f=5.6 GHz	*f*=13.75 GHz
E	$0.66 \cdot 10^6$	$0.66 \cdot 10^6$
b	*1.45*	*1.5*
F	*0.901*	*0.309*
d	*1.41375*	*1.156*

Table 1-parameters' values for Eqs. 2-4

SIMULATION RESULTS

DFIA simulations were carried out by assuming a given rainfall profile and surface wind speed, introducing the above uncertainties and errors, and generating 1000 inversions. From these, mean value and standard deviation of the estimated wind velocity, NRCS, PIA and rainfall rate profile were computed. In this paper we report some samples of a wider set of results. In particular, here we refer to a surface wind speed V'_w =3.46 m/s and to a true rainfall profile with constant rainfall rate (R'_{surf}=10 mm/h) up to 4.5 km altitude, then decreasing with a corresponding reflectivity decrease of 5dBZ/km. In Fig. 2a are plotted the mean rainfall profiles obtained at the first three iterations: notice that a good reconstruction is achieved at the third iteration. Figs 2b and 2c report respectively the mean value and standard deviation of wind speed and rain rate estimates versus the iteration number. They confirm the convergence speed of the algorithm (consider that the initial wind velocity guess was 20 m/s). Notice that no e.m. bias was imposed in this case ($\varepsilon_\sigma\%$=0). The slight bias affecting the final estimates is generated by the non linearity of the e.m. model. Such bias is in general more pronounced for the wind estimate, increasing with V_w : nevertheless, the corresponding bias on both NRCS and *R* estimates is not so sensitive to that increase.

Fig. 3, referring to the same type of profile, V_w and R'_{surf}, shows the effect of the e.m. model bias on the mean value of the R_{surf} estimates (Fig. 3a), and on the related percentage mean square error $\varepsilon_R\%$ (Fig. 3b). In general, both bias and uncertainty on *R* decrease with altitude: for instance, at 4 km altitude, the curves are similar to those of Fig. 3, but bias on the R average values ranges from 8 to 11 mm/h while $\varepsilon_R\%$ is extremely reduced, ranging from –21 to 10. Furthermore, such sensitivity to $\varepsilon_\sigma\%$ at high altitude decreases with increasing R_{surf}.

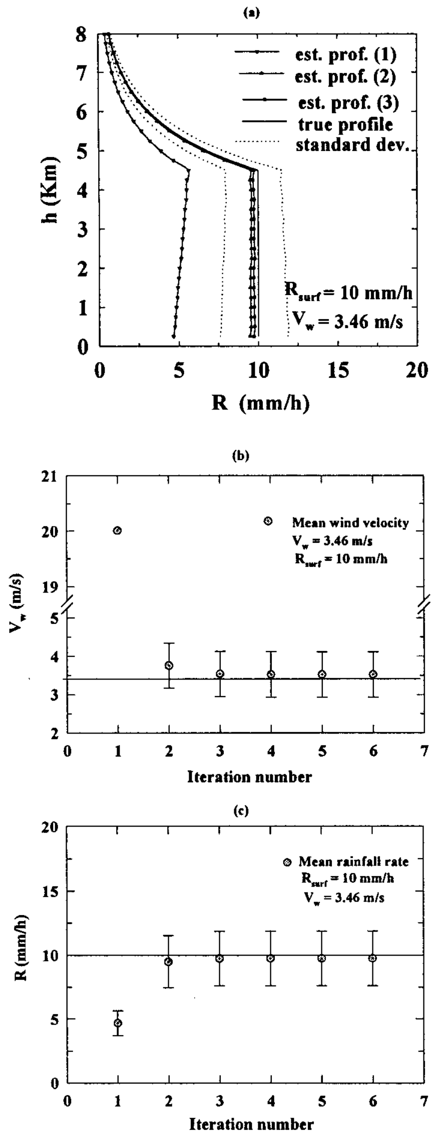

Fig. 2 – True and reconstructed rainfall profiles (a) and convergence to the surface wind (b) and rainfall (c) estimates

CONCLUSIONS

More ore less complex procedures for estimating rainfall profiles by dual frequency measurements are based on error functional minimization procedures [5],[6]. When it is possible to exploit a surface NRCS model, as in the case of the sea surface, the low band measurements be directly used to iteratively refine the high band ones such as in the DFIA. Results obtained indicate that the robustness of the DFIA is accompanied by a fast convergence.

ACKNOWLEDGMENTS

This work was supported by the Italian Ministry of University and Technological Research, and by the Italian Space Agency.

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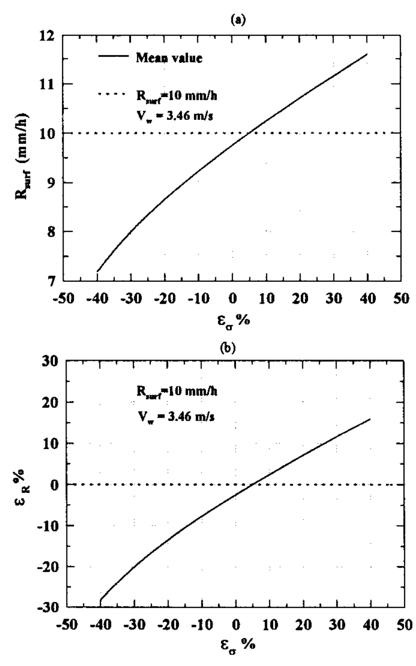

Fig. 3 – Effect of the NRCS bias in the e.m. model