P16.3 PHYSICALLY−BASED MULTIPARAMETER RADAR SIMULATION, AND COMPARISON WITH RADAR MEASUREMENTS

Caboni V. (*), C. Capsoni, M. D'Amico and R. Nebuloni

DEI, Politecnico di Milano, Milano, Italy

1. INTRODUCTION

There is a growing use of mutiparameter radars for the remote sensing of rain. Radar systems are able to monitor very large areas with a single installation, in real time. On the other hand their measurements are often quite "delicate"; the conversion of the radar measurables into meteorological quantities is not unique, depending, for example, on the model assumed for the target, on the vertical profile of reflectivity, etc. In this context, the availability of sophisticated radar simulators can prove to be extremely useful to try and discriminate the effect of the different contributions on the received echoes.

In this work a physically−based multiparameter radar simulator is presented, that is able to generate a very accurate synthetic radar signal, by solving the radar equation over a synthetic meteorological enviroment. Precipitation phenomena are modelled through a population of hydrometeors (rain drops, dry or melting snowflakes) falling through the radar resolution bin. The syntetic radar signal is generated by adding up (in amplitude and phase) all the contributions from each single scatterer, present into the virtual radar bin. As far as the radar sensor is concerned, it is possible to take into account the effect of wave polarization, antenna and receiver characterisics. The effect of propagation, like differential attenuation and phase shift, can also be introduced in the simulation, as well as effects of wind and turbulence on particles motion.

2. THE RADAR SIMULATOR

The signal received from a pulse Doppler radar is due to the superposition of signals backscattered by the hydrometeors present in the radar resolution volume (Doviak and Zrnic', 1994):

$$I\left(\tau_s,T_s\right)=H\Sigma_i\left[\frac{\left(\sqrt{\sigma_{bi}}\,l_i\left|W_i\right|\right)}{r_i^2}f\left(\vartheta_i,\phi_i\right)\cos\left(\gamma_i\right)\right],$$
$$Q\left(\tau_s,T_s\right)=H\Sigma_i\left[\frac{\left(\sqrt{\sigma_{bi}}\,l_i\left|W_i\right|\right)}{r_i^2}f\left(\vartheta_i,\phi_i\right)\sin\left(\gamma_i\right)\right],\quad (1)$$

* *Corresponding author adress*: Valentino Caboni, Dipartimento di Elettronica e Informazione, Politecnico di Milano, Piazza L. Da Vinci 32, 20133 Milano, Italy. E−mail:caboni@elet.polimi.it

where

$$\gamma_i=\left(4\pi r_i/\lambda\right)+\left(4\pi v_i T_s/\lambda\right)-\psi_i-\beta_i,\quad (2)$$

and

$$H=\sqrt{((P_t G^2\lambda^2)/(4\pi)^3)}\quad (3)$$

In Eqs. (1), (2) and (3), P_t is the transmitted peak power, $\left(r_i,\vartheta_i,\phi_i\right)$ are the coordinates of the *i*th scatterer, *G* is the one way antenna gain, λ is the wavelength, l_i is the extra attenuation due to rain and gases in the path toward and from the radar bin, W_i is the so−called Range Weighting Function (RWF), $f\left(\vartheta,\phi\right)$ is the antenna directivity function (power), σ_{bi} is the backscattering cross section of the *i*th scatterer, v_i is the projection of the scatterer velocity along the radar direction, ψ_i is the phase contribution due to the scattering function and β_i is the phase contribution due to the RWF, the antenna directivity function and the propagation path. The summation is extended over all the particles present in the radar resolution volume.

Aim of the development of the radar simulator is the possibility of generating sequences of I and Q samples according to eqs. (1), as if they were generated by a real radar system observing a real meteorological event. It works on a *per bin* basis and it's principles of operation are the following (Capsoni *et. al.*, 2001): starting from the user selected value of range, the radar resolution volume is evaluated, including effects of antenna directivity function and of RWF. Then the bin is filled with hydrometeors of different sizes that are randomly placed into the volume itself. User can choose among different drop shapes (spherical and oblate); use for the expression of raindrops' cross section an analytical model or a numerical solution (Capsoni *et. al.*, 2001); and he specify parameters defining the Gamma Drop Size Distribution (DSD) (Ulbrich, 1983). To keep computational times within reasonable limits without biasing results, it is not feasible to reproduce either the entire population of scatterers present in the bin or the correct number ratio among different classes of diameters as imposed by the DSD.

For this reason DSD is discretized in N_c classes of diameters (user selectable), each one representing a number $M_{d,m}$ of virtual particles. From N_c the simulator automatically determines the interval of diameters to be used, and $M_{d,m}$ according to the following relation:

$$M_{d,m} = \begin{cases} 1 & if\, N_{d,m} < 1 \\ N_{d,m} & if\, 1 \le N_{d,m} \le N' \\ N' & if\, N_{d,m} > N' \end{cases} \quad , \quad (4)$$

where $N_{d,m}$ is the number of particles per unit volume of the DSD. Since each virtual particle represents $Q_{d,m} = N_{d,m} / M_{d,m}$ real drops, the simulator multiplies its backscattering cross section by a factor $Q_{d,m}$. With $N_c = 200$ and $N' = 10$ errors between simulated and theoretical Power Spectral Density (PSD) are below 10% (Capsoni *et. al.*, 2001).

Once the radar equation as been solved for the current configuration of the scatterers, their position is updated for the next pulse taking into account their terminal fall speed. A random component of velocity, with a user selectable distribution, can be added to particles motion in all directions. Furthermore, user can select a profile of horizontal wind, variable with height, to be added to particle motion; he can also decide its direction respect to the azimuth of the bin. Once scatteres position has been updated, simulator solves radar equation for their new configuration and the cycle is repeated for all the pulses to be generated.

3. APPLICATION: RAINDROPS AS WIND TRACERS

The usefulness of a radar simulator of this type, lies in the capability of generating sequences of complex samples starting from a user selected sensor as well as a user selected meteorological situation. In this way one may try to discriminate the effects of different contributions on the received echoes, even in absence of appropriate analytical models.

In previous works we investigated the behaviour of time decorrelation (τ_d) of rain echoes at different elevations. With measurements and simulations we observed that in presence of wind and/or turbulence, low values of τ_d are not uncommon even at horizontal pointing (Nebuloni *et. al.*, 2000), (Capsoni *et. al.*, 2001).

The starting point of the example of simulation we'll discuss in this paper is a measure collected with our S band meteorological radar located at Spino d'Adda, near Milano, on 24 March 2001 at 22:15 UTC. Radar operation was set to "pulse mode", i.e. the antenna pointed steadly with fixed azimuth elevation alignment $(\vartheta = 10^\circ, \phi = 225^\circ)$ and a sequence of 4096 pulses was recorded at PRF=1000 Hz; pulse duration was set to $\tau = 0.5\,\mu s$ and our parabolic antenna beamwidth $(-3\,dB)$ is 2°. All adjacent cells at heights between 750 m and 1300 m were considered; rain rate varies from 4 to 7 mm/h. From this set of data, we computed PSD using Welch's averaged modified periodogram method: 16 Hanning windowed 256 points periodograms were averaged. PSD as a function of Doppler velocity $(v, [m/s])$ and height $(h, [m])$ is depicted in Fig. 1. It could be seen (Fig.1) that PSDs at heights around 1000 m show the contemporary presence of two separate peaks. One may assert that this is not uncommon in melting layer, where there are different populations of particles that should move at different mean velocities because of their nature. But for this event, on RHI recordings the bright band is visible at heights near 2000 meters from ground, while two separate peaks are visible at heights around 1000 meters.

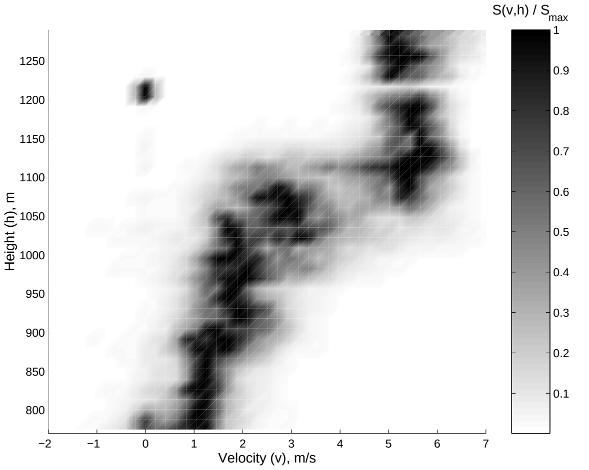

Figure 1: *PSD as a function of height and Doppler velocity* $(S(v,h))$ *computed from mesurements.* $S(v,h)$ *has been normalized to maximum.*

In our opinion a reason for aforesaid PSD shapes, could be a situation in which there is an abrupt variation of horizontal wind speed at a given height. In particular we thought that when the bin is positioned around heights where such variation take place, it will be partially under effect of both different values of wind velocity. If raindrops move at wind velocity, at those "intermediate" heights particles positioned in upper part of the bin will move at different velocity than those positioned in lower one, then the presence of two separate peaks in PSD. In this way evolution of $S(v,h)$ could be explained in following way: up to 1000 m from ground wind velocity grows from 0 to about 1 m/sec. Around 1000 meters wind velocity jumps to about 2 m/s then a second peak appears. Around heights near 1100 m wind velocity does a second jump to about 4 m/s then a third peak appears. Above 1100 m and below 1000 m only one peak in present, meaning that for such heights, particles filling bins are approximately all moving at the same velocity.

The simulation we programmed to reproduce measured $S(v,h)$ is described hereafter: we setted

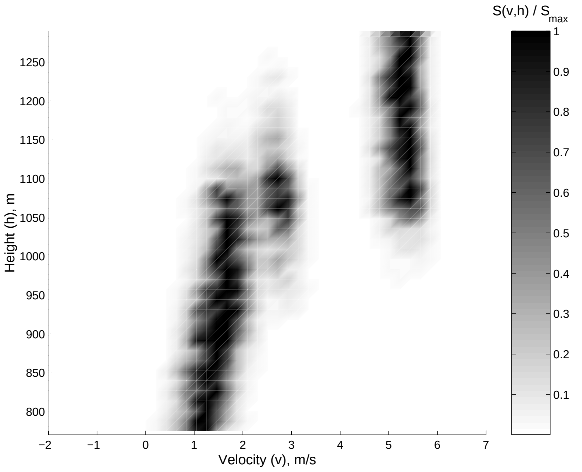

Figure 2: *PSD as a function of height and Doppler velocity $\left(S(v,h)\right)$ computed from simulation. $S(v,h)$ have been normalized to maximum. Only wind variations with height has been considered.*

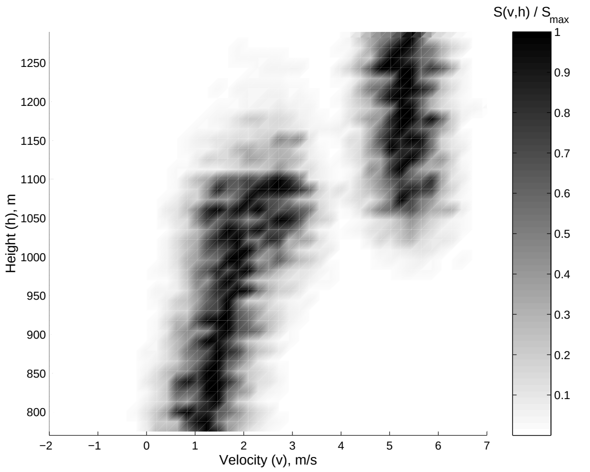

Figure 3: *PSD as a function of height and Doppler velocity $\left(S(v,h)\right)$ computed from simulation. $S(v,h)$ have been normalized to maximum. Wind variations with height and turbulence has been considered.*

up the virtual instrument to reflect our radar characteristics; for DSD we choosed a Marshall and Palmer distribution with spherical drops, and we used $N_c = 300$ classes to represent it. An horizontal wind profile, variable with height and moving toward radar in radial direction, was added to drop motion; it is described by following equation:

$$v(h) = \begin{cases} 0.003h - 2.34 & \text{if } h < 1040 \\ 1.6 & \text{if } 1040 \le h \le 1100 \\ 4.2 & \text{if } h > 1100 \end{cases} \qquad (5)$$

For each virtual bin, 4096 virtual pulses has been transmitted. PSD computed from results of the simulation are plotted in Fig. 2. Comparison between Fig.1 and Fig.2 shows that main aspects of measured $S(v,h)$ are well reproduced, showing that gradients of wind speed with height could give rise to the contemporary presence of more than one peak in PSD. Main differences seems to be in spectral width, probably meaning that also turbulence was present in measures; this would explain also the more irregular shape of measured PSD, compared with simulated one. To confirm this fact we programmed a new simulation in which also turbulence is present. We retained all characteristic of previous simulation and we added to particles motions also an isotropic random component velocity, with Gaussian distribution and standard deviation up to 0.4 m/s. PSD of new results are plotted in Fig.3, where it could be seen that the addiction of turbulence has widened PSDs, without altering mean velocities of different PSDs peaks. Our explanations on the role of wind speed and turbulence seem to be valid, even if equation (5) is not perfect to reproduce wind speed variations that gave rise to measured PSD shapes. We think that this is the main cause of differences between Fig.1 and Fig. 3.

4.CONCLUSIONS

Principles of operations of a physically based multiparameter radar simulator, developed at Politecnico di Milano, has been presented. To give an idea of its capabilities we gave an example of application; in particular we tried to reproduce rain echoes Power Spectral Density (PSD) with more than one maximum acting on horizontal wind variations with height and on turbulence. Comparing measurements and simulations it seems that abrupt variations of wind velocity with height may give rise to the contemporary presence of more than one peak in PSD, for cells located around heights where such variation take place; moreover such comparison seem to highlight also the role of turbulence that would widen PSD. Future work will be devoted to investigate in detail above effects, trying to understand how those considerations may be applied on operational radars.

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