Proceedings of ERAD (2004): 150–154 © Copernicus GmbH 2004

ERAD 2004

Preparing GPM: a comparison of radar rainfall measurements in a simulation framework

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Abstract. One of the key points to ensure the precipitation measurement quality in the precipitation missions (such TRMM and GPM) is the capability of making real time validation with ground based equipment in the GV-supersites. So a carefully addressed design of them is a crucial point.

A methodological simulation framework is proposed to provide useful information for the design of the supersites equipment and to optimize the combination of satellite and ground data to better estimate the rainfall field.

The framework consists on three basic steps:

a) Generation of high-resolution 3D precipitation fields using real radar data.

b) Simulation of the observations that ground based and spaceborne radars would have provided.

c) Comparison of the different observations against the reference rainfall field to assess the errors in each measure and the usefulness of the different procedures of corrections.

The general framework of simulation and the first results obtaining high-resolution 3D precipitation fields and radar simulations are presented.

1 Introduction

The Tropical Rainfall Measuring Mission (TRMM) satellite was launched in November 1997 as a joint scientific initiative between NASA and NASDA with the aim of collecting precipitation information from 40° N to 40° S. One of the primary sensors onboard TRMM is the precipitation radar (TRMM-PR), a 128-element active phased array system operating at 13.8 GHz and covering a swath of 215 km. Due to the tremendous success of this mission, a new joint adventure between NASA, JAXA, ESA and other partners carrying a new generation precipitation radar and called Global Precipitation Mission (GPM) is planned.

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To ensure the quality of the data provided by these precipitation missions it is necessary to compare the satellite observations with ground data over selected sites called supersites. The role of supersites has been evolving during the TRMM, and the concept of "Ground Truth" turned into "Ground Comparison", nowadays. One of the key requirements of a validation supersite for the next GPM mission will be the capability of providing error structure in real time to be used jointly with the precipitation estimates in the applications.

To assess this error structure (bias errors and special and temporal error distributions), a methodological framework based on simulation is being developed. Physically based simulation of the radar measurement process allow studying various sources of uncertainties (e.g. distance from the radar, vertical variation of the rainfall field) and permit to test different instruments characteristics and locations over different kind of events. Although a disadvantage of the simulation model is the need to make assumptions and simplifications owing to imposed limitations in information and computational resources.

Simulations experiments of ground radar precipitation observations have been performed before by Chandrasekar et al. (1990); Krajewski et al. (1993); Krajewski and Georgakakos (1985); Anagnostou and Krajewski (1997), this last two implementing physically-based simulations. Ground radar correction algorithms have been also tested under simulation in Sánchez-Diezma et al. (2001a). The simulations performed in the present experiment will continue the physical approach of these last three papers and the framework is mainly composed by three stages:

a) Generation of high resolution 3D reference precipitation fields.

b) Simulation of the different instruments measurements over the reference field.

c) Comparison of simulated fields between them and against the reference.

In the current state of development of this simulation framework the high resolution precipitation fields can be generated and ground radar measurements simulated. A first version of spaceborne radar simulations are also available.

The following sections summarize the description of these basic steps and an example of the simulations are also presented.

2 Generation of 3D high resolution precipitation fields

The aim of this first step is to obtain 3D high resolution precipitation fields over a cartesian grid with the proper low scale variation (in order to reproduce as much as possible, the realistic rainfall features).

From the point of view of stochastic models the spatial and temporal structure of rainfall from storm events can be generated using Poisson processes (Rodriguez-Iturbe and Eagleson, 1987). Anagnostou and Krajewski (1997) also use space-time stochastic models to generate rainfall fields, but obtaining a 3D rainfall field through imposing a vertical structure. Another way to deal with the generation of precipitation fields is imposing random noise on a given high quality radar-rainfall field (Krajewski and Georgakakos, 1985).

In the present work for the generation of the 3D high resolution precipitation field, volumetric data from ground weather radar is taken and interpolated into a cartesian grid up to a certain resolution. This approach has as main advantage that it maintains the 3D structure of the rainfall patterns measured by the radar without imposing a vertical structure. In order to capture as much as possible the highest resolution-quality, the data is taken close to the radar (reducing the effect of loss of power with distance-rain, attenuation, volume resolution, etc.).

Previous to the interpolation the position of the radar data is determined considering the beam refraction in the atmosphere and the curvature of the Earth, using the 4/3 equivalent Earth model described, for instance, in Doviak and Zrnic (1992).

In the process of densification, several techniques can be used, but as a first approach in order to obtain a balance between computational time and accuracy, linear interpolation is chosen. In future improvements, downscaling techniques, that suppose fractal behaviour of the rainfall variability will be used in order to get a more realistic rainfall field.

In the linear interpolation technique used two interpolations are done. With the aim of obtaining a precipitation field in polar coordinates with a resolution similar than the final one, a first one is applied in the polar data. Close to the radar this is a minor problem in azimutal dimension but in range this first interpolation is needed to obtain better results in the second one. In the second 3D interpolation, the interpolated cartesian values are calculated as the average of the n nearest 3D special neighbours. The number of neighbours clearly influences the roughness of the final precipitation field and in order to obtain the highest low scale variability, two neighbours have been chosen (from a qualitative manner). Also a resolution of 250 meters has been chosen as a compromise between computational time, ability of the interpolation technique to reproduce variability at small scale, and the resulting resolution of the simulated observed fields.

This procedure of obtaining high resolution fields is good for "medium size" volumes where there is no need to go far from the ground radar providing the data. If this procedure is used to get larger fields, the quality of the densified fields will not be homogeneous.

3 Simulation process

Using the 3D high resolution reflectivity field generated in the first step, the measurements of different instruments are simulated. Both ground radar and spaceborne radar have a similar procedure of simulation with few differences due to the special characteristics of each instrument. To calculate it, the convolution between the radar equation and the precipitation field located at certain distance and position is performed. The radar equation (Doviak and Zrnic, 1992), which relates the power received by a radar antenna and the reflectivity of the target can be expressed as:

$$\bar{P}\,(r_0) = \frac{P_t g^2 \lambda^2}{L^2\,(r_0)\,(4\pi)^3} \int_{Vres} \frac{|W_s|^2\, f^4 \sigma}{r^4} dV \tag{1}$$

where $\bar{P}\,(r_0)$ is the received power for a certain volume of resolution, $Vres$. The first part is related to the physical parameters of the radar, while the second one is the contribution of all the particles of $Vres$ to the measured power.

For each volume scan, the contribution of all the pixels of the precipitation field to the total measured power is calculated from the radar Eq. (1) separately for the pulse distribution ($|W_s|^2$) and for the normalized power (f^4) and after, the weight corresponding to the product of $|W_s|^2$ by f^4 is associated at each pixel of the precipitation field.

The range weighting function $|W_s\,(r)|^2$ describes the relative contribution of the scatterers along the range from radar inside the sampling volume. For this simulation tool, the equation for $|W_s\,(r)|^2$ used is the proposed in as Doviak and Zrnic (1992):

$$|W_s(r_0)|^2 = (\frac{1}{2}\,[erf(s+b) - erf(s-b)])^2 \tag{2}$$

where,

$$erf(y) = \frac{2}{\sqrt{\pi}} \int_0^y e^{-t^2} dt \tag{3}$$

and $b = B_6\tau\pi\big/(4(Ln(2)^{1/2}))$; $s = (2aB_6\big/c)r_b$; $a = \pi\big/(2(Ln(2)^{1/2}))$ where, B_6 is the 6dB width of the receptor, τ is the pulse width of the transmitter, $r_b = r - r_0$ and c is the speed of light.

On the other hand, f^4 is often approximated by a Gaussian function, here the used is the proposed by Probert-Jones (1962). For the ground radar, circular symmetric:

$$f^4(\phi) = \exp\left(-\frac{8Ln(2)\phi^2}{\phi_3^2}\right) \quad (4)$$

where ϕ is the angle respect the axis of the beam, and ϕ_3 is the 3 dB power angle.

And for the spaceborne radar:

$$f^4(\phi,\theta) = \exp\left(-8Ln(2)\left[\left(\frac{\phi}{\phi_3}\right)^2 + \left(\frac{\theta}{\theta_3}\right)^2\right]\right) \quad (5)$$

where ϕ and θ are the angles respect the axis of the beam in cross-track and along-track respectively, and ϕ_3 and θ_3 are the 3 dB power angles of the same directions.

The final step consist on calculating the convolution between the weights and the corresponding values of the precipitation field, in order to obtain the simulated measurements. This procedure of simulating the observations of an instrument (calculating separately the contribution of all the pixels and after applying the convolution between the weights and the precipitation field) allows reducing the computation time if several simulations are done with the same radar specifications and location, and different precipitation fields.

For simulating spaceborne radar, it is considered to be a cross-track instrument and only a single swath is simulated. To get the full volume scan over precipitation field, several simulations have to be done with different satellite position each time (simulating the satellite moving), which does not represent an additional difficulty. Due to the process of simulation, the weights of each pixel have only to be calculated once, and then, the convolution between weights and the precipitation field done once for each satellite position. The beam range start and the number of gates (different for each beam) have been also taken in consideration.

4 Data comparison

Once the different instrument measurements over the same reference precipitation field are performed, the last step is the comparison between them and against the reference field, in order to obtain the error structure of each one. Simulation has good advantages since not only the observed field for each instrument is available, but also the reference field that can be considered as "the truth" for the comparison.

The first comparing technique can be the direct comparison between simulated data and the reference field, resampled to a common grid, pixel by pixel. Also comparisons based in accumulations (that in the real world suffer from the satellite revisit time) can be applied in a simulation tool where this is not an issue.

Another possible way to compare these two instruments is to use pdfs of radar R before or after classification in rain types (Amitai et al., 2004). The classification will allow for better evaluation of the algorithms under different conditions, and potentially for "extrapolation" of uncertainties to regions with the same rain type. The pdfs can represent the distribution of rain volume by rain rate, i.e. they can be constructed according to the relative contribution made by each rain intensity to the total rain volume:

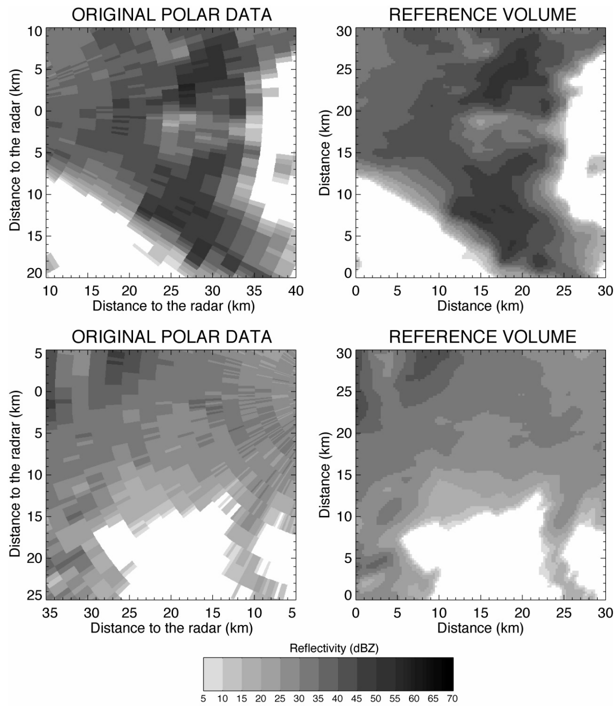

Fig. 1. First PPI of the data measured by the Barcelona INM C-band radar (left column) and the first level of the high resolution volume obtained with the described interpolation process. The first row correspond to a convective case and the second is more stratiform.

$$PDF(R_i) = \frac{\sum_{R_i-\Delta R}^{R_i+\Delta R} R}{\sum_{0}^{\infty} R} \quad (6)$$

These kind of pdfs are less sensitive to the instrument rain detection thresholds than the pdfs of occurrence, and have a direct hydrological significance because the larger intensities have a more important role (Amitai et al., 2004).

5 Application and results

Several 3D high resolution precipitation fields (of 30x30x10 km) have been generated with the described technique using data form the Spanish National Weather Service (INM) C-band radar located near Barcelona (see its main characteristics in Table 1). Before the interpolations, the data is corrected by problems due to stability control of the radar, ground clutter suppression and substitution, and correction of loss of power due to screening effects (Sánchez-Diezma

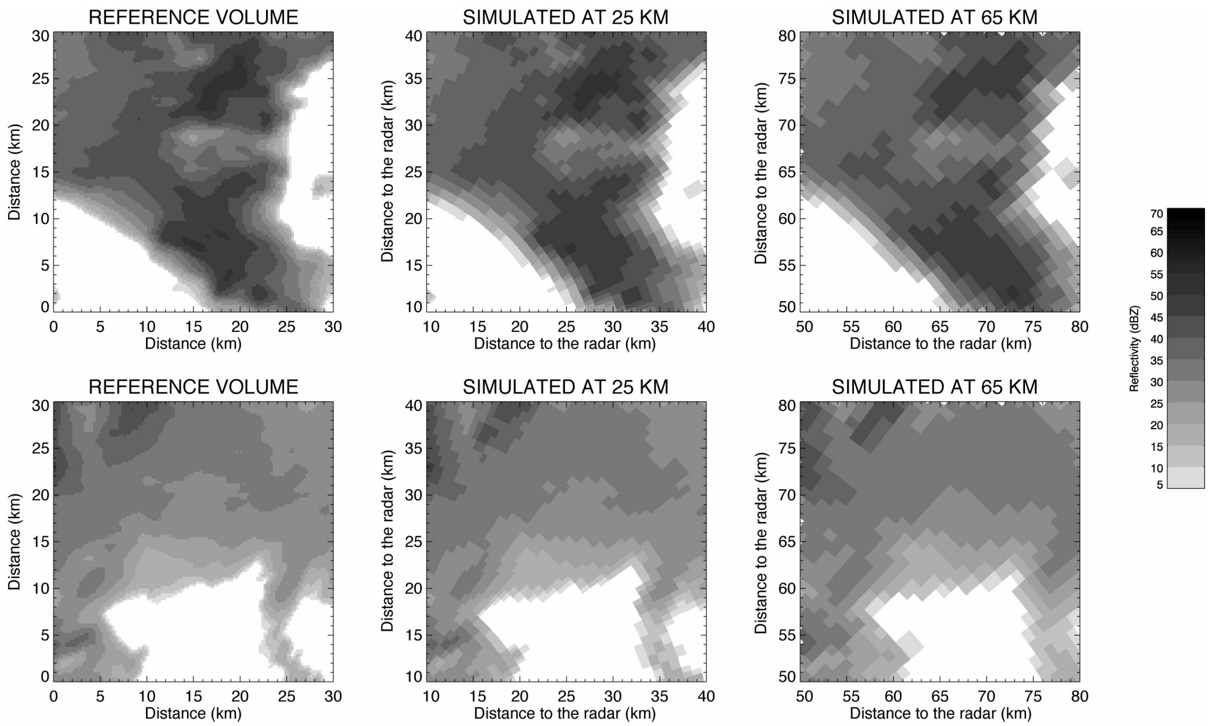

Fig. 2. Ground radar measurement simulation over the two high resolution precipitation fields at 25 and 65 km distance from radar. The first column images correspond to the first height level of the reference volume and the other to the first PPI of the simulated radar.

Table 1. Specifications of the INM (Spanish National Weather Service) C-band radar located near Barcelona (Spain).

Latitude	41°24′33″
Longitude	1°53′9″
Height (amsl)	664 m
Transmitted Power	250 KW
PRF	250 Hz
Frequency	5.60 GHrz
Beam width	0.9°
Pulse duration	2 μs
Number of azimuts	420
Antenna speed	6 rpm
Num. elevations	20

Table 2. Specifications of the TRMM Precipitation Radar before and after the boost suffered in August 2001.

Height	350 Km (pre-boost)/402 Km (post-boost)
Flight velocity	7 Km/s
Transmitted Power	500 W
PRF	2776 Hz
Frequency	13.8 GHrz
Beam width	0.71°
Pulse duration	1.6 μs
Number of beams	49
Scan angle (Cross track scan)	±17°
Number of gates	From 122 to 139 depending on the beam
Horizontal resolution	4.3 Km (pre-boost)/5 Km (post-boost)
Vertical resolution	250 m
Swath width	220 Km (pre-boost)/245 Km (post-boost)

et al., 2001b; Sempere-Torres et al., 2001; Sempere-Torres et al., 2003). Figure 1 shows the densification of two fields, one convective and other more stratiform.

Simulations of ground radar and spaceborne radar have been performed over these two 3D fields with the specifications shown in Table 1 for the ground radar, and in Table 2 for the spaceborne radar (TRMM-PR specifications before the boost).

Figure 2 shows the simulations for ground radar located at 25 and 65 km of the densified volume. Therefore this simulation illustrates some effects induced by the distance to the radar. Notice that when simulation of the reference field located at 65 km from the radar is performed, the degraded field suffers from the decrease of resolution due to a wider beam and the increasing height of the beam.

Figure 3 shows the simulation of the spaceborne radar measurement over the same fields. The degradation of the fields is much higher in horizontal dimension due to the resolution. In vertical dimension this radar is getting better resolution than the ground one (one value each 250 m in front of 20 elevations, which are sparse far from the radar).

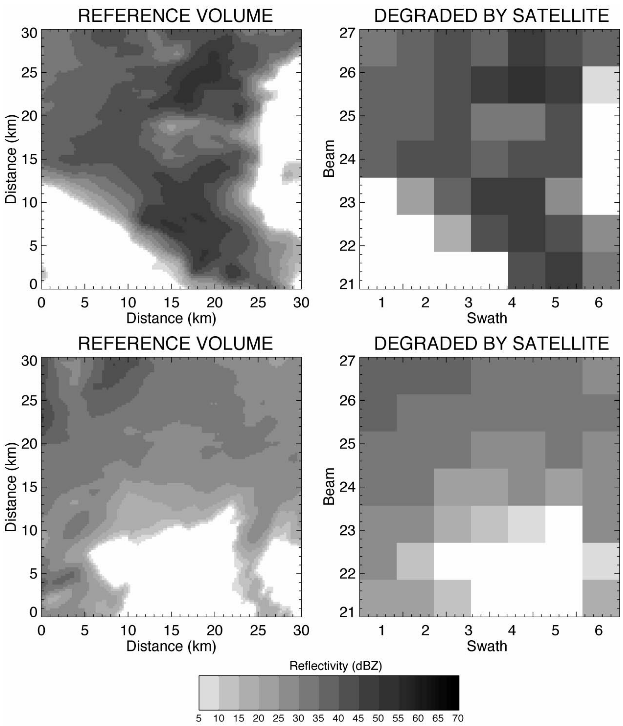

Fig. 3. Spaceborne radar measurement simulation over the two high resolution precipitation fields. Te firs column images correspond to the first height level of the reference volume and the second column to the lowest measurement of the satellite.

6 Summary

This simulation framework can provide important information for studies of error sources, such as smoothing of horizontal and vertical reflectivity gradients due to radar sample volume averaging, increase of sample volume height with range, non uniform beam filling, attenuation, and beam-blocking effects. All these studies will evolve in designing the characteristics and location of the ground equipment in order to get a better precipitation field to compare with the satellite data, and in getting the error distribution of each measurement.

The simulation of the spaceborne radar has to be improved adding the interaction of the beam with the Earth, and other instruments (such as vertical profilers) can be included in the framework. The vertical resolution of the three-dimensional precipitation field might be increased due to the vertical resolution of the spaceborne radar. Simulation of the rain attenuation is also planed.

Acknowledgements. This work is done within the framework of the EU funded project VOLTAIRE contract number EVK2-2002-CT-00155. The authors also want to thank the Spanish National Weather Service (INM) for providing the radar data.

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