Efficient radar forward operator for data assimilation and model verification (1)

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1 Introduction

Weather radar systems provide unique information on dynamical and microphysical characteristics of cloud structures and precipitation with a high temporal and spatial resolution. The new weather radar network of the German Weather Service (Deutscher Wetterdienst, DWD) comprises 16 (soon 17) C band dual polarisation Doppler radar systems evenly distributed throughout Germany for complete coverage and with a temporal resolution of 5 minutes.

The DWD runs the non-hydrostatic limited area numerical weather prediction model of the Consortium for Small Scale Modeling (COSMO), called “COSMO model” (formerly “Lokal Modell” LM) [2],[3]. COSMO is a cooperation of 7 European national meteorological services including the German Weather Service. More information on COSMO can be found on the webpage: http://www.cosmo-model.org

Up to now radar data are not used in the COSMO model, except within the framework of latent heat nudging and for a simple nudging method of the radial wind. However, future applications are planned to make better use of radar data within an upcoming new LETKF data assimilation system. Since the model is also used for higher resolution cloud resolving studies using a modern two-moment bulk scheme [4], the radar data can be used together with the output of the COSMO model in the context of data assimilation as well as model and cloud microphysics verification.

In order to enable comparisons between measured data and numerically modeled data a radar forward operator that calculates the radar observables from the prognostic output of the COSMO model has been developed. Starting from the prognostic output of the model (e.g. wind, temperature, hydrometeors) given on the model grid the aim of the radar forward operator is to simulate the radar variables reflectivity, radial wind and polarisation parameters in the same coordinate system as a “real” radar would measure them. Several additional physical processes and important radar measuring characteristics/errors at different levels of complexity are taken into account. The Operator was created in a comprehensive and modular design and hence by subsequent neglect, simplification and/or approximation of single physical effects, the “best” balance between computational efficiency and physical accuracy for each of the two applications (data assimilation and model verification) can be investigated. A detailed description of the design of the radar forward operator and first results are given in the following.

In an accompanying paper “Efficient radar forward operator for data assimilation and model verification (2)” by Y. Zeng [1] more details of the operator are represented with regard to its application in LETKF radar data assimilation.

2 Radar Forward Operator

An overview of the schematic structure of the radar forward operator is shown step-by-step in Figure 1. As already stated, the operator uses the prognostic variables of the COSMO model given on the model grid. The main quantities needed for further calculations are the three-dimensional wind components (u, v, w), the temperature T and information on hydrometeors. Depending on the microphysical bulk scheme we distinguish between cloud droplets, cloud ice, raindrops, snow, graupel using its mass densities \( q_c \), \( q_i \), \( q_r \), \( q_s \), \( q_g \) in case of the one-moment scheme and hail as sixth type of precipitation particle using the mass densities and the number densities of all six hydrometeor classes in case of the two-moment scheme [4], [5], [6].

As a start the temperature dependent refractive index \( m \) of the particles is calculated. Here one can choose between different formulas of approximation for water and ice. Special emphasis is given to melting particles composed of a mixture of ice, water and air depending on the degree of melting. In this case the choice is between three popular Effective Medium Approximations (EMA), see [7], [8], [9]. In case of the Maxwell-Garnett-Formulation, which assumes small spherical or spheroidal inclusions of different materials are suspended within a hosting material (matrix), numerous selectable (sub-)possibilities for a three-component mixture are added. Some of these different EMAs lead to significantly different results (mainly because one of the components, water, is a strong dielectric), whose spread might be regarded as a lower bound of inherent “natural” uncertainty.
Prognostic variables of the COSMO-model:
- \( q_c, q_i, q_r, q_s, q_g, \ldots \)
- \( u, v, w, T, \ldots \)

Vertical interpolation of values from model grid onto radar beam

Calculate propagation of radar beam, consider as:
- constant (4/3 earth model)
- variable (depending on \( m \))

(consider shading effects)

Amplitude attenuation of radar reflectivity by atmospheric hydrometeors (and gases)

Calculation of radial wind from 3d wind components on radar beam

Beam weighting function: weighted spatial mean over measuring volume increasing with distance

Figure 1: Conceptual flow chart of the full comprehensive and modular radar forward operator including all important physical processes. Red means not implemented yet and * indicates calculations where lookup tables are required due to computational complexity.

Now the radar reflectivity \( \eta \) and hence the equivalent radar reflectivity factor \( Z_e \) can be calculated on the model grid,

\[
\eta = \int_0^\infty \sigma_b(D, m)N(D)dD \quad \rightarrow \quad Z_e = \eta \frac{\lambda^4}{\pi|K_{w,0}|^2}
\]

with \( \sigma_b \) backscattering cross section, \( N \) particle size distribution, \( D \) diameter of the particles, \( \lambda \) wavelength of the radar and \( K_{w,0} \) reference value of the dielectric constant of water. The computation of \( \sigma_b \) can be based either on full Mie scattering theory or with more efficient formulas employing the Rayleigh approximation together with simple approximations for the refractive index. In case of Mie-scattering, the particle prototype can be chosen to be a homogeneous sphere or a two-layered sphere whichever is appropriate (e.g., dry/melting snowflake, melting hail). Afterwards a summation over all types of hydrometeors still has to be done.

Using the same rationales as for the reflectivity the extinction coefficient \( \Lambda \) can be calculated

\[
\Lambda = \int_0^\infty \sigma_{ext}(D, m)N(D)dD
\]

with \( \sigma_{ext} \) extinction cross section including side scattering effects and absorption. Note that the calculation of \( \sigma_{ext} \) requires the use of Mie theory. One further remark on this point: Compared with the simpler and more efficient Rayleigh approximation, calculations using Mie theory are very demanding and computationally expensive. Optimisation of the computation of Mie scattering can be done by means of lookup tables which are currently being implemented.

Since the radar forward operator has to work on parallel supercomputer architectures, parallelisation techniques also have to be considered for good computational efficiency. One strategy is to divide the radar volume in “azimuthal slices” and distribute them evenly in a way that each computing processor gets about equal work to do. This is necessary to achieve good load balancing and avoid idle times of single processors.

In the next step the propagation of the radar beam is calculated considering beam bending due to atmospheric refraction. This can either be done once—assuming as constant in time—using the 4/3 earth approximation (to save numerical effort) or for every radar time step depending on the variable refractive index as a function of temperature, pressure and vapor pressure. A
more detailed description of the computation of the microwave beam bending can be found in the extended abstract by Zeng following this abstract [1].

Shadowing by orographic obstacles can be additionally taken into account but is not fully implemented by now. Afterwards the values of reflectivity, extinction and model wind can be interpolated trilinearly onto the radar beam.

Knowing the path of the radar beam to the scattering particles depending on radial distance \( r \), azimuth \( \phi \) and elevation \( \Theta \), the attenuation of the radar beam due to atmospheric hydrometeors and gases can be calculated. Using the extinction coefficient \( \Lambda \), the so-called two-way attenuation coefficient \( I_{N}^2 \) is defined as:

\[
I_{N}^2 = \exp \left( -2 \int_{0}^{r_{0}} \Lambda(r, \phi, \Theta)dr \right)
\]

with \( r_{0} \) distance of the scattering particle to the radar. To get the attenuated reflectivity (\( Z_{a} \)), \( Z_{e} \) has to be multiplied by \( I_{N}^2 \).

The radial wind is easily calculated from the wind components, that are now given in the coordinate system of the radar beam. Additionally, a reflectivity weighting and the fall speed of the hydrometeors can be taken into account.

At this point, all radar observables are given on the radar beam lying on a single line along the beam axis. For the increasing pulse volume with distance a Gaussian beam weighting function can be employed horizontally and/or vertically. This was implemented using a Gauss-Legendre quadrature with a selectable number of integration points. More details can be found in part (2) by Zeng [1] and in [10].

Finally a few words on polarisation parameters: At the moment, they have not been implemented in the operator but it is planned for the near future to include at least some polarimetric moments, possibly by means of the program SynPolRad by Pfeifer et al. [11]. However, the computation of the polarisation parameters will drastically increase the runtime of the forward operator and hence again lookup tables depending on temperature, mass densities and the shape of the hydrometeors (including canting angle distributions and axis ratios of the spheroids as a function of size) are mandatory.

3 First Results

Having all relevant processes implemented, the nearly complete radar forward operator embedded in the COSMO model can be tested in its present state. This has been done on the NEC SX-9 vector-parallel supercomputer of the DWD. First simulations were conducted using an idealised test case, a convective system triggered by a warm bubble along the lines of Weisman and Klemp [12]. At first, one radar station was simulated with a resolution of 130 range bins of 1 km in radial direction, 20 elevations and 360° azimuths in a temporal resolution of 5 min. For the model the horizontal grid spacing has been chosen to 1 km with a time step of 6 s. The operator was tested with the different adjustments which have been explained in the previous section. Some of the results are shown in Figure 2 for the reflectivity after two hours of model run using two different radar wavelengths. The results in the first column have been obtained by applying Rayleigh scattering in combination with an approximation of the hydrometeors refractive index described by Oguchi [9]. Compared with Mie scattering shown in the second column, the Rayleigh calculation becomes inaccurate at high values of reflectivity due to the presence of partially melted large graupel. The third column shows the same Mie calculation but additionally considering attenuation by hydrometeors. One can see a big influence of this effect increasing towards smaller wavelengths. All other aspects of the operator, like, e.g., refractive beam bending depending on the actually simulated model temperature, pressure and humidity, and smoothing with the beam weighting function have also been successfully tested (see paper by Zeng [1]).

The next step in testing the operator has been to simulate true meteorological situations and more than one radar station. One example of such a simulation run is shown in Figure 3 for the 04.09.2011, comparing pseudo-composites of the 16 current DWD radar stations of both simulated and measured radar reflectivities, in this case a simple plot of all the 1.5 degree constant elevation scans (PPI, plan position indicator). Thus, reflectivity often shows “jumps” at intersections of radar boundaries because of the different scan altitudes. This simulation run serves to demonstrate the technical functionality, and virtually any number of radar stations can be simulated within one COSMO-model run on supercomputer architectures. The run time of the radar operator was less than 10% of the total model run time using the same configurations for all radars as described above for the idealised experiments and using Rayleigh theory.

4 Conclusion and Outlook

First simulations done with the current version of the radar forward operator show good results so far. However, the program is still under development, a few processes have to be completed and some polarimetric moments need to be implemented (see red indications in Figure 1). More work has to be invested in making the computations more efficient.

The application of the radar forward operator enables comparisons between simulated and measured radar data for interesting case studies (e.g. of convective hail cells), using for example the CFAD (contoured frequency by altitude diagram) method, which compares vertically stratified areal statistics. Thus, hints and conclusions about the representation of microphysical processes within the model system can be drawn, which is an important step for further improving cloud microphysical schemes.
Rayleigh theory  |  Mie theory  |  Mie theory + extinction

Figure 2: Simulations using the radar forward operator: radar reflectivities of an idealised test case.

Figure 3: Radar composite with 16 radar stations of a real synoptical situation, date: 04.09.2011, time: 3:30 pm. Left: radar data simulated using the forward operator. Right [13]: radar data measured by the 16 current radar stations of DWD.
References

[1] Y. Zeng et al., 2012: Efficient radar forward operator for data assimilation and model verification (2). 7th ERAD, Toulouse, France


