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Optimisation of spaceborne cloud profiling radar vertical and radiometric resolution requirements for resolving highly layered cloud structures

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Abstract. EarthCARE, a candidate Earth Explorer Core mission of ESA (European Space Agency), aims to improve our knowledge of the impact of clouds and aerosols on the Earth's radiative budget. If the mission is selected, the satellite will carry two nadir sounding active instruments: a Cloud Profiling Radar (CPR) and a backscatter lidar. In addition, a multispectral cloud-imager and a broadband radiometer complement the payload. The objective of the present study was to optimise the parameters of the CPR for retrieving accurate radiative profiles for highly layered cloud structures. Realistic three-dimensional cloud scenarios taken from ground-based experiments have been used for simulating the spaceborne radar response to cloud layers. A radar simulator was developed initially for one-dimensional simulation of the radar echoes and then improved to a three-dimensional simulation. The cloud microphysical properties were retrieved using a model as a function of the reflectivity factor and ice crystals size distribution, based on statistic studies from in-situ measurements. An extensive parametric analysis was performed for various vertical resolutions and sensitivities that have direct impacts on the radar design and necessary resources on-board the satellite. The analysis demonstrated that the proposed radar characteristics will meet the top-of-the-atmosphere radiative flux density estimation accuracy of 10 W/m^2 as recommended by WCRP.

1 EarthCARE Candidate Earth Explorer Mission

The Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) is a mission jointly proposed by European and Japanese scientists in the frame of the Earth Explorer Core missions (SP-1257(1), 2001). EarthCARE is based upon more than two years of scientific exchanges between Japan and Europe, on the work previously carried on ATMOS-B1 (99P0A1-D011, 1999) (JAXA) and the Earth Radiation Mission (ESA) and on the joint preparation of the Report for Assessment for the User Consultation Meeting held in Granada in 2001. At the end of the Assessment cycle, EarthCARE was one of the three missions selected for Phase A level study.

EarthCARE has been specifically defined with the scientific objectives of determining, for the first time, in a radiatively consistent manner, the global distribution of vertical profiles of cloud and aerosol field characteristics to provide basic essential input data for numerical modelling and global studies of the divergence of radiative energy, the aerosol-cloud-radiation interaction, the vertical distribution of water and ice and their transport by clouds, and the vertical cloud field overlap and cloud-precipitation interactions.

Reflecting the above requirements on EarthCARE, the following payload elements are required to fulfil the mission objectives:

– a backscatter lidar to determine vertical profiles of aerosol physical parameters;

– a Cloud Profiling Radar (CPR) for the retrieval of the micro- and macroscopic properties of clouds, precipitation and their convective motions;

– a multi-spectral imager to provide information of the horizontal structure of cloud fields in support of the vertical profiles measured by the active instruments;

– a broadband radiometer to measure short-wave (SW) and long-wave (LW) fluxes at the top of the atmosphere (TOA) as a constraint on the radiative flux derived from the vertical profiles of atmospheric properties and in particular the cloud-aerosol profiles measured by the active instruments and other passive instruments on board.

In synergy, the backscatter lidar, the CPR and the multi-spectral imager can retrieve vertical profiles of cloud physical parameters, and the broadband radiometer will validate the TOA flux derived through the retrieved physical parameters.

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2 CPR Characteristics

As a part of the cooperative agreement between ESA, JAXA and NICT (National Institute of Information and Communication Technology), the CPR will be developed by NICT/JAXA as a payload contribution to EarthCARE. A unique feature of this instrument is the emission of microwave pulses that penetrate deep into lower cloud layers, which can not be viewed by passive optical sensors or reached by the lidar. It is designed to attain a high sensitivity for detecting a large majority of so-called 'radiatively significant clouds' and has a Doppler capability to measure vertical cloud motions and light precipitations.

The latest design of the CPR can be found in Kumagai (2002). Table 1 summarises the instrument design and expected performance, which reflect the result of the optimisation analysis presented in this paper.

3 CPR System Simulator

Details concerning equivalent reflectivity profile calculations, detectability and radiometric accuracy requirement are explained in a preliminary study (Tinel et al., 2002). Using 3D scenarios implies the introduction of horizontal distance integration and to take into account the beam filling effect. A simplified inverse model has been used in order to reduce time of calculations. The radar simulator is explained in Sect. 3.1, and Sect. 3.2 and 3.3 respectively present the simplified inverse model and radiative transfert model.

3.1 3D Simulator

The radar simulator is composed of four modules allowing to retrieve the reflectivity profiles "measured" by the radar from the "true" reflectivity profiles.

The input to the simulator is the so-called "True" cloud profile Z_{true}(h) derived from actually measured cloud structures. The Attenuation Module accounts for the signal attenuation through the atmosphere and cloud layers in the satellite geometry, i.e. measured from the top. The Beam Filling Effect Module takes into account the spatial integration. The Noise Module simulates the effects of the speckle and thermal noise. Finally, the Convolution Module generates the "Measured" cloud profile Z_{meas}(h) by simulating the radar transfer functions (PTR and IR). The noise characteristics is appropriately scaled in order to account for the oversampling of the signal by the radar (100 m sampling), hence the samples are correlated.

3.2 Microphysical inverse model

In order to reduce calculation time, a realistic inverse model built from in-situ microphysical data has been used. This inverse model relates the normalisation parameter N_0* (which characterizes paricle size distribution) (Testud et al., 2000) to the apparent reflectivity, the extinction coefficient and the ice water content.

$$N_0^* = 5.5.10^8 * Z_{meas}^{-0.418} \tag{1}$$

$$IWC = 0.45835 * N_0 *^{-0.122}\, \alpha^{1.122} \tag{2}$$

$$IWC = N_0^* * 10^{\left[0.0036X^4+0.1505*X^3+2.3403X^2+16.695X+36.48\right]}$$
$$\text{with } X = \log_{10}\left(\frac{Z_{meas}}{N_0^*}\right) \tag{3}$$

Thus it is simple to derive from reflectivity the corresponding N_0*, IWC and α in order to perform radiative transfer computations.

3.3 Radiative transfer (RT) model

The RT model is extracted from the physical package of the LMD (French laboratory, CNRS) atmospheric general circulation model and can be run in a single-column mode (one-dimensional). The short-wave radiation model was designed by Fouquart and Bonnel (1980), and the long-wave radiation model was designed by Morcrette (1991), which use a plane-parallel geometry approximation applied on each vertical measurement profile.

The input data necessary to run the radiative transfer code are the temperature and specific humidity profiles. The ozone is prescribed as long-term mean climatological values. Cloud-related parameters are the cloud fraction, cloud overlap, cloud emissivity and optical thickness. They are retrieved from radar observation. The cloud emissivity is calculated through the cloud liquid (or ice) water path W (g/m^2):

$$\varepsilon = 1 - e^{kW} \tag{4}$$

where k is the absorption coefficient (m^2/g) with the values of 1.33 for warm clouds and 0.09 for cold clouds.

The cloud optical thickness τ is calculated as a function of the cloud liquid (or ice) water path W (g/m^2) and the effective radius of cloud droplets r_e (in μm):

$$\tau = \frac{3}{2}\frac{W}{r_e} \tag{5}$$

Given a cloud scenario, the RT model is run to derive the four "reference" radiative fluxes (upward solar, upward IR, downward solar, downward IR), associated with the "true" radar reflectivity profile introduced as input of the space borne CPR simulation. The "measured" reflectivity profile by the CPR is then inverted and itself introduced as input of the RT model to derive four "retrieved" radiative fluxes.

The optimisation criteria are based on the comparison of the "reference" and "retrieved" radiative fluxes. Two criteria are considered:

The first one is based on the estimate of the RMS (root mean square) difference between any of the four retrieved flux profile and the corresponding reference one. This RMS

Table 1. Design parameters and expected performance of the CPR (*TOA = top of the atmosphere).

Orbit altitude	410–420 km
Mission duration	$\geq$2 years
Frequency	94.05 GHz
Polarisation	Linear or circular
Beam pointing	Fixed vertical (nadir)
Antenna aperture size	$\leq$2.5 m diameter
Transmitter peak power	$\cong$1800 W
Pulse length	3.3 μs (unmodulated)
Pulse repetition frequency	5.3 to 6 kHz (orbit position dependent)
Altitude range	−0.5 to 20 km
Vertical sampling interval	100 m
Vertical resolution (half-power width)	$\leq$400 m
Antenna beam footprint size (−3 dB contour)	$\leq$700 m
Along-track integration (on-board)	1 km
Dynamic range of radar reflectivity factor	$\leq$−38 dBZ to $\geq$+30 dBZ (for 10 km integration at TOA*)
Doppler measurement accuracy	$\leq$1 m/s in the range $\pm$10 m/s
Radiometric resolution	$\leq$1.44 dB

difference is representative of how well the profile of the various fluxes are retrieved, and thus of how well the vertical distribution of heat associated with the cloud radiation process is captured by the CPR.

The second one is more traditional: it considers the comparison of the reference and retrieved TOA (Top Of Atmosphere) fluxes (upward Solar and IR).

The assumption on the cloud overlap and cloud fraction also influences the radiative transfer calculations. Following the latest trend in the use of general circulation models, all simulations are performed using the random-maximum overlap assumption. A cloud fraction of 0.9 is used.

4 Cloud scenarios

Representative cloud scenarios have been selected from three cloud data bases:

- the South Great Plains (SGP) and the Surface HEat Budget of the Arctic ocean experiment (SHEBA) deployed in the framework of ARM (Atmospheric Radiation Measurements program);
- the Cloud Lidar And Radar Experiment-1998 (CLARE98),
- the CLOUDNET data base.

The choice of each scenario is guided first by the multilayered character of the cloud structure, and second by the availability of:

- ground-based radar reflectivity profiles;
- associated temperature profiles from radiosounding or model if radiosounding is not available;

Table 2. Pairs of τ and z_{min} used for the simulations.

Pulse length / Vertical resolution		2.31 μs / 270 m	3.3 μs / 385 m	4.62 μs / 539 m
Baseline design	$\boldsymbol{Z_{min}}$(dBZ)	−18.3	−21.3	−24.3
	$\boldsymbol{Z_{Thr}}$ (dBZ)	−28.5	−31.5	−34.5
Reduced design	$\boldsymbol{Z_{min}}$(dBZ)	−12.3	−15.3	−18.3
	$\boldsymbol{Z_{thr}}$(dBZ)	−22.5	−25.5	−28.5

- associated humidity profiles from radio-sounding or model;
- cloud base heights from ceilometer.

4.1 Radar performances

In order to test the radar performances, three pulse lengthes corresponding to three different vertical resolutions have been tested (Table 2). Each of them was tested with two radiometric sensitivity Z_{min} (EarthCARE baseline design and one reduced design with a 6 dBZ degradation) and with application of corresponding thresholding Z_{th}.

4.2 Cloud scenario presentation

We choose here to present the results of one of the scenarios ("oceanic" mid-latitude case) from CLOUDNET data base using the RASTA (CETP) french 95 GHz radar. Radar data were recorded on the 15 November 2003 on the SIRTA site (Site Instrumental de Recherche par Teledetection Active – Remote Sensing Instrumental Site). The reflectivity is measured with the 94 GHz ground-based zenith-pointing RASTA radar (Fig. 1).

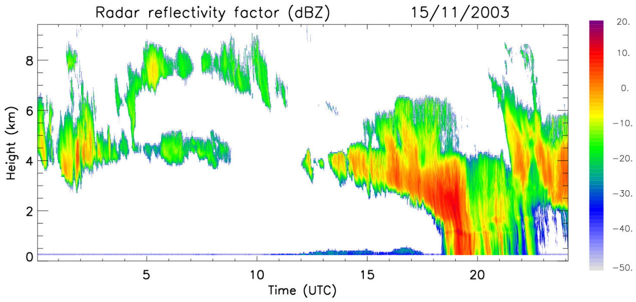

Fig. 1. Illustration of apparent reflectivity of RASTA radar on the 15 November 2003 on SIRTA site (Courtesy of SIRTA).

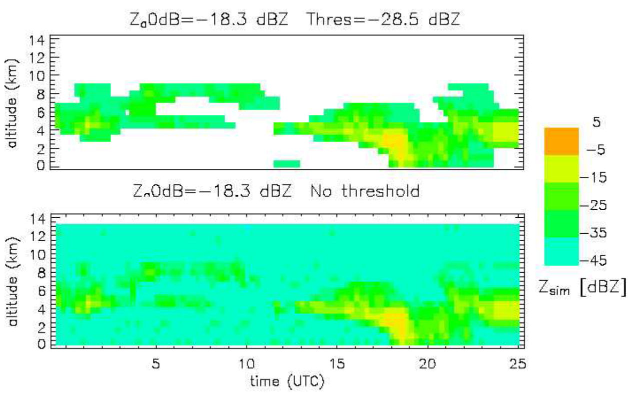

Fig. 2. Illustration of simulated reflectivity from the CPR simulator for the case of the 15 November 2003 on SIRTA site. Reduced sensitivity design, 529 m vertical resolution, −28.5 dBZ thresholding applied (top), without thresholding (bottom).

- a single cloud layer extends from 4 km altitude up to 6 km altitude from 0000 to 03:00 UTC, then from 3 km altitude up to 5 km altitude from 03:00 to 09:00 UTC.

- a second layer occurs from 7 km altitude up to 8 km altitude from 04:00 to 11:00 UTC,

- a single layer extends from 3 km altitude up to 6 km altitude from 12:00 to 24:00 UTC, with a cloud base altitude decreasing to the ground level from 19:00 until the end of the day.

Radar measurements have been performed from 00:00 until 24:00 UTC with a pulse-burst cycle of 30 s. Thermodynamical profiles are given by Meteo France (Trappes site located at 20km from the SIRTA site) at 23:14 UCT on the 14 November 2003, and at 11:17 UTC and 23:17 UTC on the 15 November 2003.

4.3 Simulation results

A further experiment was carried out to analyse the effect of applying a threshold on the 'measured" Z profiles. As a matter of fact, all "measured" profiles are noisy in the area of low reflectivity or in absence of clouds. Such noise, if

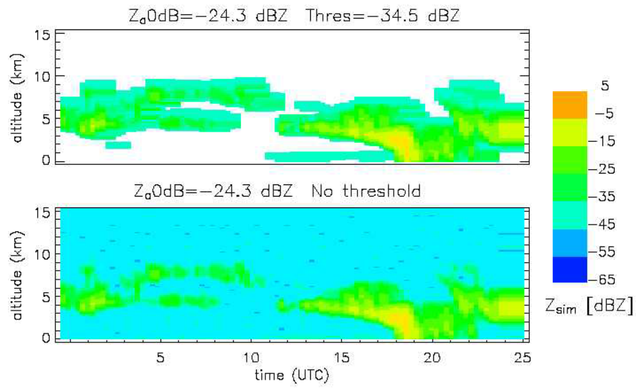

Fig. 3. Illustration of simulated reflectivity from the CPR simulator for the case of the 15 November 2003 on SIRTA site. EarthCARE baseline design, 529 m vertical resolution, −34.5 dBZ thresholding applied (top), without thresholding (bottom).

not removed, will contribute to the flux estimates as ghost-clouds, hence possibly introducing further errors. Thus for each simulation, the flux calculations were performed in two different ways:

- a thresholding was applied at the sensitivity limit Z_{min} below which all values were set to zero;

- no thresholding applied, i.e. the complete profile including noise is used for flux calculations.

Figures 2 (reduced design) and 3 (EarthCARE baseline design) represent simulated reflectivities with thresholding application and without for 529 m vertical resolution. Some information on clouds is lost when thresholding is applied, whereas ghost clouds appear without thresholding. The mean noise levels are lower for the baseline design (−55 dBZ) than for the Reduced design (−35 dBZ).

Figure 4 presents the results concerning the upward Solar and IR TOA flux errors for 529 m vertical resolution and for thresholding of −34.5 dBZ and −28.5 dBZ respectively applied on EarthCARE (plain) and reduced (dotted) designs. Solar fluxes are only present during the day hence from 07:00 to 16:00 UTC. Mean values TOA errors for solar fluxes are from 0 up to 4 W/m^2 for the baseline design as they reach 8 W/m^2 for the reduced design. Mean values TOA errors for IR fluxes are from 0 up to 8 W/m^{-2} for both designs and differ from less than 1 W/m^2 from a design to another. Without thresholding (Fig. 5), solar fluxes TOA erros increase due to the presence of ghost clouds and reach 34 W/m^2 for the baseline design and 37 W/m^2 for the reduced design. This proves the importance of the application of a thresholding if taking the recommendation of the WCRP for the TOA flux density estimation accuracy of 10 W/m^2. Taking into account a thresholding or not does not affect so much IR flux TOA errors because of the presence of ghost clouds in low altitudes.

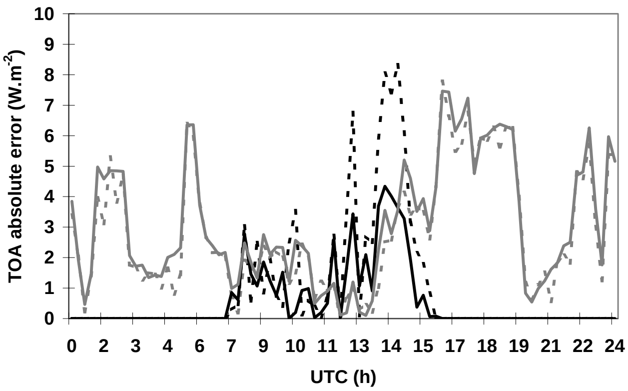

Fig. 4. Retrieved IR (grey lines)/Solar (black lines) upward fluxes TOA errors from the CPR simulated data (4.62 pulse length). Plain lines and dotted lines respectively represent results from the Baseline and Reduced designs. Thresholding applied.

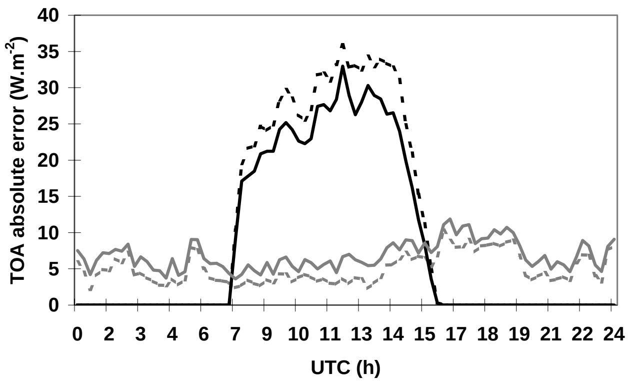

Fig. 5. Retrieved IR (grey lines)/Solar (black lines) upward fluxes TOA errors from the CPR simulated data (4.62 pulse length). Plain lines and dotted lines respectively represent results from the Baseline and Reduced designs. No thresholding applied.

5 Conclusion

The CPR is one of the core instruments to be flown for the EarthCARE, candidate Earth Explorer mission. For meeting the scientific objectives of the mission according to the WCRP requirement and at the same time keeping the mission affordable, it was necessary to optimise its performance in terms of its vertical resolution vs. detection sensitivity. This study presented the result of such an analysis based on simulations using realistic cloud scenarii. Errors in estimating radiative fluxes across the atmospheric layer were calculated by comparing the results of radiative transfer calculations for the "true" and "measured" reflectivity profiles. Errors were calculated in 7 specific cloud profile scenarii, attempting to cover some variety of climatic conditions. One of the cloud scenarios was presented in this paper.

For the simulated cloud profiles, the optimum radar parameter combination was found to be with a pulse-length of 4.62 μs, corresponding to a vertical resolution of 539 m, and a detection sensitivity of better than or equal to -34.5 dBZ. For this parameter setting, the TOA flux estimation error remained below 10 W/m^2 in all scenarii. Effects of degrading the detection sensitivity by 6 dB with respect to the Baseline design were also analysed. It is expected that for clouds of lower reflectivity (low optical thickness), larger differences in flux estimation errors will occur between the two simulated sensitivities.

The simulator developed for this study will be incorporated into a complete mission simulator, capable of generating synthetic data of all payload-instruments on-board the EarthCARE satellite. Such a mission simulator will be a basis to demonstrate the overall performance of the proposed mission for evaluation at the end of the phase A level study.

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