Numerical scattering simulations for interpreting simultaneous observations of clouds by a W-band spaceborne and a C-band ground radar

Anna Cinzia Marra¹*, Gian Paolo Marra¹ and Franco Prodi²

¹Institute of Atmospheric Sciences and Climate (CNR-ISAC), Strada Provinciale Lecce-Monteroni km 1.2, 73100 - Lecce, Italy
²Institute of Atmospheric Sciences and Climate (CNR-ISAC), Via P. Gobetti 101, 40129 - Bologna, Italy
*Corresponding author, e-mail address: a.marra@isac.cnr.it

Abstract

The spaceborne W-band (94 GHz) Cloud Profiling Radar (CPR) onboard the CloudSat (CS) satellite, which was launched in 2006, is providing valuable information about global cloud properties. This work aims at interpreting collocated time/space observations from CPR on CS and a ground C-band (5.6 GHz) Radar (GR), with the help of numerical simulations of electromagnetic scattering returns from populations of monodisperse spheres of ice and liquid water. Two cloud systems over Apulia region are investigated. CPR and GR images have been geo-referenced, then combined and displayed for analysis. The numerical simulations of the two radar reflectivities are used as a tool in the inversion procedure, aiming at identifying the hydrometeors, in their phase and size distribution, in the cloud volume simultaneously observed by the two radars. The possible vertical profiles of hydrometeors are presented.

Keywords: radar meteorology, hydrometeor identification, numerical modelling of scattering.

Introduction

Weather radar is a key tool to study microphysical characteristics of clouds and precipitation. Precipitation radars in particular operate at frequencies in the X, C or S bands. Millimeter wavelength radars, such as W or Ka bands, are used to investigate non-precipitating clouds, since attenuation, especially due to liquid water, increases rapidly at higher frequencies. So their use is hindered when volumes containing large amounts of liquid precipitation are to be investigated. Instead, because of a relatively low attenuation by ice, cloud radars are used to analyze precipitating ice and snow clouds [Matrosov et al., 2008a]. Comparisons have been made between spaceborne and ground radar reflectivities to provide an insight into the internal structure of clouds and cloud systems. In particular studies have been recently presented comparing data from W-band Cloud Profiling Radar (CPR) on
board CloudSat (CS), operating at 94 GHz, and ground radar (GR) observations. Protat et al. [2009] compare CPR reflectivities and basic ice cloud properties with ground-based radar observations, showing generally good agreements between the two datasets. Combined CPR and GR observations have also been used to quantitatively estimate rainfall and ice particles in hurricanes [Matrosov, 2011] and, by using attenuation based reflectivity gradient method, retrieve rain characteristics [Matrosov et al., 2008b]. Numerical scattering simulations at typical values of parameters of falling snow have been used in order to derive frequency maps of reflectivity and to use these maps on measured data to predict radar outputs at frequencies where no direct observations are available [Leinonen et al., 2011]. The effectiveness of this approach has been demonstrated for the purpose of predicting Ku/Ka observations from a C-band ground radar and W-band CS measurements.

The present study aims at developing a method to collocate the CPR and GR data and to use the numerical methods of scattering as a tool in the inversion procedure in investigating the microphysical characteristics of the hydrometeors in the common reflecting volume. The problem is to find which population of hydrometeors is responsible for the received CPR signal, essentially the inverse problem. An immediate, and obvious, solution is to provide in situ observations [Austin et al., 2009] or to integrate the CPR measurements with airborne cloud radar observations [Baker et al., 2008]. But this is only occasionally possible, apart cost considerations. The use of the outputs of cloud resolving models and of the comparison of radar outputs with those calculated from the model outputs has also been pursued [Woods et al., 2008]. In this work our efforts were focused to solve the problem by taking advantage of the fact that hopefully the same reflectivity volume, containing the same meteorological targets, is observed by the two radars operating at different wavelengths. In other words we look for the specific hydrometeor population compatible with the output of both radars. The development of such multifrequency methods can be used in the framework of the Global Precipitation Measurement (GPM) mission that will carry the first space-borne Ku/Ka-band (13.6/35.5 GHz) Dual-frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI) to advance our understanding of Earth’s water and energy cycle, and improve forecasting of extreme events.

**Methodology**

To solve the inversion problem making use of observations of CPR and GR, it is necessary to know the radar characteristics, to develop a procedure to collocate their outputs and finally to define a methodology for the numerical simulations of the two radar reflectivities used as a tool in the inversion procedure.

**Characteristics of the two active sensors**

The spaceborne active sensor CPR on CS is a nadir looking radar measuring the power backscattered by clouds as a function of distance from the radar and acquiring global time series of vertical cloud structure [Tanelli et al., 2008]. The vertical reflectivity profile data of the cloud, measured by the CPR along its path in its leg over Apulia, were obtained from Cloud-Sat Data Processing Center (http://cloudsat.cira.colostate.edu). A C-band ground radar, located in Martina Franca, at 40.63 °N and 17.31 °E, provided
reflectivity data. The radar was operated by a private company for weather surveillance and operational services from 2008 to 2010. This C-band radar works at 5.6 GHz and has a maximum radius coverage of 200 km. The radar was driven by the TITAN software system developed at National Center for Atmospheric Research (NCAR) by Dixon and Wiener [1993]. Although the radar could work in Doppler mode, only reflectivity measurements were available from this instrument. Moreover, data were collected during azimuthal scans at fixed elevations, i.e. PPI (Plan Position Indicator) scans, but only post-processed data of Cartesian volumes were available.

**Space-time collocation procedure**

In general it is not easy to collect significant cases of coincident observations of narrow swath satellite sensors and ground radars. In this case the main difficulty was due to a very limited dataset of GR data. Moreover the projection of CS passes at a distance of less than 50 km from the radar site less than twice a month and unfortunately clouds or precipitation were not always present. This obviously produces only few cases of simultaneous observations by both radars.

Firstly it has been looked for all the CS passages close to the GR radar site and then it has been checked if GR observations were available for the same days. Then GR scans that best coincide also in time with the CS transit have been selected, in order to compare the cross-section given by CPR with the corresponding cross-section as reconstructed by the GR. To make the comparison possible it is necessary to reduce one data set to the projection of the other and overlap them for a first qualitative evaluation and successive analysis. The CPR data vector was superimposed on the raster GR data by making use of the GIS GRASS (Geographic Resources Analysis Support System) Open Source Software (http://grass.osgeo.org). The CPR data vector was projected in lat/lon WGS84 by the CloudSat Data Processing Center and the raster GR data were provided by TITAN software in azimuthal equidistant projection. Thus, after a geographic reprojection of the CPR data vector, a GRASS query was done to extract the reflectivity of the raster GR data corresponding to all points in CPR data vector. This query was iteratively done for all layers of the raster GR data, corresponding to the heights from 1 km to 17.5 km.

Comparing results from different radars at different locations and using different wavelengths, differences are expected due to a number of reasons, which would include miscalibration, mismatching of geometry of observation, different scattering properties of cloud particles and different sensitivities of two sensors, the latter resulting from technical characteristics of radars.

In the following an attempt is made to explain the observed differences in reflectivity profiles in terms of scattering modelling of cloud particles. Here it is important to note that to provide simultaneous measurements, a given ground radar should be preprogrammed using CS orbit predictions, i.e. it should perform Range Height Indicator (RHI) scans with the antenna oriented along the CS track and a mobile ground radar could be the right tool for that use. In fact, as observed by Leinonen et al. [2011], since performing the sector scan with the a ground radar takes minutes, rather than the seconds needed by CloudSat to cover the corresponding lag, there is a slight time mismatch, varying with location, between the measurements, which results in a spatial mismatch in the observed weather pattern. This has to be taken into account, especially during rain events, because, while for snowfall
Leinonen et al. [2011] found quite small errors even for strong winds, this could be not true for rain, due to its lower spatial homogeneity compared to snow.

In the case studies presented in this paper, the simultaneity of data measured by the CPR and those by the GR is considered acceptable, on the basis of the distance of the cloud from the GR, the vertical resolutions of both radars, and the relatively good correspondence of GR observations with CPR transit time. Moreover, because we were in need to use radar data operated with a non-research oriented protocol, we made some calculations in order to estimate the error that can be due to the different ways of operation of the two radars. To this purpose we considered two GR scans, performed just before and after the CS passage. For typical wind speed of about 25 m/s and a time difference of about 1 minute, at least for the lowest elevations of the radar scans, the displacement of the cloud system is about 1500 m, which is still smaller than the CloudSat along-track resolution of roughly 1.7 km. This condition is fulfilled in the case studies where no relevant wind-speeds are involved, as for example for the winter case study discussed here. In our case, from our analysis, we found that also for the summer case study, which refers to a rapidly moving system, the error due to the time mismatch is within the radar resolution.

**Numerical modelling of scattering and reflectivity simulations**

Before describing the methodology applied in this paper, in order to study if the reflectivity profiles measured at different wavelengths can be explained in terms of monodisperse spherical particles of suitable phase and size, it is worth mentioning the one used by CPR team. The CPR 2B-CWC-RVOD product provides retrieval of microphysical properties of clouds, which is the same goal of this paper. The retrieval assumes a lognormal distribution of liquid and ice cloud particles, which are considered sufficiently small to be modelled as Rayleigh scatterers at CloudSat radar wavelength. A correction for Mie effects is then applied only to ice components of clouds. CPR retrievals are performed separately for the two phases and the two sets of results are then combined to obtain a composite profile compatible with the input measurements, using a simple scheme based on temperature as reported by the ECMWF model. In this 2B-CWC-RVOD scheme the portion of the profile colder than -20 °C is deemed pure ice, and the portion warmer than 0 °C is considered pure liquid. In between these temperatures, the ice and water profiles are scaled linearly with temperature, to obtain a profile that, going from all ice at -20 °C to all liquid at 0 °C, matches the radar measurements over the whole range.

Moreover, the 2B-CWC-RVOD algorithm estimates liquid cloud properties using a radar forward model which includes the effects of attenuation by liquid cloud droplets. The liquid retrieval takes into account that the measured reflectivity factor $Z'$ will be reduced from the intrinsic reflectivity factor $Z$ according to the following expression:

$$Z'(z) = Z(z)e^{-\int_{\text{path}} \sigma_{\text{abs}}(z')dz'}$$  \[1\]

where the path integral is over the portion of the cloud between $z$ and the radar and attenuation is considered as being purely due to absorption, because scattering effects are much smaller than absorption effects in the Rayleigh approximation framework. An error
related to the calculation of the attenuation has been identified in the forward model by the science team responsible for the CPR 2B-CWC-RVOD product. Due to a sign error (which is hopefully being corrected as part of the R05 product release), the forward-modelled attenuated reflectivity values can be larger than the unattenuated values and effective radii and liquid water contents are typically underestimated by the retrieval. These effects, which are not present in the retrieved ice cloud properties, are most pronounced for those profiles containing dBZ > -15 (i.e., those profiles which likely contain precipitation).

Departures from log-normal distribution, for example due to the presence of drizzle or rain within the cloud, obviously degrade the accuracy of the retrieval. Moreover, while for thin ice clouds the cloud ice particles are sufficiently small to be modelled as Rayleigh scatterers at the CloudSat radar wavelength, the error introduced by use of the Rayleigh approximation on the large particles that violate the Rayleigh criterion may be significant, even if these coarser particles are few in number.

For all these reasons in this work the assumption that particles are smaller than the wavelength is not made, i.e. the combination of information from both radars is done in the framework of Mie theory.

In this simple scheme it is assumed that measured reflectivity at each height level could be due to a number of spherical particles, all equal in size, made of ice or liquid water, depending on the temperature of the selected level. The reflectivity $Z$ (in units of $\text{mm}^6 \cdot \text{m}^{-3}$) is computed as

$$Z = 10^{12} \frac{4}{\pi^5} \frac{\lambda^4}{|K_w|^2} N\sigma(r) \quad [2]$$

where $\lambda$ is the wavelength (cm), $K_w = (m^2 - 1)/(m^2 + 2)$ is the dielectric factor of water at the selected wavelength, computed from the complex refractive index of water $m$, $\sigma(r)$ is the radar cross section for particle radius $r$ (cm$^2$), and $N$ is the number concentration of particles (cm$^{-3}$).

The reflectivity in units of dBZ is obtained by taking $10 \log_{10} (Z)$ with $Z$ in units of $\text{mm}^6 \cdot \text{m}^{-3}$.

The radar cross section for individual particles has been computed using a Mie scattering simulation code [Bohren and Huffman, 1983], which requires the knowledge of particle size and refractive index. This last parameter has been calculated for ice and liquid water at the temperature corresponding to each level, by using a code based on the approach described by Ray [1972], for the liquid component, and by Warren [1984], for the ice component. As far as $K_w$, the values 0.93 for the C-band wavelength and 0.75 for the W-band, as suggested by Tanelli et al. [2008], have been used.

For the same reflectivity profiles, it has also been simulated the signal attenuation by cloud ice and liquid water, by taking into account contributions by both scattering and absorption.

It is worthwhile to stress that the choice of monodisperse spheres has been carefully evaluated. In fact, because in Rayleigh regime radar returns are proportional to the sixth power of droplet diameter, it is evident the role played by sizes of particles in the observed reflectivity profiles. Before starting scattering simulations, some tests have been performed, by comparing reflectivities simulated for log-normal size distributions of spheres and for monodisperse spheres with size equal to the effective radius of the log-normal distribution.

Due to the negligible observed differences, it has been decided to choose monodisperse spheres as a reliable key in this attempt to make an inversion of reflectivity measurements.
This approach obviously opens the way to more rigorous modelling of scattering, e.g. using polydisperse populations of hydrometeors and other more realistic simulations.

**Results and discussion**

In the present study two meteorological events occurred over Apulia region are investigated: one of them refers to a winter non-precipitating stratiform cloud, while the second one is related to a summer precipitating convective cloud.

**Winter non-precipitating stratiform cloud**

The first case study concerns a light precipitation event over Apulia region and the surrounding seas. It occurred on January 30, 2010 and it was chosen as both GR and CPR data were available for the investigated region. Meteorological conditions over the area of interest are almost stationary during the event, as revealed by large scale maps, satellite and radar images. However this persistence of cloudiness over the southern part of Apulia region does not led to rains over the area, as no relevant precipitation were recorded during the analyzed period.

Figure 1 represents the vertical profile of reflectivity acquired by CPR along a segment passing over Apulia, the Region Of Interest (ROI) in Southern Italy. The vertical cross section of radar reflectivity was measured from 12:05:58 to 12:07:28 UTC on 30 January 2010. The image clearly depicts a variety of high and low clouds that extends from the surface to about 10 km in height.

![Figure 1 - CPR image acquired on 30 January 2010. It corresponds to the red segment in Figure 3.](image)

For this analysis scans that best coincide with the CS path have been selected, at about the same time as the one shown in Figure 1. CS takes 90 seconds to overpass the ROI between 12:05:58 and 12:07:28 UTC and the GR performs a complete scan of the volume every 4 minutes, so the GR data used in this analysis were acquired from 12:08 to 12:12 UTC. Figure 2 shows the superimposition of a section of the CS path, represented by the red line, on MODIS image at 12:05 UTC of 30 January 2010, while Figure 3 shows the GR reflectivity map at 12:08 UTC.
Figure 2 - MODIS image at 12:05 UTC of 30 January 2010 and CS path (red line) superimposed.

Figure 3 - GR reflectivity map at 12:08 UTC and CS path (red line) superimposed in the ROI on 30 January 2010.
Figure 4 shows the results of the GRASS query done to extract the reflectivity of the raster GR data corresponding to all points in CPR data vector. In particular the vertical scan acquired during the CS transit is represented in Figure 4, left, while Figure 4, right, shows the vertical profile of reflectivity values extracted from the GR data measured at 12:08 UTC, above the latitudes and longitudes corresponding to the CS path. From comparison of the two datasets, it has been noticed the presence of a cloud system, in the heights from 2 to about 8 km, extending horizontally within the central portion of the selected trajectory, which is observed by both radars. However the large echo in CPR section, at more than 20 km of southward distance from closest approach, is not seen by GR.

Moreover, above 5 km, GR shows echoes only for a short distance, while CPR detects cloud particles up to 8 and 9 km for almost the whole path. To better understand the variation of reflectivity in between the above heights, two different distance coordinates along the CS trajectory (see indices 22732 and 22828 in Fig. 4) have been selected. These profiles are representative of two significant areas: the 22828 coordinate corresponds to a position where both GR and CPR reveal a signal from the cloud, while the 22732 one corresponds to a position where only CPR observes the presence of a cloud structure. Simple calculations can show that typical cloud envelopes are undetected being below the minimum detectable reflectivity. Unfortunately, while it is well known that CPR reaches a sensitivity of around -29 dBZ, GR sensitivity, which could explain the lack of echoes in the GR 22732 profile, is unknown.

Figure 5 shows the reflectivity vertical profile measured by the two radars for the index 22828. In general, the GR observations show a relatively good correspondence in the 2-5 km height interval to the trends seen in the reflectivity profile obtained by the CPR vertical scan. However, the maximum of reflectivity, observed by GR, is at about 13 dBZ and occurs at 3 km, while the CPR vertical profile reveals a first peak of reflectivity of 9 dBZ at 2.5 km and a secondary peak of 6 dBZ at 5 km. Moreover, in the CPR profiles of Figure 5 it can be further noticed that CPR is also able to detect the presence of clouds well above 6 km, that remain undetected by the GR, to at least
a 10 km height, above which the CPR reflectivity becomes noisy. This has to do with the much higher frequency of the CPR and with the microphysical characteristics of the high clouds.

**Figure 5 - Reflectivity vertical profile measured by GR and CPR for the index 22828.**

Details about the GR calibration are not available and maybe its miscalibration, together with the different observing geometry, could explain some of the observed differences in the vertical reflectivity profiles. Anyway, information about the minimum detectable signal of the GR could improve the quality of discussion. The winter case study is related to a non precipitating cloud. The 0°C level is at about 1.7 km and therefore most of the cloud is at a temperature below the freezing level. For this reason the role of ice particles is assumed to be dominant for this case study and then attenuation by ice, which is not relevant as for liquid water, could be negligible. The results of numerical simulations, shown in Figure 6, seem to support this consideration. In spite of many attempts, in this case study it was not possible to find a unique population of hydrometeors responsible for the signal detected by both radars, i.e. a distribution of hydrometeors able to reproduce, at the two different wavelengths, the different reflectivities measured by the two radars. In fact the distribution of hydrometeors, which is able to reproduce the CPR measurements, produces the same simulated reflectivity also at the GR wavelength, apart a small offset due to the different value of $K_w$. In general, radar reflectivity assumes equal values independent of the particles size or the wavelength for particles much smaller than the wavelength. For this reason the results of these scattering simulations could be interpreted in support of the validity of Rayleigh scattering regime for
these cloud particles. In other words, this cloud seems to be composed by hydrometeors, which are smaller than the wavelength also at CPR wavelength. As expected, attenuation is almost completely negligible at GR wavelength. On the other hand, at 94 GHz, attenuation is present, but does not explain the differences in the reflectivities measured at two different wavelengths.

Figure 6 - Results of reflectivity simulations for the winter case study of 30 January 2010. The GR attenuated reflectivity is not plotted because it is indistinguishable from the GR unattenuated one.

Figure 7 and Figure 8 show the comparison of ice and liquid water radii and number concentrations retrieved in this study with those retrieved by CPR algorithm. Obviously this comparison has to take into account the different distributions of hydrometeors considered in these approaches, monodisperse for this study and log-normal distributed according to CPR retrievals.

It has been assumed that water can be present from the ground level up to a height of 4 km (corresponding to a temperature of -14.3 °C), i.e. it has been restricted the temperature range used by CPR for the mixed phase. Moreover, while a slightly bigger radius for the liquid particles has been obtained, it has also been observed a strong decrease of concentration of the same particles, when compared with the CPR retrieved values. Anyway, all the particles sizes fall in the Rayleigh regime, which can explain the absence of differences in the simulated reflectivities at the two wavelengths. If this is true, the differences in the measured reflectivities could be mostly due to miscalibration of the GR, rather than to attenuation.
Figure 7 - Hydrometeor radii retrieved in the present paper for the winter case study, compared with those provided by the CPR retrieval algorithm.

Figure 8 - Hydrometeor number concentrations retrieved in the present paper for the winter case study, compared with those provided by the CPR retrieval algorithm. Please note that this study and CPR retrieved values of ice number concentration are the same.
Summer precipitating convective cloud

The second meteorological event, occurred on July 6, 2009, is a typical airmass summer convective storm. The radar images show two cells, one of which is stronger and fast moving toward Taranto Gulf, while the second one, which is considered in the present study, interests the Northern and Central part of Lecce Province, for about one hour.

CS takes 91 seconds to overpass the ROI between 12:08:03 and 12:09:34 UTC (Fig. 9) and the GR data used in this analysis were acquired from 12:06 to 12:10 UTC. Figure 10 shows the superimposition of a section of the CS path, represented by the red line, on MODIS image at 12:05 UTC of 06 July 2009, while Figure 11 shows the GR reflectivity map at 12:06 UTC.

Figure 9 - CPR image acquired on 06 July 2009. It corresponds to the red segment in Figure 11.

Figure 12, left, shows the vertical scan acquired during the CS transit, while Figure 12, right, shows the vertical profile of reflectivity values extracted from the GR data measured at 12:06 UTC, above the latitudes and longitudes corresponding to the CS path. Unlike the winter stratiform cloud, in this case both radars show the ability to observe the whole cloudy system, even if there are still some differences with the different sensitivity of the two instruments.

For this case attention has been focused on a selected coordinate indicated with 22758, which refers to the portion of the cloud with the maximum vertical extension and with the maximum value of reflectivity, measured by GR. The vertical profiles measured by GR and CPR are shown in Figure 13, where it is also evident the role played by attenuation of 94 GHz signal, due to the presence of heavy rain, especially at low heights. Going from top to bottom, in fact, reflectivity values measured by CPR show a strong decrease compared with GR. This behaviour will be very important in this attempt to simulate measurements by means of scattering properties of hydrometeors.

However, differences between values of reflectivity at about 12 km, where the effects of attenuation should be negligible, could be due to miscalibration of GR, that in general seems to show a systematic overestimation of reflectivity.
Figure 10 - MODIS image at 12:05 UTC of 06 July 2009 and CS path (red line) superimposed.

Figure 11 - GR reflectivity map at 12:06 UTC and CS path (red line) superimposed in the ROI on 06 July 2009.
Figure 12 - Vertical scan acquired by the CPR (left) and by the GR on the same path of CS at the same time (right), on 06 July 2009. The distance coordinate 22758 (which corresponds to a distance from closest approach of -13.8 km), for which reflectivity profile and numerical simulations are discussed in the text, is also shown.

Figure 13 - Reflectivity vertical profile measured by GR (solid line) and CPR (dashed line) for the coordinate 22758.

For the summer case study, due to the presence of precipitation, it is very interesting to study the role of attenuation of signal, which should affect mainly the W-band reflectivity profile. In other words, it is necessary to look for a suitable distribution of spherical hydrometeors which can reproduce the observed behaviour of reflectivity, in particular the increasing differences between values measured at the two different wavelengths, going from top to bottom of the cloud. Such kind of hydrometeors should be able to produce a reflectivity trend very similar to that measured by GR, when equation [2] is used for the wavelength of
5.5 cm and with the refractive index calculated at this wavelength. On the other hand, the same hydrometeors should produce an attenuated reflectivity very similar to that provided by CPR, when equation [2] is used at the CPR wavelength.

In these simulations it has been tried to take into account the presence of both ice and liquid water and it has been assumed that water can be present from the ground level up to a height of 8.5 km (corresponding to a temperature of -29.7 °C), i.e. the temperature range used by CPR for the mixed phase has been extended. In fact, while the 2B-CWC-RVOD product applies a semiautomatic procedure, by assuming the presence of a mixed phase in a temperature range between -20 °C and 0 °C for all the reflectivity profiles, we took into account the different characteristics of the studied clouds. The different assumptions about the temperature range for the mixed phase for the two case studies are due to variations in vertical motions and associated cloud liquid water content. Strong vertical motions in convective updrafts provides copious supercooled droplets for riming. Weaker vertical motions in the stratiform updraft results in lower concentrations of supercooled droplets and less riming. In this respect Rosenfeld and Woodley (2000) report in situ measurements in deep convective clouds from an aircraft, showing that most of the condensed water remains liquid down to -37.5 °C.

The results of simulations are shown in Figure 14, where measured data are compared with simulated ones.

![Figure 14 - Results of reflectivity simulations for the summer case study of 06 July 2009. The GR attenuated reflectivity is not plotted because it is undistinguishable from the GR unattenuated one.](image-url)
In this case study it was possible to find a distribution of spherical hydrometeors, which can produce reflectivity values with a trend very similar to the measured one. In particular, as expected, attenuation can be neglected at the GR wavelength, for which the attenuated and unattenuated reflectivities are practically identical. Reflectivity simulated at CPR wavelength shows a completely different behaviour. The unattenuated reflectivity, in this case, is close to GR reflectivity, but, when corrected for attenuation, it becomes very similar to that measured by CPR.

This result means that, at least for this case study, differences between reflectivities measured by the two radars could be due mostly to the presence of attenuation. Moreover, when the values of effective radius and number concentration retrieved in this work are compared with those provided by CPR algorithm (Figs. 15 and 16), while no remarkable differences have been found as far as the ice component is concerned, the values retrieved with these simulations are far bigger than those provided by CPR for the liquid component. This seems in agreement with the fact that, due to the error related to the calculation of the attenuation identified in the CPR forward model, effective radii of the liquid component are in general underestimated in the 2B-CWC-RVOD product.

**Conclusions**

Comparisons between radar measurements at different wavelengths can improve knowledge of microphysical characteristics of clouds. In this paper it has been presented a methodology to collocate measurements recorded by the spaceborne W-band CPR onboard CloudSat and a C-band ground radar.
Figure 16 - Hydrometeor number concentrations retrieved in the present work for the summer case study, compared with those provided by the CPR retrieval algorithm.

This methodology allows for a quantitative comparison between measurements recorded at different wavelengths. Combined space and ground radar measurements can be affected by a spatial and temporal mismatch. The former is mainly due to the incomplete overlapping of the CPR and GR bins, which are different in size, while the latter is strongly dependent on the different scanning speeds, with CPR moving very fast over the area of interest and the GR scanning the reflectivity volume at a very limited speed. In spite of these problems, anyway, the collocation procedure described in this paper works well and is a reliable technique for comparison between different observations. An improvement of this methodology could be reached if both radars sample exactly the same volume in space. In this perspective, it is planned a measurement campaign using the RIVONA project radar network, composed of two C-band radars, one of which is also dual polarimetric, and a mobile Ka-band (35 GHz) radar, which can be moved in locations where the vertical scan can be made on the same plane described by CPR in its transit. Such simultaneous vertical mapping of the clouds by spaceborne and ground based radars adds opportunities to analyse and accurately determine the vertical composition of clouds in terms of the spatial distribution of ice and liquid water.

A reliable time-space collocation procedure is necessary for the application of a numerical method of scattering simulations. The main purpose of an inversion procedure is to identify phase and size distribution of hydrometeors in the cloud volume observed by the radar. Although the inversion can be also applied to a single wavelength radar measurement, in this paper it has been shown how the availability of two wavelength measurements provides a lot of information in order to make the inversion procedure more efficient. In fact, the
analysis of the two selected case studies has taken advantage from the fact that the same reflectivity volume has been observed by both radars. In particular, for the summer case study it has been shown how attenuation has to be taken into account when the inversion procedure is applied in case of heavy rain systems. In this framework the radar echo at 94 GHz has been explained in terms of signal attenuation by liquid water. In the same perspective the comparison of the vertical profiles of hydrometeors retrieved in the present study with those provided by the CloudSat microphysical product aims at emphasizing the improvement that can be reached if measurements at different wavelengths are available. On the other hand, for the winter case study, by using observations and numerical simulations at two different wavelengths it has also been shown that the inversion procedure results seem to support the miscalibration of the ground radar as the cause of the lacking agreement between measurements at different wavelengths.

The inversion procedure presented in this paper, applied to more case studies, in particular to other clouds of different microphysical characteristics and eventually complemented by airborne radar observations, can become a more and more valuable tool for investigating the microphysical characteristics of hydrometeors. Moreover, modelling of hydrometeors can be improved by using more sophisticated approaches, that can also consider more realistic size distributions of hydrometeors and particle shapes different from spheres (e.g. T-Matrix or DDA), even if it is known that size factor is more relevant than shape factor in scattering simulations. In this context, a primary aid could be provided by simultaneous observations of the same reflectivity volume by means of dual polarimetric radars, which can add information about hydrometeor shape.

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References
Austin A., Heymsfield J., Stephens G.L. (2009) - Retrieval of ice cloud microphysical parameters using the CloudSat millimeter - wave radar and temperature. Journal of Geophysical Research, 114 (D8-A23). doi: http://dx.doi.org/10.1029/2008JD010049.
Barker H.W., Korolev A.V., Hudak D.R., Strapp J.W., Strawbridge K.B., Wolde M. (2008) - A comparison between CloudSat and aircraft data for a multilayer, mixed phase cloud system during the Canadian CloudSat-CALIPSO Validation Project. Journal of Geophysical Research, 113, (D8-A16). doi: http://dx.doi.org/10.1029/2008JD009971.
Bohren C.F., Huffman D.R. (1983) - Absorption and Scattering of Light by Small Particles. Wiley-Interscience, New York. ISBN-10: 0471293407.
Dixon M., Wiener G. (1993) - Titan: thunderstorm identification, tracking, analysis, and nowcasting - a radar-based methodology. Journal of Atmospheric and Oceanic Technology, 10: 785-797. doi: http://dx.doi.org/10.1175/1520-0426(1993)010<0785:TTITAA>2.0.CO;2.
Leinonen J.M., Moisseev D., Chandrasekar V., Koskinen L. (2011) - Mapping Radar Reflectivity Values of Snowfall Between Frequency Bands, IEEE Transactions on Geoscience and Remote Sensing (0196-2892), 49 (8): 3047-3058. doi: http://dx.doi.
Matrosov S.Y., Shupe M.D., Djalalova I.V. (2008a) - Snowfall retrievals using millimeter-wavelength cloud radars. Journal of Applied Meteorology and Climatology, 47: 769-777. doi: http://dx.doi.org/10.1175/2007JAMC1768.1.

Matrosov S.Y., Battaglia A., Rodriguez P. (2008b) - Effects of multiple scattering on attenuation based retrievals of stratiform rainfall from CloudSat. Journal of Atmospheric and Oceanic Technology, 25: 2199-2108. doi: http://dx.doi.org/10.1175/2008JTECHA1095.1.

Matrosov S.Y. (2011) - CloudSat measurements of landfalling hurricanes Gustav and Ike. Journal of Geophysical Research, 116, D01203. doi: http://dx.doi.org/10.1029/2010JD014506.

Protat A., Bouniol D., Delanoe J., May P.T., Plana-Fattori A., Hasson A., O’Connor E., Rsdorf U.G., Heymsfield A.J. (2009) - Assessment of Cloudsat Reflectivity Measurements and Ice Cloud Properties Using Ground-Based and Airborne Cloud Radar Observations. Journal of Atmospheric and Oceanic Technology, 26: 1717-1741. doi: http://dx.doi.org/10.1175/2009JTECHA1246.1.

Ray P.S. (1972) - Broadband complex refractive indices of ice and water. Applied Optics, 11 (8): 1836-1844. doi: http://dx.doi.org/10.1364/AO.11.001836.

Rosenfeld D., Woodley W.L. (2000) - Convective clouds with sustained highly supercooled liquid water down to -37.5°C. Nature, 405: 440-442. doi: http://dx.doi.org/10.1038/35013030.

Tanelli S., Durden S.L., Im E., Pak K.S., Reinke D.G., Partain P., Haynes J.M., Marchand R.T. (2008) - CloudSat’s Cloud Profiling Radar After Two Years in Orbit: Performance, Calibration, and Processing. IEEE Transactions on Geoscience and Remote Sensing, 46 (11): 3560-3573. doi: http://dx.doi.org/10.1109/TGRS.2008.2002030.

Warren S.G. (1984) - Optical constants of ice from the ultraviolet to the microwave. Applied Optics, 23: 1026-1225. doi: http://dx.doi.org/10.1364/AO.23.001206.

Woods C.P., Waliser D.E., Li J.L., Austin R.T., Stephens G.L., Vane D.G. (2008) - Evaluating CloudSat ice water content retrievals using a cloud-resolving model: Sensitivities to frozen particle properties. Journal of Geophysical Research, 113, D00A11. doi: http://dx.doi.org/10.1029/2008JD009941.

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