Radar scattering by stratocumulus: often much lower than expected. Why?

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ABSTRACT

A comparison study of cloud radar data and air borne in situ observations, using data of the 2001 BBC campaign in Cabauw, the Netherlands, showed that a cloud radar could receive substantially less power than expected. This particular case was the starting point for an in depth study of how often this effect occurred and how strong it could be. In this paper we will show the results of this study, based on long term observations at Cabauw, The Netherlands and data from the mobile ARM facility, collected during its deployment in the Black Forest in 2007.

1. INTRODUCTION

Cloud radars are crucial instruments in observation strategies to study the role of clouds in the climate and weather system. They are the only instruments that can collect information about the internal structure of water clouds. Other instruments, like lidar or radiometers, are only capable of observing the cloud boundaries or the cloud as a whole. In recent years many algorithms have been developed that use the cloud radar data (mostly in combination with other instruments) as input to derive physical cloud properties, like the number concentration, liquid water content, or effective radius. In such algorithms, radar data is used in a qualitative sense – its accuracy is therefore of the utmost importance.

Retrieval algorithms are a quantitative implementation of the inverse problem: how can we extract the physical cloud properties from the measurements? Central to this problem is good understanding of the interaction between the radar waves and the cloud particles. In most common retrieval algorithms it is assumed that the radar signal is the result of incoherent addition of the radar waves coming from the individual droplets, and that the droplets are scattering in the Rayleigh regime: the droplet size is much smaller than the radar wavelength.

We have used the incoherent Rayleigh scattering theory to simulate radar reflectivities from dropsize distributions that were measured with an FSSP on board of an aircraft flying through stratocumulus, and compared these simulations with actual radar observations with a cloud radar on the ground. The result was unexpected: the radar measured much less than what the standard scattering theory predicted. After having ruled out the effect of potential instrumental errors, we decided to look into more data to see how common this *radar discrepancy*, as we baptized it, is. This paper is the first report on this. In an accompanying paper [1] the impact on radar-based retrieval of the liquid water content of clouds is discussed.

2. COMPARISON OF RADAR OBSERVATIONS AND IN SITU SIMULATIONS

The BBC campaigns were organized in Cabauw, The Netherlands in 2001 and 2003. Many ground-based remote sensing instruments were installed to make detailed observations of water clouds, and on selected days aircrafts were used to sample microphysical properties of the clouds (see [2] for more details). Figure 1 shows the 94 GHz radar reflectivity during one of the campaign days. Close to this radar, a 35 GHz cloud radar produced similar observations.

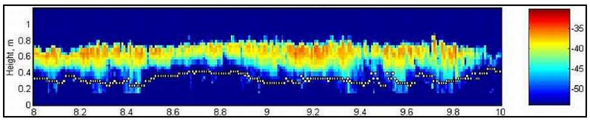

Figure 1) *Radar observation of stratocumulus (95 GHz) as function of time (UTC). Date: 23-9-2001.*

An instrument aircraft was flying through the cloud deck that the radar was sampling. With the FSSP instrument on board of the aircraft cloud droplet size distributions were measured. We have used the FSSP data to calculate the radar reflectivity factor. Since the aircraft and the radar were never sampling the same cloud volume at the same time, only statistical comparisons between radar observations and simulations are meaningful. Figure 2 shows the histograms of radar observations at 35 and 94 GHz, and histograms of the expected values.

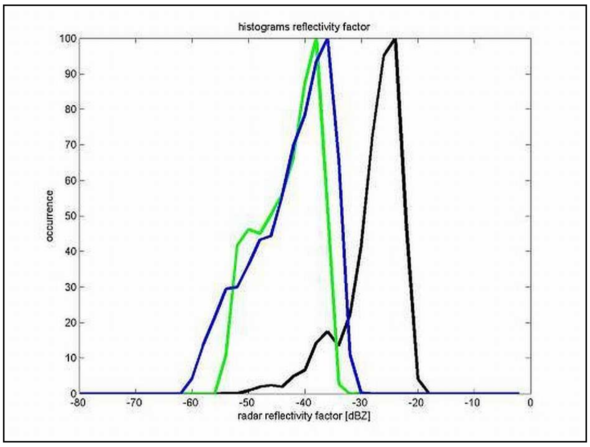

Figure 2) *Histograms of radar observations and simulations. Blue: 94 GHz observation; green: 35 GHz observation; black: FSSP-based simulation*

At both frequencies the radar measures much less (~ 12 dB) than expected. Also on another occasions dur-

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ing the BBC campaign such large differences were observed.

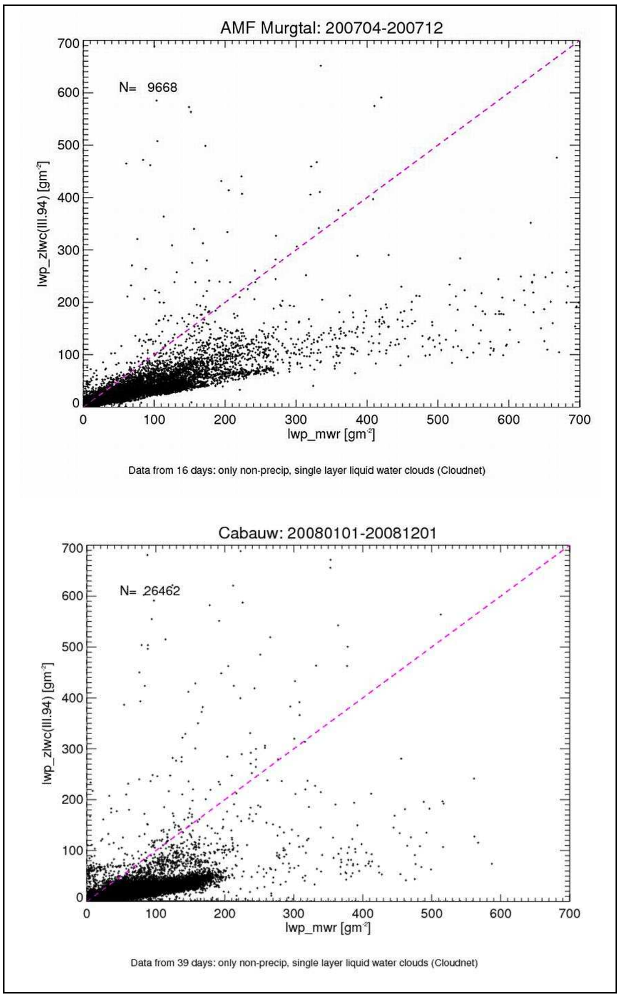

Figure 3) *Comparison of the liquid water path derived from the cloud radar and the microwave radiometer at the two sites: the ARM mobile facility during its deployment in the Black Forest in 2007 and Cabauw, The Netherlands.*

3. A LONG TERM LOOK AT THE RADAR DISCREPANCY WITH SENSOR SYNERGY

Long term comparisons of aircraft in situ data and radar observations are not feasible. To overcome this problem, we have analysed data sets in a somewhat indirect way:

- We calculated the liquid water content from the radar reflectivity using well-known Z-LWC relationships [3]. These relationships are based on incoherent Raleigh scattering and on in situ aircraft observations of the dropsize distribution.
- We integrated the retrieved liquid water content over the vertical cloud expansion to obtain the liquid water path LWP.
- And, finally compared this LWP with the one that is retrieved from a microwave radiometer.

In the ideal case, these two differently retrieved LWP's are equal. The advantage of this approach is that much more data is available, over longer time spans, and in different regions. Figure 3 shows the result for two sites: the ARM mobile facility during its deployment in the Black Forest, Germany in 2007 and Cabauw, the Netherlands. We have only selected those observations with single water cloud layer, based on visual inspection of the data and the CloudNet classification scheme. We also looked into the data sets of Chilbolton and Lindenberg, but further discussions about the data processing procedures were needed before we could make a proper judgement of the usefulness of those data sets for this study.

Figure 3 clearly shows that the radar-retrieval produces less liquid water content than the microwave radiometer. This is all the more intriguing, because both sites have different radars and microwave radiometers.

4. INSTRUMENTAL OR EXPERIMENTAL EFFECTS?

The results were examined in more detail and several tests were performed to be sure that no technical reason could explain it:

1) Radar calibration. The 35 GHz cloud radar at Cabauw was cross-checked with cloud radars in the CloudNet network, and the 3 GHz radar TARA at Cabauw. No differences were found that could explain the radar discrepancy. Furthermore, it is unlikely that different radars have the same calibration offset.

2) Signal processing. In case of spectral processing, clipping of the Doppler spectrum would cut off tails of the spectrum and thus artificially reduce the signal power. The radars involved in our data use both spectral and pulse-pair processing and do not show different behaviour.

3) Antenna near-field effects. If the clouds are in the near field of the antenna, less power will be received. This would mean that the radar discrepancy has to show some height dependence. This was not observed.

4) The measurement strategy. Were during the BBC campaign the radar and aircraft sensing the same clouds? The answer is: no. The aircrafts is flying long horizontal tracks and the radar is measuring in a fixed vertical column. This means that a one-to-one comparison can not be made; a statistical approach has to be used. To decrease the influence of distance between the aircraft and radar, a subset of the data was analyzed in which the aircraft was flying close the radar at Cabauw. This did not reduce the radar discrepancy.

5) Cloud inhomogeneity at scales larger than the radar volume. In such case temporal integration may average optically thin and thick parts of the clouds, thereby lowering the mean. If this were the case, than shortening the integration time would change the variance of the radar reflectivity with the maximum values at least corresponding to a uniformly radar volume. The radar data of the example of Figure 1 was reprocessed with an integration time of 0.06 seconds. No significant effect was seen, meaning that the cloud

deck was rather homogeneous. This was also confirmed with video observations of the cloud field.

6) Cloud inhomogeneity at scales smaller than the radar volume. An obvious sub-volume variation results from the level of adiabicity of stratocumulus. The radar reflectivity factor is derived assuming that the radar volume is uniformly filled with cloud droplets and that no spatial gradients of the dropsize distribution occur inside the radar volume. In ideal adiabatic clouds the particles grow while they ascend deeper into the clouds and reach a maximum at the cloud top. They will evaporate at the cloud boundaries or if they grow large enough, leave the cloud as drizzle. This means that care has to be taken with the assumption of uniform volume filling, especially in case of adiabatic clouds in which a spatial gradient of the liquid water content is to be expected. In the radar equation such inhomogeneity is not considered, which can lead to errors. Such errors can amount to several dB, but not to the values we have observed.

In conclusion, we could not find a technical issue, or one related to the measurement strategy that could explain our observations.

5. SOME THOUGHTS ON INCOHERENT SCATTERING

We have not discussed scattering yet. The standard weather radar approach is to assume incoherent Rayleigh scattering by the particles in the radar volume: the received radar signal is due to the incoherent summation of separately backscattered radar waves. This requires:

1) sufficient randomness of the particle position to ensure that the distribution of the phase difference of fields due to separate scatterers is uniform; as a rule of thumb: the standard deviation of the distances neighbouring particles should be larger than a quarter-wavelength: stdev (δd) > λ/4 [4] , or in the time domain:

2) that during the observation time the scatterers are moving fast enough to change the inter-particle distance by more than half a wavelength;

In case of rain or drizzle these conditions are easily satisfied. The particle distance is larger then the wavelength, and the fall speed of the droplets ensures sufficient phase shifts. In case non-drizzling stratocumulus clouds, this is not so obvious. The concentration is of the order of several hundred droplets per cm3 , which, in the case of 8 mm cloud radar, still implies many droplets at inter-particle distances less than a wavelength. This would certainly violate requirement 1. Furthermore, under wind free conditions the fall velocity of cloud droplets is given by [5]

$v = \varepsilon \cdot D^2$ (ε = 4.75e-5 when D is in micron) (1)

For particles smaller than 14 micron, the fall speed is less than 10 mm/s. Large particles of 40 micron have a fall speed of 76 mm/s, which is less than a wavelength per second. These small numbers show that in the absence of external forces like turbulence, the average inter-particle velocity difference can easily be of the order of half radar wavelength per second or smaller. Turbulence air motions randomizes the velocities of cloud droplets, but less so at smaller scales. In such case, requirement 2 is also violated.

In conclusion: we can not assume incoherent Rayleigh scattering, as is done traditionally, to calculate the reflectivity factor of non-drizzling water clouds. It will work fine for rain and drizzle, but it may be erroneous for other cases.

6. AN ALTERNATIVE APPROACH

Incoherent scattering assumes that the cloud droplets are, on average, separated by more than half a wavelength, and randomly moving. This is not the case in stratocumulus, where tens of droplets may exist in a parcel of half-wavelength diameter (e.g. for an 8 mm radar). Scattering by such media may better be calculated by treating the cloud as a semi-continuous medium.

How to do this? We have developed the following approach – *which should still be considered as a thought experiment* .

1) If the cloud is a semi-continuum, we have to consider the spatial scales of the variability of the refractive index in the radar volume and its variation in time. This does not necessarily coincide with scattering by separate droplets;

2) Turbulence will spatially mix cloud parcels and create disorder in the cloud. The size of these parcels will vary in the range of spatial scales of turbulence. Beyond these range, turbulence will not, or hardly, create new and smaller parcels anymore – what is left are small cloud parcels with a more or less uniform distribution of droplets. These parcels are small coherent structures, since turbulence does not significantly change the particle position, and therefore the phase relationships anymore. If the turbulence is isotropic, these remaining parcels may be treated as spheres. The size of these remaining parcels may be several mm or smaller, depending on the inner scale of turbulence. In the end, what we have is a randomly moving set of small parcels filled with cloud droplets.

3) We treat the small parcels as the scatterers. They are modelled as spheres with a diameter equal to the microscale of turbulence (usually of the order of 1 mm). The spheres are basically air parcels filled with cloud droplets. With the Maxwell Garnett mixing formula we can calculate the refractive index.

4) We calculate their backscattering properties with Mie-theory.

7. FIRST RESULT OF THE PARCEL SCATTERING MODEL

The model of section 6 was applied to the same FSSP data as was used for the calculation of Figure 2. Figure 4 shows the result. We have used a microscale of turbulence equal to 1 mm for this particular case.

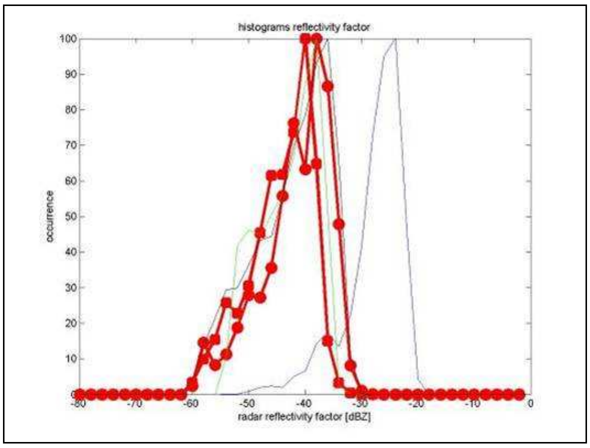

Figure 4) *Same as figure 1, but with the results of parcel scattering model superimposed on it. The red lines, for 35 and 94 GHz, are now on top of the actual radar observations.*

Now the simulations fit nicely with the actual radar observations. Like said earlier, this alternative approach should still be regarded as a thought experiment. It merely shows that using cloud radars for the study of non-drizzling water clouds may not be that self-evident, and that we have to revisit the fundaments of radar scattering theories when applied to these atmospheric phenomena.

8. DISCUSSION

Initial calculations with the effective parcel model have shown to produce acceptable results, more in line with radar observations. Furthermore, this mechanism may also explain why cloud radars do not always observe stratocumulus clouds, even when e.g. lidar observations indicate a thick water cloud. However, it should still be regarded as an initial attempt to explain the radar observations. More observations of the radar discrepancy are needed. Under which conditions does it occur? And how often? What is the frequency dependence? Based on analysis of the multi-year Cloudnet data base we estimate it to be present in 10 to 20 % of the time- it only occurs in non-drizzling stratocumulus clouds. A study of the radar discrepancy requires a careful statistical classification of cloud types, because it will differ with cloud types. The effective parcel model is a rough description of the scattering parcels. The relevant questions are

- Do the small cloud parcels, with a coherent distribution of droplets, really occur?
- What are their sizes and shapes?
- How to calculate the refractive index of such parcels? Currently we use the Maxwell Garnett theory, but this implicitly assumes that the droplets in side the parcel are not necessarily correlated.
- How to treat a collection of small parcels? In the current approach, we use incoherent addition of the waves coming of these parcels, but the physical link with turbulence may impose some coherency.

9. CONCLUSIONS

We have analysed cloud radar observations of non-drizzling water clouds at two sites in Europe. In many cases it was found that a cloud radar measures much less reflectivity than expected. It could not be attributed to instrumental errors. This implies that radar-based retrieval algorithms need to be used with care. They easily underestimate the amount of liquid water in the cloud. Furthermore, it could also explain why cloud radars do not always see water clouds. One of the potential reasons for the radar discrepancy lies in the assumed scattering mode: it is not self-evident that the theory of incoherent Rayleigh scattering can be used. The cloud droplets are not always moving fast enough for this. Initial scattering calculations, assuming scattering by parcels filled with droplets, produced values that agreed with the observations.

It is however clear that further research is needed.

10. ACKNOWLEDGEMENTS

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