Retrieval of the microphysical properties of mixed-phase clouds using Doppler polarimetric tools

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ABSTRACT

Nowadays, it is still not really clear how the large variety of different cloud microphysical characteristics influences the radiative balance at a global scale. This leads to great uncertainties in assessing the cloud radiative forcing effect. Observation strategies are developed to better determine the worldwide relative proportion of clouds, in term of phase, particle habits, particle size distribution and orientation.

In this work, it is proposed to focus on a method developed at the Delft University of Technology to retrieve the microphysics of the ice phase of mixed-phase cloud using the S-Band atmospheric radar TARA. After a brief description of the system, section 1 describes how, combining the Doppler and polarimetric capabilities of the radar, spectral polarimetric parameters can be measured and linked to microphysical cloud properties. In a second part, an overview of the retrieval technique within mixed-phase clouds is provided. Particle orientation and shape are first categorized, followed by the determination of ice PSD and integrated values such as Ice Water Content. Finally, some TARA data are taken as an example to illustrate the technique and be compared with in-situ measurements.

1. RADAR MEASUREMENT PRINCIPLE

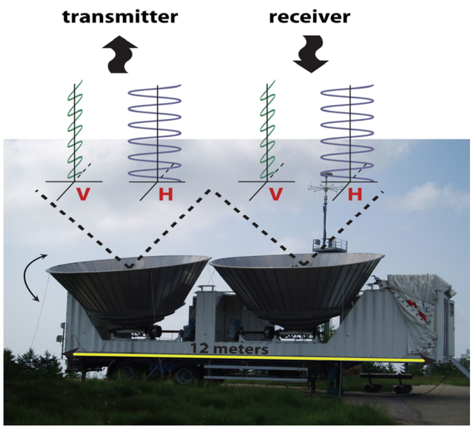

Figure 1. *TARA overview.*

For the research carried out in this paper, the radar TARA (Transportable Atmospheric RAdar) is used as shown in figure 1. TARA is a Doppler FMCW radar composed of two large antennas, one continuously transmitting while the other is receiving the backscattered signal. Furthermore, the main beam of each antenna is equipped with polarisers allowing measurement at horizontal or vertical polarisation states. Because of that, high resolution Doppler and full polarimetric measurements can be performed.

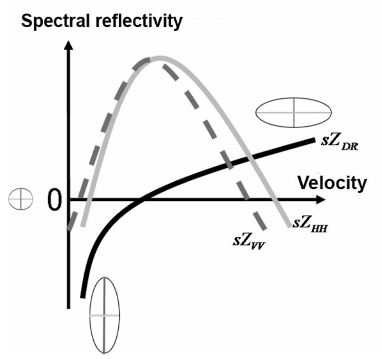

Figure 2. *Spectral polarimetric radar parameters $sZ_{HH}(v)$ and $sZ_{DR}(v)$ in relation with the orientation and shape of the ice particles being probed assuming spheroidal shapes.*

Microphysical properties of clouds can be expressed in terms of particle phase, particle size distribution (*PSD*), shape, velocity, and orientation. Using a Doppler polarimetric radar to retrieve the mentioned parameters appears to be quite convenient. The *PSD* is related to the Doppler effect induced by the motion of the hydrometeors, whereas particle shape/orientation can be linked to the radar polarisation diversity of the medium being probed [2]. As shown in Fig.2, the developed microphysical retrieval technique takes advantage of both radar capabilities using a combination of two spectral polarimetric parameters, the spectral horizontal reflectivity $sZ_{HH}(v)$ and the spectral differential reflectivity $sZ_{DR}(v)$. They are described as follows,

$$sZ_{HH}(v) = N(D(v))\sigma_{HH}(D(v))\left|\frac{dD}{dv}\right|dv\,, \qquad (1)$$

$$sZ_{DR}(v) = \frac{\sigma_{HH}(D(v))}{\sigma_{VV}(D(v))}\,, \qquad (2)$$

where the subscripts *HH* and *VV* denote the transmission and the reception with respective horizontal and vertical polarisation. *N(D(v))* (in $mm^{-1}m^{-3}$) is the particle size distribution, *v* (in $m.s^{-1}$) the Doppler velocity related to the particle fall velocity, and σ the radar cross-section.

Mixed-phase cloud regions have the particularity to be associated with bulk of clouds where a great spatial and time variability, as well as a large panel of particle sizes and types at different phases (supercooled liquid water or ice) are observed.

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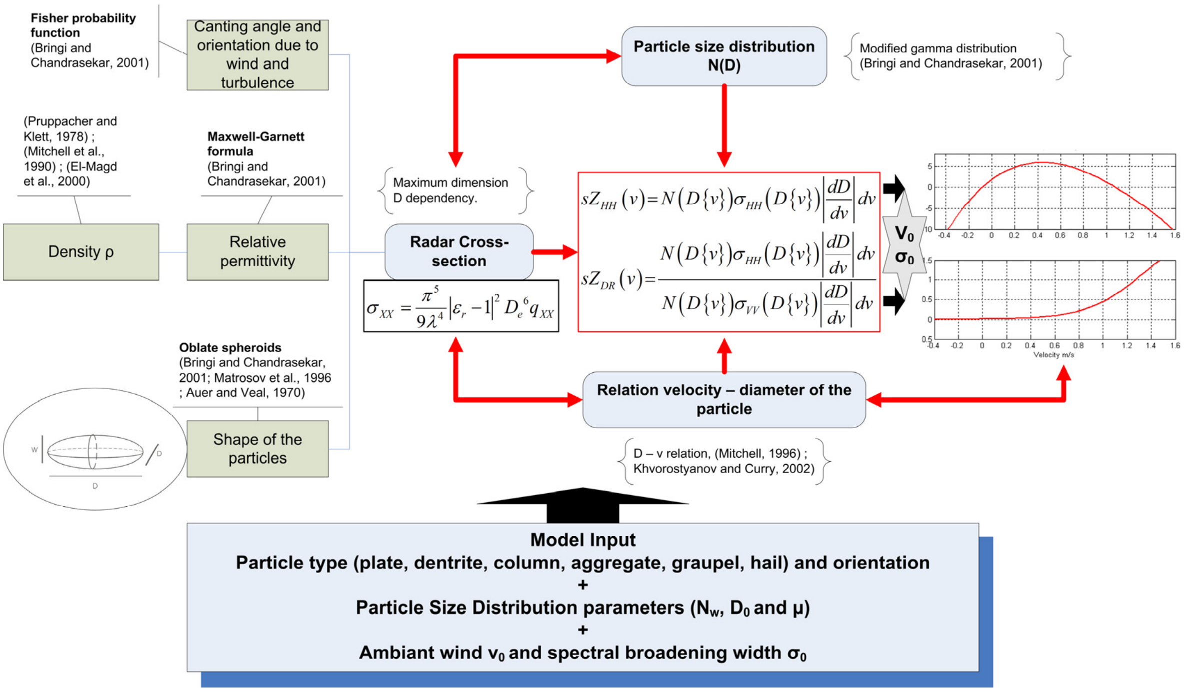

Figure 3. *Microphysical model overview. The model outputs are the $sZ_{HH}(v)$ and $sZ_{DR}(v)$ spectra displayed on the right hand side of the figure.*

Measurement devices have thus to be able to combine high spatial and time resolution besides particle recognition capability in order to accurately determine the unstable mixed-phase state. Nowadays a good microphysical characterisation of such cloud is still difficult to achieve [3]. This radar has the great advantage to work at S-Band. At such frequency, the supercooled water droplets present within mixed-phase clouds are not detected in the radar signal, making direct measurement of the ice phase possible.

2. MICROPHYSICAL RETRIEVAL PRINCIPLE

For the retrieval, a microphysical model was built in 2005 at Delft university with the aim of simulating the above spectral radar observables (eq.1 and 2) for any controlled microphysical environment [4]. Figure 3 is providing an overview of such model. The inputs of the retrieval technique are composed of the ice particle type(s), the main orientation(s), the ambient wind parameter, the spectral broadening factor σ_0 as well as the 3 parameters of a modified gamma distribution for each particle type *i*, with the following form,

$$N_i(D)=N_w f(\mu)\left(\frac{D}{D_0}\right)^{\mu}\exp\left[-(3.67+\mu)\frac{D}{D_0}\right], \qquad (3)$$

with N_w the intercept parameter (in $mm^{-1}m^{-3}$), D_0 the median volume diameter (in mm) and μ the shape factor. Each input is determined stepwise from different methods within the retrieval technique and is applied for each radar cell (specific range and time bin). Every step is explained in the following subsections:

2.1 Retrieval of the number of Particle types and orientation

First, a categorisation of each radar cell is performed in order to determine the number of particle types and their respective main orientation. This classification is based on the main slope and values per Doppler bins of the observed spectral differential reflectivity. The number of particle types is characterized from the number of extrema (maxima or minima) found in each Doppler spectrum at specific Doppler bins. For example, one minimum at low fall velocity and one maximum at high velocity bin can be determined, on figure 2, on the sZ_{DR} spectrum. Up to a total of three particle types can be determined in the retrieval, random fluctuations of $sZ_{DR}(v)$ rather than different ice crystal types being considered otherwise.

Currently, only three main particle orientations are characterized in the retrieval based on sZ_{DR} values:

- Horizontal alignment: for particle type with positive sZ_{DR} values (> 0.3 dB)
- Vertical alignment: for particle type with negative sZ_{DR} values (< -0.3 dB)
- Random ice crystal orientations otherwise. (sZ_{DR} ~ 0)

2.2 Retrieval of the particle habits

As featured in figure 3, a rather simple habit categorization scheme is employed in the retrieval. Different spectral polarimetric tools are used for that purpose.

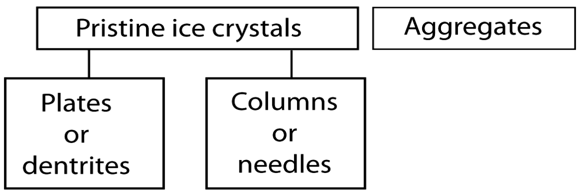

Figure 4. *Type of particles characterized from TARA measurements alone. For such categorization, low riming is assumed within the mid level clouds being probed.*

A first step is performed to discern aggregates from pristine ice crystals, making use of the spectral cross-correlation parameter, defined as,

$$s\rho_{co}(v) = \frac{\langle S_{HH}(v) S^*_{VV}(v) \rangle}{\sqrt{\langle |S_{HH}(v)|^2 \rangle \langle |S_{VV}(v)|^2 \rangle}} \quad (4)$$

where S_{HH} and S_{VV} account for the spectral scattering matrix elements. A really high value for $s\rho_{co}(v)$ above 0.995 is observed when aggregates predominate within the radar volume for specific Doppler bins. Conversely, simulations performed on $s\rho_{co}(v)$ for different pristine ice show lower values [1].

The type of pristine ice is next investigated using the integrated radar linear depolarisation ratio *LDR*. This parameter strongly depends on the axis ratio and canting angle of the particle. According to [1], significant differences in the *LDR* values between plate and column like ice crystals are expected where particle are not randomly oriented, making *LDR* the most appealing parameter for pristine ice type retrievals. At 45° antenna elevation, *LDR* around -15 *dB* is found in the simulations for columns, whereas *LDR* is mostly down to -20 *dB* for plates.

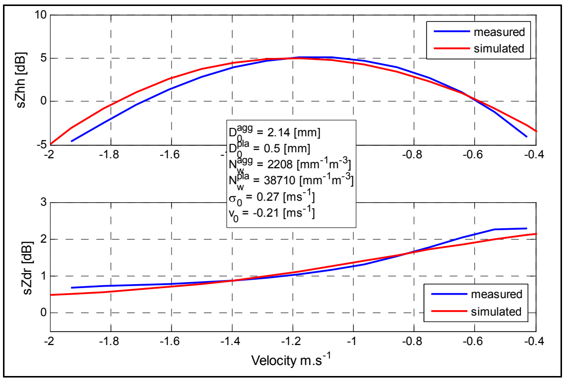

Figure 5. *Example of output retrievals obtained after fitting the simulated Doppler spectra with the measured one. A configuration 'aggregates with horizontally aligned plates' was determined in the retrieval.*

2.3 Retrieval of the particle size distribution and spectral broadening parameter.

At this stage of the retrieval, the already determined input parameters, mentioned above, are implemented within the microphysical model. It has to be noticed that ice crystal habits are a priori converted to spheroidal approximation for that purpose. The remaining parameters, i.e, the ambient wind, the spectral broadening factor, as well as D_0 and N_W of the modified gamma distribution for each particle type, are introduced in a non-linear least square fitting algorithm. Such optimization procedure is minimizing the error between the fitted simulated spectrum and the measured one, by varying the above non-defined parameters,

$$\min_{\psi} \sum_{v=v_{\min}}^{v_{\max}} \left(sZ_{XX}^{meas}(v) - sZ_{XX}^{mod}(v,\psi) \right)^2 = \zeta(\psi), \quad (5)$$

where *meas* and *mod* denotes the measured and simulated spectrum respectively, the subscript *XX*, the type of polarimetric measurement (copolar HH, or differential DR), since the fitting is carried both on $sZ_{HH}(v)$ and $sZ_{DR}(v)$. Ψ contains all the inputs parameters which are still undefined.Such fitting analysis is well explained in [4].

2.4 Retrieval results

At the last step of the retrieval, each estimated or minimised model input is managed as microphysical outputs. An example of such outputs is provided on figure 5 for a specific radar cell. Aggregates and plates are present in the resolution volume in that example.

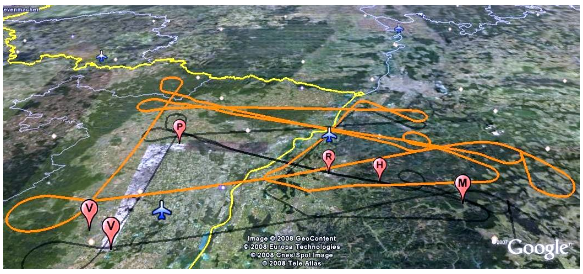

Figure 6. *COPS region overview. Each letter corresponds to the ground-based site measurements deployed during the campaign.*

3. COPS CASE STUDY : 21/07/07

In this last section, we illustrate the retrieval technique with TARA measurements taken in the frame of the COPS campaign (Convective and Orographically-induced Precipitation Study) at the border between France and Germany, on July 21st, 2007. Six ground-based stations equipped with remote-sensing and in-situ instrument were spread all over the COPS area as shown on figure 6. The radar was located on the supersite H on the very top of a plateau besides other ground-based devices (lidars, other radars, radiometer, meteorological station…) giving the possibility to perform inter-comparison studies. The 21/07/07, combined aircraft measurements could be performed with the ATR42 aircraft belonging to the Safire fleet in the frame of EUFAR activities.

3.1 Meteorological conditions

For that day, the meteorological situation was mainly

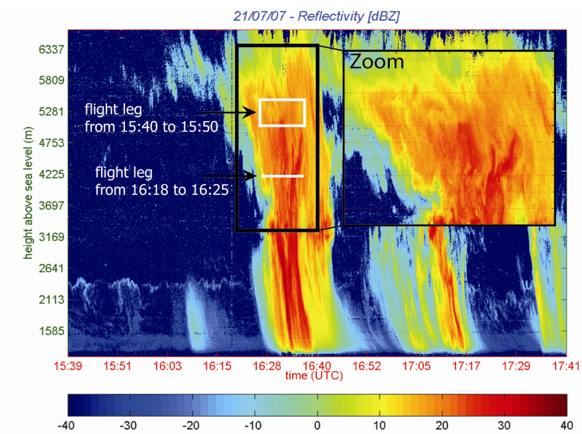

Figure 7. *reflectivity profile obtained with the TARA radar on the 21/07/07. The black box around 16:30 bound the cloud region where the retrieval technique is applied.*

driven by a quite intense mesoscale convective system triggered with orographical activities over the Black Forest mountains and moving northeastwards over the eastern half of the COPS area in the course of the day. This situation led to widespread mid-level clouds overcast. Figure 7 represents the cloud situation used for the illustration of the retrieval (black box). A well developed ice or mixed-phase cloud with his bottom characterized by the bright band (at 3200m) due to the melting of ice crystals is observed on the reflectivity profile.

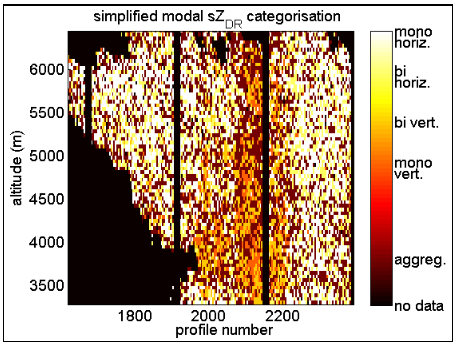

Figure 8. *Particle orientation and number of habits determined per radar cell from the retrieval technique*

3.2 Particle type and orientation

Different particle orientations and habit configurations (from 1 to 3 types of particle habits per radar cells) could be determined from sect. 2.1. They are depicted in different colors in figure 8. Especially two regions, with the presence of either horizontally or vertically aligned particles, can be well observed within the study box, and might be due to a change in the cloud dynamic. In terms of crystal habits, aggregates, alone or coupled with plates, could be retrieved from sect. 2.2. Such particle shapes could also be observed from the 2D images of ice crystals provided by the aircraft data from a PMS 2DC probe.

3.3 Some microphysical results

Figure 9 displays the time averaged profiles of the microphysical properties retrieved for aggregates and

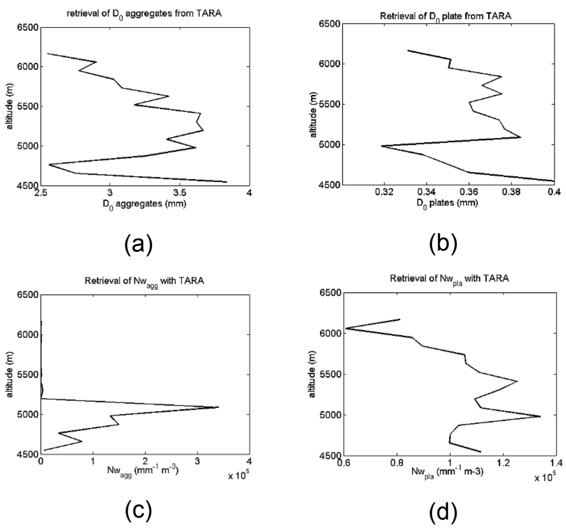

Figure 9. *averaged profiles of D_0 (top) and N_W (bottom) obtained from the retrieval technique for aggregates (left) and plates (right).*

plates (sect.2.3) from the melting layer top to the top of the study box. A typical cloud situation with pristine ice formation on top (high N_W^{pla} around 5500 m compared to aggregates) leading to aggregation below (increase of D_0^{agg}) was observed this day.

As shown in figure 10, the integrated retrieved outputs, the ice water content (IWC) and the total particle concentration (N_T), could also be statistically compared with the ATR42 data for a flight leg around 5200 m. Despite of some differences in the shape of the distribution of the histograms (mainly due to differences of data processing for each device as well as differences in the number of data available), good correlations are found between the two instruments.

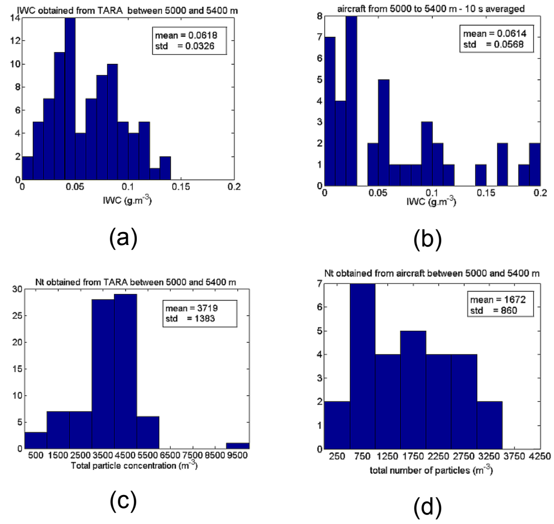

Figure 10. *statistical comparison of the IWC (top) and N_t (bottom) between TARA (left) and the ATR42 aircraft (right) during the first overpass.*

4. CONCLUSIONS

Based on a quite simple and straightforward approach, the technique already shows some promising results. The technique is still in its infancy though, and some weaknesses could already be noticed on the high sensitivity of the outputs to the radar parameters. Other cloud situations have to be tested in the future in order to improve and assess the retrieval technique.

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