TOWARDS THE RETRIEVAL OF ICE CRYSTALS PROPERTIES WITHIN MIXED-PHASE CLOUDS USING DUAL POLARIZATION SPECTRAL RADAR MEASUREMENTS

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1. INTRODUCTION:

Among mid-level clouds, the coexistence of ice particles with tiny but dense water droplets are easily observed when the temperature goes down 0°C \[^{[3]}\]. They can occur in the form of layers of few hundreds thick either above or embedded within thicker ice clouds \[^{[6]}\].

Because of their notable presence as well as their microphysical specifications, mixed-phase clouds (and mainly the water phase) are potentially considered of great importance on the earth radiative budget \[^{[2]}\] and cloud evolution. Nowadays such clouds are still poorly represented in Global Climate Models (GCMs) and Forecast Models. Therefore, in order to evaluate and develop cloud parameterization schemes, observation of particles size distribution (PSD), shapes, orientations, size-mass relation and phase distributions are required.

Up to now observational datasets are mainly available from aircraft in-situ measurements \[^{[4],[5],[8],[9]}\]. To be able to get a wider time and spatial scale, remote sensing retrieval schemes are also under development \[^{[8]}\]. Among them a new technique is built in the university of Delft for remotely determining the properties of the ice particles within mixed-phase clouds from measurements taken by the S band Doppler Polarimetric radar TARA and combining it with a microphysical model which characterizes the bulk of atmosphere being probed \[^{[11]}\].

This constitute a first step in the retrieval of ice water content (IWC) and liquid water content (LWC) from a radar / lidar synergy since radars and lidars are sensitive to different type of particles.

This extended abstract will be mainly dedicated to show the possibilities of developing and evaluating the remote sensing retrieval technique explained above using collocated aircraft in-situ and ground-based measurements which have been taken during the COPS campaign (Convective and Orographically-induced Precipitation Study) last summer (2007). During this period a complete set of sensors were deployed in an area located in the border of France and Germany, and in a scale large enough to study mesoscale processes (figure 1). In this abstract only TARA data will be shown as ground-based measurements.
The abstract is structured as follow. Section 2 gives an overview of the retrieval technique from both radar and model point of view. Section 3 will focus on the aircraft measurements obtained from an accepted EUFAR proposal (European Fleet for Airborne Research), and their combination with the radar data. Finally section 4 is going to account for the different ways to improve and assess the retrieval technique using the full panel of instruments available. Since data are still under process up to now, no results will be introduced in this last section.

2. OVERVIEW OF THE RETRIEVAL TECHNIQUE:

The retrieval technique was first meant to characterize the microphysical properties of ice particles above the melting layer [11]. This idea is going to be further developed and extended to mixed-phase layer studies. The retrieval is based on an iterative comparison of expected scattering properties from ice crystals (obtained with a microphysical model) and spectral dual-polarization measurements from radar observations (Transportable Atmospheric Radar - TARA). This method uses the possibility to differentiate several types of hydrometeors by combining polarimetric and Doppler measurements [10]. Thus, for comparison purposes both the radar and the model can provide the polarimetric parameters spectral horizontal reflectivity (sZHH) and spectral differential reflectivity (sZDR) which gives the axial ratio (from dual polarization) versus the size (from Doppler velocities) of the ice particles, assuming they can be modeled as oblate or prolate spheroids (figure 2):

\[
sZ_{HH}(v)dv = \sum_{i=1}^{n} N_i(D_i\{v\})\sigma_{HH,i}(D_i\{v\}) \left| \frac{dD}{dv} \right| dv
\]

where the subscripts HH and VV denote respectively horizontal and vertical transmitting and receiving polarization modes of the radar, i represents the particle type, N(D) is the particle size distribution, the Doppler velocity v is related to the terminal fall velocity and \(\sigma\) is the radar cross section.

![Figure 2](image)

Figure 2 - relation polarimetric spectral parameters (sZHH, sZVV and sZDR) with shape of the particles being probed.

- **a- the microphysical model:**

Ice crystals within mixed-phase clouds consist of many different types of particles. Previous research came up with more than 60 different types (Mogano and Lee, 1966). By using the velocity and shape dependency of the radar cross section, differentiation between several types of spheroidal particles can be performed in the model. Figure 3 summarizes the modelization procedure to get the Doppler spectrum. This model is well explained in Spek et al., 2008 [11].
b- **Tara: microphysical mode**

Measurements are performed with the Transportable Atmospheric S band RAdar TARA. This radar has the advantage to get a direct measurement of the ice phase of mixed-phase clouds since supercooled water droplets are small enough (~ few µm) to be not detectable at this working frequency (3.3 GHz - ~ 10 cm wavelength). The specifications used for optimum microphysical measurements are featured in table 1.

<table>
<thead>
<tr>
<th>Signal generation</th>
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<tr>
<td><strong>Frequency</strong></td>
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<td><strong>Sweep time</strong></td>
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<td><strong>Polarization sequence</strong></td>
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<table>
<thead>
<tr>
<th>Doppler</th>
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<td><strong>Max Doppler velocity</strong></td>
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<tr>
<th>Other</th>
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<td><strong>Radar elevation angle</strong></td>
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The spectral differential reflectivity is easily affected by noise and clutter due to its low value (~ 1 dB). Spectral polarimetric tools have been used to suppress clutter and remove spectral aliasing\[12],\[13].

![Figure 4 – fitting of the two radar observables with the ones retrieved from the microphysical model assuming plates and aggregates in the cloud](image)

**c- fitting process:**

The retrieval procedure is based on a least square optimization that simultaneously minimizes fit residuals in a Doppler power spectrum and spectral differential reflectivity.

As shown in figure 4 the algorithm obtains the following six parameters by fitting modeled spectra to the measured ones: four
particle size distribution parameters for two different types of ice crystals, the spectral broadening parameter and the ambient wind velocity.

From this result time series of the microphysical properties of the clouds can be retrieved. Figure 5 gives an example of time series obtained for the median volume diameter as well as the particle concentration assuming the presence of plates and aggregates within the cloud being probed.

Figure 5 - retrieved time series of median volume diameter and concentration

3. SETTLEMENT OF THE CAMPAIGN – CASE OF THE 21/07/07:

In order to assess and improve the retrieval technique, a measurement campaign has been performed last summer taking advantage of, in one hand, a full set of ground-based sensors provided for the campaign COPS and, in the other hand, 10 flight hours obtained from the accepted EUFAR proposal OSMOC (Observation Strategy for Mixed-phase Orographic Clouds). The case of the 21/07/07 is exposed in this section since it represents the only day where TARA data used for the retrieval was combined with EUFAR activities. The meteorological situation was mainly 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 lead to widespread mid-level clouds overcast.

Figure 6 - Flight pattern within the COPS area

a- radar TARA during COPS

The radar was located on the supersite H on the very top of a plateau (see figure 6) besides other ground-based devices (lidars, other radars, radiometer, meteorological station...) giving the possibility to perform inter-comparison studies. Antennas were directed towards the M supersite. About 6 days have been performed with the microphysical radar measurement mode as described in the previous section. Among them the 21/07 and 29/08 could be combined with aircraft measurements (using the ATR42 aircraft within the EUFAR proposal and the BAE146 aircraft respectively). Figure 7 shows the reflectivity profiles obtained the 21/07 together with the aircraft path.

Figure 7 - Reflectivity profiles from the 21/07

Melting layer formation can be observed at about 2200m, leading to rainfall over the site H. The flight path is located just above this melting layer within the altostratus layer for temperature close to the freezing level.
During this measurement different sZ_\text{DR} behaviors have been noticed (figure 8). As previously mentioned this parameter is directly linked to the microphysical property of the observed bulk of atmosphere which means that every configuration can be considered as a variation in the microphysics within the cloud. The ones close to 3000 m are in the same order of altitude than the flight level and thus can be compared with the in-situ data when flying over the sites.

b- Aircraft in-situ measurements during COPS:
From 20/07 to the 29/07 4 flights measurements through mixed-phase clouds have been performed with the French aircraft ATR42 from the Company Safire. Figure 6 exposes the flight pattern carried out the 21/07 which has also been used the following three flights. It mainly consists of a first gradual ascent from site P to site M in order to detect mixed-phase region within the cloud height. Some horizontal legs with triangular shape were following at the specific flight levels previously determined during the ascent. These legs were meant to sample the heterogeneity of the clouds as well as optimizing the inter-comparison with the different sites P, R, H, M and V (figure 6).

The aircraft was equipped with the following instrumentation:
- Basic avionic sensors: to get time series of pressure, temperature and humidity along the flight path.
- 2 LWC probes (king and Gerber): to get time series of the Liquid Water Content along the flight path.
- A PMS FSSP100 located below the aircraft wing: to measure the PSD from 1 to 50 µm.
- 2 PMS 2D-C probes located below the aircraft wing: measuring the PSD, shape and orientation of the particles from 100 to 800 µm with 25 µm resolutions. Unfortunately one of them didn’t work during the campaign.

The two last ones are needed to derive the PSD for a wide range of particles sizes.
This will be possible for a size range going from 1 to 50 µm and from 100 to 800 µm. The rest of the spectra will have to be interpolated. Furthermore it has to be noticed that when dealing with mixed-phase cloud regions, assumptions have to be taken into account in order to interpret the in-situ data:

- Water droplet and ice particle distributions are assumed to be not overlapped in size.
- Following Heymsfield et al., 2007 [4] particles with size below D_t will be assumed spherical:

\[
D_t = \left( \frac{6a}{0.91\pi} \right) \exp \left( \frac{1}{3-b} \right)
\]

Where \(a\) and \(b\) are two parameters describing the mass dimension relationship and 0.91 account for the threshold density where the non-sphericity of the particle appears.

Figure 9 shows some ice particles which were probed during the flight of the 21/07 with the PMS 2D-C probe. These images constitute the output of a linear array (oriented perpendicularly to the airflow) which is recorded as a function of time, such that 2D images of individual cloud particles can be constructed.

Plates and dendrites were the predominant pristine ice which could be found. The region (a) is mainly composed of different pristine ice particles (plates and dendrites). This has been probed at a temperature level below -12°C. Region (b) depicts some rimed aggregates (graupel) and dendrites. A liquid phase has been determined in parallel with both the King and Gerber probes. Finally region (c) consists of low rimed aggregates and dendrites. Both (b) and (c) were probed above -4°C and are typical of mixed-phase layers.

d- determination of the spatial scale for inter-comparison between devices:

When dealing with different instruments, scale issue is often encountered due to different space resolution for each device. For inter-comparison purpose, horizontal and vertical spatial scales will be determined such that microphysical homogeneity within a bulk of cloud can be assumed.

Horizontal scale is going to be evaluated using the combination of the 2D-C data from the horizontal legs of the flight pattern and time series of the radar measurements. Same products are going to be employed for the vertical scale but this time using the ascents and spirals performed during the flights as well as the range information of the radar. This work is not achieved yet and will be done as long as all data are processed and calibrated.

More information on the instrumentation and flights performed can be found on the Eufar website (www.eufar.net) under the project name OSMOC.

4. POSSIBLE IMPROVEMENTS OF THE RETRIEVAL TECHNIQUE:

Because most of the data are still under investigation, no final retrieved results are available yet. But the intended directions to improve the retrieval technique are given below.
a- $sZ_{DR}$ behavior as input for the microphysical model:

As shown in section 3 (figure 8) a set of different $sZ_{DR}$ behaviors could be found when measuring with TARA. Two main parameters can be responsible of such differences by directly affecting the signal backscattered in the vertical and horizontal polarization. This is the shape and the orientation of the particles.

During the experiment various shapes could be discerned from pristine ice crystals to more complex forms (aggregates). Level of rimming could also be considered as a driven parameter in the final shape of the crystal. For instance graupels (quite spherical) could be observed when strong rimming occurred.

Measurements showed also specific orientations. Figure 10 gives an example taken the 23/07 where orientation could be easily checked within columns event.

![Figure 10 -columns preferred orientation during flight of the 23/07](image)

In the microphysical model used for the retrieval, particles are assumed to be horizontally oriented following a Fisher probability distribution (see Spek et al., 2008 [11]) and only a few shapes-particle size relationships are available. Those assumptions turn to be often incorrect when looking at the 2D images. Then, because of the lack of parameterizations for pristine shapes (columns and rimming level not implemented yet), for sizes and for orientations, only a few measured $sZ_{DR}$ behaviors can be retrieved.

New Shape-size relationships and their integration within the radar cross-section calculation (related to the orientation of the particles) should be implemented in order to model every kind of $sZ_{DR}$ behaviors encountered during the measurements.

b- Improvement of the PSD – implementation of gamma distribution:

For the microphysical model a form of particle size distribution has to be selected. The gamma distribution and the exponential distribution are commonly used in the literature. The general form of the gamma distribution is given by

$$N(D) = N_w f(\mu) \left( \frac{D}{D_0} \right)^\mu \exp \left( -\left(3.67 + \mu \right) \frac{D}{D_0} \right)$$

where $N_w$ is the intercept parameter (mm$^{-1}$ m$^{-3}$), $D_0$ the median volume diameter (mm) and $\mu$ the shape parameter. This equation can be reduced to an exponential distribution for $\mu=0$.

In the microphysical model, only the exponential PSD is currently employed. However a sensitivity analysis of the shape parameter revealed that $sZ_{DR}$ is quite affected by this parameter. Figure 11 exposes a sensitivity analysis of the model for $sZ_{DR}$ assuming presence of plates (dendrites) and aggregates within the bulk of cloud.

![Figure 11 -PSD dependency on shape parameter $\mu$ within the microphysical model. The value of $sZ_{DR}$ increase with $\mu$.](image)

In order to include the shape factor in the model some relations ‘shape factor $\mu$ – slope coefficient $\Lambda$’ can be drawn as shown in Brandes et al., 2006 [1] with the gamma distribution described as

$$N(D) = N_0 D^\mu \exp(-\Lambda D)$$
Where $N_0$ is now a number concentration parameter (mm$^{-1}$ m$^{-3}$) and $\Lambda$ is the slope term.

**c- Improvement of some other relations:**
Numerous particle area and mass dimension relationships exist in the literature [4,9]. They both come in the computation of the particle fall velocity. As explained in Spek et al., 2008 [11] a change in one of this relation has a significant effect on the spectral differential reflectivity. Using PSD obtained from in-situ measurements the optimum relationships can be assessed by fitting $sZ_{DR}$ modeled with the ones measured.

5. CONCLUSION
A technique to retrieve the microphysical properties of the ice phase within mixed-phase clouds has been presented in this abstract. First observations ($sZ_{DR}$ behavior and 2D images of the ice crystals) revealed that the retrieval technique is not suitable for every cloud conditions and need to be extended. A specific attention is given to show how to assess and improve this technique by using a synergy of ground-based and in-situ measurements. After calibration of all the data, new parameterizations will be implemented following section 4. First results are going to be presented during the poster presentation.

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**REFERENCES**


