Responses to Review Comments on “Identification of multiple co-located hydrometeor types in Doppler Spectra from scanning polarimetric cloud radar observations”

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We sincerely appreciate the editor’s thorough review and thoughtful feedback provided throughout both rounds. Their valuable input has significantly contributed to enhancing the clarity and overall quality of the manuscript. Below we provide our responses to the 4 remaining comments, including the updated text passages. References to line numbers refer to the revised manuscript (without tracked changes).

Sincerley,

Majid Hajipour and co-authors.

Editor Comment #1:

– **Abstract lines 7-8: the paper does not bring forth that you can ultimately differentiate five hydrometeor types**

Authors Response #1:

We revised lines 5-9 of the abstract as below:

“The previously developed main-peak approach focuses only on the part of the Doppler spectrum with the highest signal-to-noise ratio to retrieve the shape and orientation of the dominant hydrometeor types within stratiform clouds. With the extended technique, referred to as the spectrally resolved approach, the section of the Doppler spectrum containing valid data points exceeding the noise level is analyzed by dividing it into five equally spaced parts. This allows to retrieve up to five distinct velocity-segregated hydrometeor types.”

Aside the update on the “5-parts issue”, we also introduced a few typographical/grammar corrections to the abstract.

Editor Comment #2:

– **Caption Fig. 1: explicitly state that you are showing an idealized picture, otherwise the figure is misleading**

Authors Response #2:

We updated the caption of Fig. 1 as follows:

“Illustration of an idealized Doppler spectrum containing 5 different hydrometeor types. The division into five parts enables the potential identification of up to five different hydrometeor types; however, the actual number of

retrievable distinct types depends on the spectral and microphysical characteristics of the observed cloud. Positive Doppler velocities indicate the impact of turbulent motion on the Doppler spectrum."

Editor Comment #3:

- **In Section 3.2, the division into five classes needs to be physically justified. Especially the sentences "This division into five parts was chosen because it is the best estimate to represent different hydrometeor types, accounting for various shapes"**
  and
  "The amount of 5 parts was empirically chosen for this study, because usually not more than that amount of different particle shapes can be expected in a cloud volume"
  need a quantitative reasoning, respectively confirmation through citation of relevant literature.

Authors Response #3:

We revised the discussion on the choice of five spectral parts in Sect. 3.2 by modifying/extending the first two paragraphs of this section as below (lines 223-265). Indeed, there was no study yet which stated that never more than 5 hydrometeor types exist. But the existing studies which dealed with Doppler spectra separation usually don't report more than a maximum of 5 different peaks. For instance the PeakTree-related publications of Radenz and Vogl. We hope that this situation becomes more evident in the updated text.

"Ice particles adopt varying shapes, such as oblate, prolate or irregular, at the top of the cloud before descending based on their size. Along their descent, these particles interact by colliding either with other ice particles or with supercooled liquid droplets, or they grow by water vapour diffusion. The growth processes induce alterations in their shape, size, fall speed, and trajectory. Radar signals received from these particles can be used to discern their reflectivity and fall speed, when the radar is pointed vertically (e.g., to 90◦ elevation). Consequently, the Doppler spectra observed with a vertically pointing cloud radar offer insights into the variability of sizes and shapes of the ice particles (Bühl et al., 2019; Vogl et al., 2024). In the low-velocity range around 0 m s−1 typically cloud droplets or small or low-density ice crystals, such as primarily ice crystals or secondarily formed ice occur. At intermediate velocities from ≈ −0.5 to −1.5 m s−1 usually aggregates of ice crystals or drizzle droplets exist. The high-velocity range from −2 m s−1 and faster, typically corresponds to graupel or small hail. Rain droplets and large hail can take much faster fall velocities of 5 to 10 m s−1. The width of the Doppler spectra is thereby characterized by size- and shape-dependent fall velocities of the particles, which are super-imposed by influences of turbulence and (predominantly in case of off-zenith antenna pointing angle) horizontal wind variability that cause additional broadening of the spectrum (Radenz et al., 2019). Nevertheless, as the above-mentioned references point out, zenith-pointing cloud radar observations of Doppler spectra only allow for the classification of different co-located particle shapes when certain assumptions are taken which are usually based on the observations of particle fall velocity or the temperature regime of the particle formation.

This study thus extends the main-peak shape and orientation retrieval through the spectrally resolved approach, which assumes that different hydrometeor types in a cloud volume are separated by their distinct fall speeds, as explained in the previous paragraph and as illustrated in Fig. 1. In Figure 2 the block diagram of the spectrally resolved approach is presented. As for the main-peak approach, the spectrally-resolved shape and orientation retrieval is based on observations of the Doppler spectrum over a range of elevation angles. In contrast to the main-peak approach, the Doppler spectra observed at all elevation angles are divided into five equal parts, as illustrated in Fig. 1. To achieve this, for each Doppler spectrum, the starting and ending points are identified, then the spectrum's width is divided evenly into five parts. The average values of ZDR and RHV are then calculated for *each part. These determined ZDR and RHV values are subsequently used for the independent retrieval of hydrometeor shape and orientation. While the conventional main-peak approach provides only one pair of ZDR and RHV, this approach yields five pairs for each Doppler spectrum over the range of elevation angles. Thereby, in principle any amount of spectral parts can be selected in the algorithm. The amount of five spectral parts was empirically chosen based on findings from prior studies (e.g., Shupe et al., 2004; Kollias et al., 2007; Kalesse et al., 2016; Vogl et al., 2024) which showed that Doppler spectra observed in mixed-phase clouds commonly exhibit up to five distinguishable spectral peaks, which are typically associated to different particle populations (e.g., drizzle, different habits of small primary and secondary cloud ice, aggregates, or rimed particles). On the other hand, the shape and orientation retrieval approach requires a sufficient amount of data points and homogeneity at all elevation angles of the analyzed RHI scans, as is discussed in Section 3.1. A number of 5 Doppler spectra parts thus represents a practical balance between spectral complexity and interpretability. Note, that the different parts are not necessarily associated to individual peaks in the Doppler spectra, as they are e.g. derived by the peakTree method of Radenz et al. (2019). As will be outlined below, the observation of a cloud layer at different elevation angles makes it virtually impossible to track individual peaks in the Doppler spectra over the range of elevation angles. Instead, we assume that the fall attitude of the individual hydrometeor types contained in the cloud volume is similar at all elevation angles. E.g., the fastest-falling Doppler spectrum part at all elevation angles is associated to one hydrometeor type, and so on. Generally speaking, instead of spectral peaks the spectrally resolved approach aims on identification spectral regimes of distinct hydrometeor properties.*

Subsequent to the separation of the Doppler spectra at all elevation angles, the spectrally resolved approach operates akin to the main-peak approach, but for each spectral part separately. It compares the observed values of ZDR and RHV with their modeled counterparts using minimum mean square error function for each data point. By identifying the best agreement, the approach retrieves the polarizability ratio and degree of orientation. Thus, five sets of values for polarizability ratio and degree of orientation are obtained for each height level and elevation angle, signifying to distinguish up to five distinct hydrometeor shapes and orientations."

Editor Comment #4:

– **Instead of the Doppler spectrum depiction in terms of hydrometeor classes, I could imagine that argumenting with a composite analysis of different Doppler spectrum regimes could resolve these issues.**

Authors Response #4:

We also appreciate the reviewer's suggestion to frame the analysis as a composite of different Doppler spectrum regimes. We agree with this framing and have added a clarifying paragraph (Section 3.2 and Conclusion) to emphasize that our approach allows decomposition of the Doppler spectrum into interpretable regimes rather than strict classification into physical hydrometeor types. The paragraph is:

In Section 3.2, we now write in lines 260-261:

"Generally speaking, instead of spectral peaks, the spectrally resolved approach aims on identification of spectral regimes of distinct hydrometeor properties."

In the conclusions section we write in lines 606-613:

"Instead of interpreting the Doppler spectrum segmentation as a strict classification of hydrometeor types, we emphasize that our approach provides a decomposition of the spectrum into distinct Doppler regimes. These

regimes reflect variations in particle fall velocities and, by extension, microphysical characteristics such as size, shape, or phase. This composite view allows us to capture the internal variability of the cloud without assigning specific hydrometeor classes to each spectral part. Such a representation aligns with previous studies (e.g., Shupe et al., 2004; Kollias et al., 2007), which observed that Doppler spectra often exhibit multiple peaks or broadened components due to the coexistence of diverse hydrometeor populations. By dividing the spectrum into five parts, we aim to resolve this complexity in a practical and interpretable way, facilitating further analysis of cloud microphysics and dynamics."