Radar spectral polarimetric processing to improve Doppler spectra of rain and clouds for enhanced profiling and microphysical retrievals

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ABSTRACT

Spectral polarimetry is based on combined simultaneous Doppler and polarization measurements, with a close look on the polarization dependence of the radar signal per velocity bin of the Doppler spectrum. The principle of radar spectral polarimetry and the main steps of the related processing are given in the paper. The processing results in clutter- and noise-free atmospheric spectrographs (Doppler spectra for every height).

When the processed spectrographs are integrated to calculate the classical Doppler moments, the resulting estimates of reflectivity, mean Doppler velocity, Doppler width and polarimetric parameters are improved. Improved profiles have the potentiality to lead to better estimates of rain rates, liquid water and ice water content, and wind. In the paper, illustration is provided in the context of wind profiling, which employs as input mean Doppler velocity profiles.

Another application consists of linking the processed Doppler spectrum with the Particle Size Distribution (PSD) of the medium being probed. Thus, in addition to the more traditional method of expressing the Doppler spectrum in its statistical moments, spectral polarimetry can also provide detailed microphysical information of precipitation and clouds in the case of slant profiling. One illustration is shown in the case of mixed-phase clouds.

Both illustrations are part of the extended data set collected by the S-band TARA (Transportable Atmospheric RAdar) within the COPS campaign (Convective Orographycally-induced Precipitation Study) in the black forest in Germany during the summer of 2007.

1. SPECTRAL POLARIMETRY

The complex Doppler velocity spectrum of the radar signal is measured for each radar resolution volume at different polarizations, for example $S_{VV}(v)$, $S_{HV}(v)$, $S_{VH}(v)$ and $S_{HH}(v)$, v being the Doppler velocity and *VV*, *HV*, *VH* and *HH* the polarization settings. From them a spectral target covariance matrix (1) can be calculated,

$$\begin{bmatrix} \langle S_{HH}(v)S^*_{HH}(v)\rangle & \langle \sqrt{2}S_{HH}(v)S^*_{HV}(v)\rangle & \langle S_{HH}(v)S^*_{VV}(v)\rangle \\ \langle \sqrt{2}S_{HV}(v)S^*_{HH}(v)\rangle & \langle 2S_{HV}(v)S^*_{HV}(v)\rangle & \langle \sqrt{2}S_{HV}(v)S^*_{VV}(v)\rangle \\ \langle S_{VV}(v)S^*_{HH}(v)\rangle & \langle \sqrt{2}S_{VV}(v)S^*_{HV}(v)\rangle & \langle S_{VV}(v)S^*_{VV}(v)\rangle \end{bmatrix} \tag{1}$$

The symbol < > indicates time-averaging. Because of the random distribution of atmospheric particles, time-averaging of the spectral target covariance matrix elements is carried out. Implicitly in (1), the reciprocity condition $S_{HV}=S_{VH}$ is applied and the matrix is polarimetrically calibrated. The spectral reflectivity, which depends on the Doppler velocity v, is defined as

$$sZ_{XY}(v) = \left\langle |S_{XY}(v)|^2 \right\rangle = \left\langle \sum_{i=1}^{n} N_i\left(D_i\{v\}\right)\sigma_{XY,i}\left(D_i\{v\}\right)\left|\frac{dD_i}{dv}\right| dv \right\rangle \tag{2}$$

It describes the classical Doppler power spectrum acquired with a transmitted *Y* polarization and a receiving *X* polarization, where *X* or *Y* stands for *H* or *V*. The sum is on the type of particles (aggregates, plates, columns, ..), N_i is the particle size distribution (PSD) and σ_i the radar cross section, corresponding to the particle type *i*. The equivolumetric diameter D_i is related to the Doppler velocity *v*. The corresponding reflectivity factor is:

$$Z_{XY} = \sum_{v} sZ_{XY}(v)\ , \tag{3}$$

Diverse spectral polarimetric parameters, i.e., polarimetric parameters which depend on the Doppler velocity, can be estimated from the spectral target covariance matrix (1). We shall consider three spectral polarimetric parameters in this paper. The first two ones are used to discard the Doppler velocity bins of non-atmospheric echoes (clutter and noise) by a thresholding technique [1]:

$$sL_{dr}(v) = \frac{\langle S_{VH}(v)S^*_{VH}(v)\rangle}{\langle S_{HH}(v)S^*_{HH}(v)\rangle} = sL^{HH}_{dr}(v)\ , \tag{4}$$

$$sL^{VV}_{dr}(v) = \frac{\langle S_{HV}(v)S^*_{HV}(v)\rangle}{\langle S_{VV}(v)S^*_{VV}(v)\rangle}\ , \tag{5}$$

The cross-polar echo (*VH* or *HV*) of hydrometeors is very weak compared to the co-polar one (*HH* or *VV*). Therefore values of those parameters larger than 0.3 (-5 dB) reveal clutter or noise contamination. The third parameter is employed for microphysical retrieval to discriminate different types of ice particles [2]:

$$sZ_{dr}(v) = \frac{\langle S_{HH}(v)S^*_{HH}(v)\rangle}{\langle S_{VV}(v)S^*_{VV}(v)\rangle} = \frac{\left\langle \sum_{i=1}^{n} N_i\left(D_i\{v\}\right)\sigma_{HH,i}\left(D_i\{v\}\right)\left|\frac{dD_i}{dv}\right| dv\right\rangle}{\left\langle \sum_{i=1}^{n} N_i\left(D_i\{v\}\right)\sigma_{VV,i}\left(D_i\{v\}\right)\left|\frac{dD_i}{dv}\right| dv\right\rangle}\ , \tag{6}$$

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So far, research is carried out to retrieve two PSD's within the radar resolution volume, for example aggregates (sZ_{dr} near 0 dB, large fall velocity) and plates (sZ_{dr}>0.5 dB, small fall velocity) or aggregates and columns (sZ_{dr} negative, small fall velocity). Fig. 1 illustrates this concept.

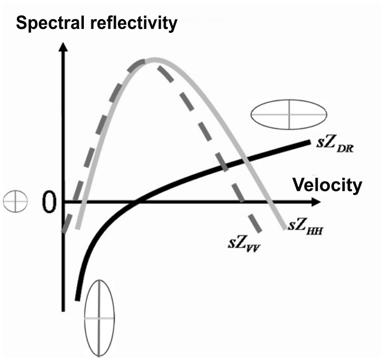

Figure 1. *Measured Doppler spectra, $sZ_{HH}(v)$ and $sZ_{VV}(v)$, in dB. Their difference is $sZ_{dr}(v)$, which indicates a spherical shape at 0 dB, horizontally orientated spheroids when it is positive and vertically oriented spheroids when it is negative*

There are thus two main advantages for using spectral polarimetry. The first one is the possibility to remove the Doppler bins related to non-atmospheric echoes in the Doppler spectrum. This can be used in the elevation range 0-90 deg. The second one is the possibility to directly retrieve microphysical parameters from the polarimetric Doppler spectra. For this purpose, slant profiling near 45 deg is recommended.

2. PROCESSING

Doppler spectra at different polarization settings are acquired for every radar resolution volume. One example is given in the top panel of Fig. 2. The Doppler spectra of a cloud (2000-6000 m), which is going to precipitate, are influenced by the horizontal wind due to the elevation of 75 deg. The mean Doppler velocity consists of the mean fall velocity and a wind component.

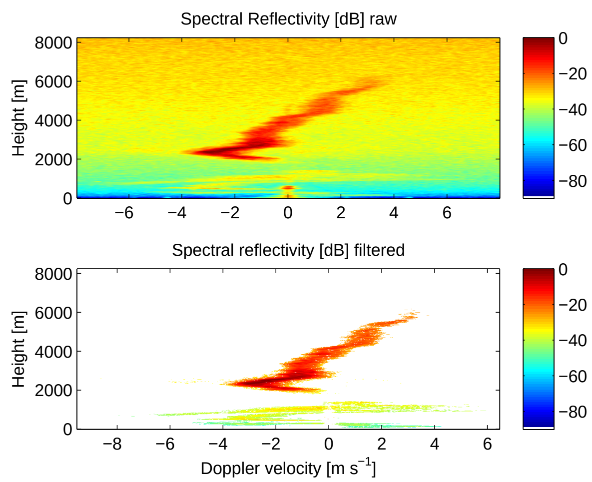

Figure 2. *Measured Doppler spectra, $sZ_{VV}(v)$, for each height. They represent a cloud layer between 2000 and 6000 m (3 July 2007, 9:21 UTC, Hornisgrinde).*

The processing consists of removing the Doppler bins of the Doppler spectra, which contain non-atmospheric echoes. Therefore the Doppler bins, 5 dB above the noise level (classical filter) and related to spectral linear depolarization ratios inferior to -5 dB (spectral polarimetric filter), remain. The result can be seen in the bottom panel of Fig. 2. Under the cloud layer, weak atmospheric echoes are present. They are probably a superposition of weak drizzle and refractivity index variation echoes.

3. PROCESSING RESULTS

3.1 Wind profiling

From one processed spectrograph, integrated parameters like the mean Doppler velocity for each height can be calculated:

$$v_{XY} = \frac{\sum_v v \cdot sZ_{XY}(v)}{\sum_v sZ_{XY}(v)}, \qquad (7)$$

One profile of mean Doppler velocity is thus acquired. Fig. 3 shows profiles of mean Doppler velocities estimated from the three beams of TARA (elevations 90, 75 and 69 deg). Compared to a polarimetric filtering technique directly operating on the profiles, which removes clutter contaminated data, the advantage of a spectral polarimetric technique is the correction of the profiles data [1].

Spectral polarimetric filtering is only possible when the beam is polarimetric (elevation 75 deg). However the characterization of non-atmospheric Doppler bins can be extended to the non-polarimetric beams Doppler spectra in the first 2000 m [3]. This leads to partial clutter reduction in the non-polarimetric beams.

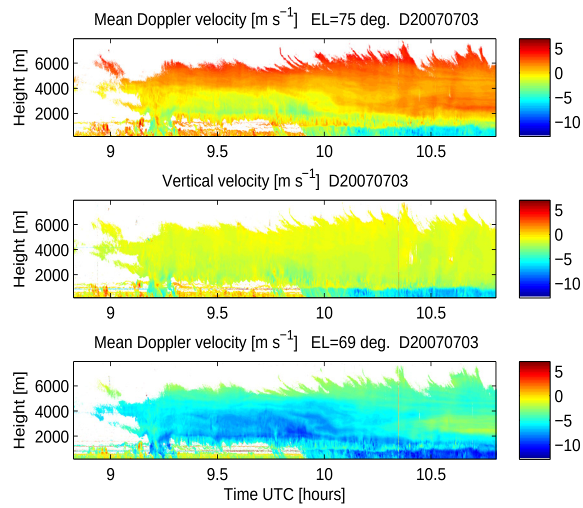

Figure 3. *Estimated mean Doppler velocities after spectral polarimetric processing (3 July 2007). A cloud layer (2000-6000 m) precipitates. Until 10:00, there are clear air echoes when no precipitation occurs. In that case only, the vertical velocity is the vertical wind velocity.*

Finally the horizontal wind is calculated from these 3 mean Doppler velocities (Fig. 4). It is assumed that the 3 beams measure the same atmospheric object. The calculation is performed when data are available for the 3 beams. Therefore if clutter data remain in the case of the non-polarimetric beams, they may not be used to estimate the horizontal wind and the final vertical velocity because there is no data for the polarimetric beam. This is an indirect spectral polarimetric filtering.

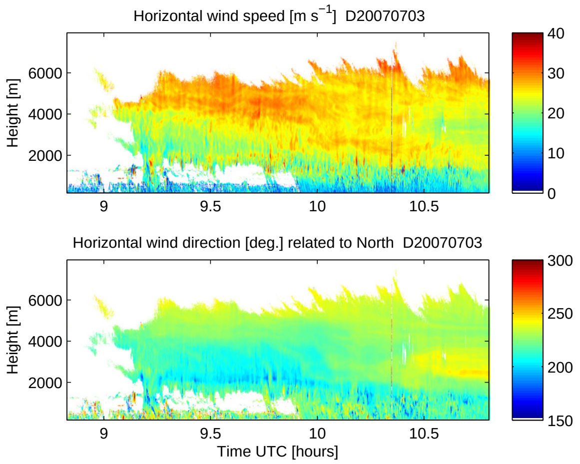

Figure 4. *Horizontal wind (speed and direction). The time and the height resolution are 3 s and 16 m.*

During the COPS campaign [4], TARA was located at the top of a mountain (Hornisgrinde) pointing in the direction of site M (Murg valley, 15 km away) where ARM mobile facility has been deployed. From the site M, a radiosonde is launched at 11:00. This sensor provides the horizontal wind. It takes about 21 min for the radiosonde to go from the altitude 1158 m (TARA altitude), equivalently height 0 m, to height 6000 m. Fig. 5 shows estimated TARA horizontal wind profiles during this time period. In Fig. 6 they are averaged in time to be compared qualitatively with the radiosonde profile.

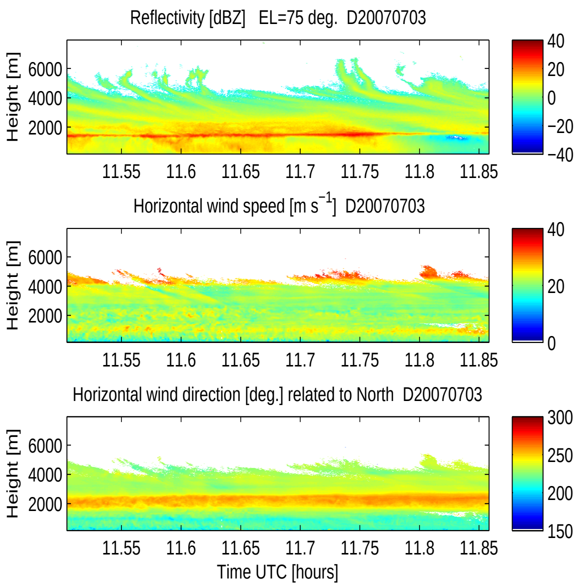

Figure 5. *Horizontal wind (speed and direction) during precipitation. The reflectivity measured by the polarimetric beam is depicted in the upper plot.*

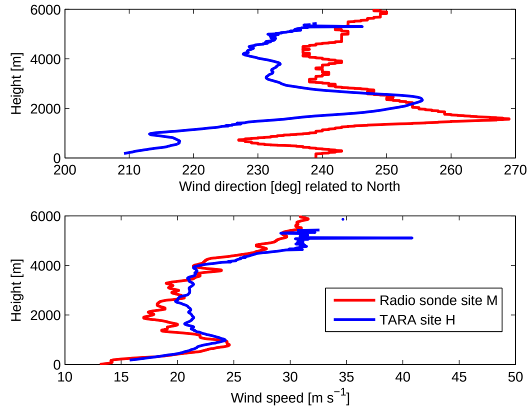

Figure 6. *Horizontal wind (speed and direction) during precipitation measured by TARA (average on 21 min) and a radiosonde. There is a good agreement between both sensors.*

Note the layered profiles of the wind direction in Fig. 5, which demonstrate the robustness of the processing (there is no dependence on the reflectivity values). At height 4000 m (top of the precipitating cloud), the wind speed significantly increases (nearly 10 m s^{-1}). This wind shear is measured as well by the radiosonde. Above and below the melting layer at height 1000 m, we notice a series of cells with larger wind speed of short time duration (20 s). When averaged, the wind speed measured by the radar and the radiosonde exhibits a peak at about 1000 m.

3.2 Microphysical retrievals

As explained in section 1, when the radar antennas are settled at 45 deg elevation, spectral polarimetric parameters can be used as a tool for the retrieval of cloud microphysical properties. A technique was developed at the University of Delft with the aim of retrieving the particle size distribution of different ice particle types found in the radar volume being probed, using Doppler polarimetric radar measurements. The method lies on the fitting of the measured $sZ_{dr}(v)$ (eq. 6) and $sZ_{HH}(v)$ (from the TARA radar), with simulated ones obtained by optimizing and inverting the input parameters of a microphysical model with a stepwise least square algorithm procedure described in [2],

$$\min_{\psi} \sum_{v=v_{\min}}^{v_{\max}} \left(sZ_{XX}^{meas}(v) - sZ_{XX}^{\mathrm{mod}}(v,\psi) \right), \quad (8)$$

where *meas* and *mod* denotes the measured and simulated spectrum respectively, the subscript *XX* the type of polarimetric measurement (copolar *HH* or differential *dr*) and ψ a variable which contains all the input parameters optimized in the model.

The optimized microphysical inputs ψ_{opt}, i.e, the retrieval outputs, are composed of the intercept parameter N_w, the median particle diameter D_0 and the shape factor μ for each ice particle types (assuming a modified gamma distribution), as well as the mean ambient wind parameter v_0 and the spectral broadening value σ_0 due to presence of turbulence. It has to be pointed out that, in order to make the model run, a prior determination of the particle types and their relative orientations is also performed. It is explained in detail in [4].

An example of the fitting process, on the measured Doppler spectra $sZ_{dr}(v)$ and $sZ_{HH}(v)$, is presented on Fig. 7 for a specific radar cell in a mixed-phase cloud region. For this example, a combination of aggregates and horizontally aligned particles was determined and considered in the microphysical model. The result of the retrieval technique is displayed within the text box.

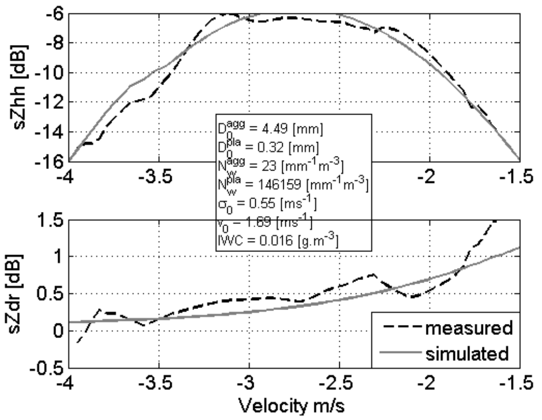

Figure 7. *Example of the fitting process performed on $sZ_{HH}(v)$ and $sZ_{dr}(v)$. The text box in the middle provides the optimized input parameters.*

Fig. 8 represents the ice *PSD* (*N(D)*) computed from the above retrieved parameters, such as,

$$N(D) = N_w f(\mu) \left(\frac{D}{D_0} \right)^{\mu} \exp\left(-(3.67+\mu) \frac{D}{D_0} \right) \quad (9)$$
$$f(\mu) = \frac{6}{3.67^4} \frac{(3.67+\mu)^{\mu+4}}{\Gamma(\mu+4)}$$

The ice water content *IWC* and total particle concentration N_t of the radar cell can be computed from the moments of such distribution (3rd and 1st moment respectively).

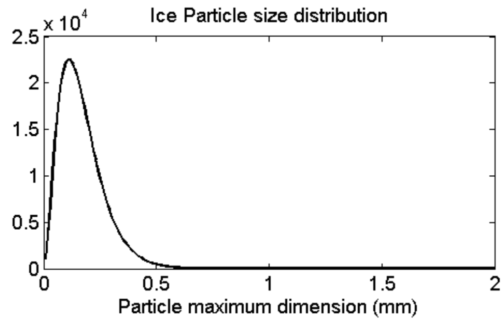

Figure 8. *Ice particle size distribution obtained from the output of the retrieval of figure 7. A modified gamma distribution with a shape factor μ=1 is used.*

This retrieval method is still under construction, but already promising microphysical results have been obtained and inter-compared with other instruments during the COPS campaign in the summer 2007. In [4], a case study (21/07/07) is provided for a mixed-phase cloud case, in order to illustrate such technique.

4. CONCLUSIONS

Spectral polarimetry advantages in terms of processing and new possibilities for microphysical retrievals are being assessed. The COPS campaign, with two months of TARA raw data, offers a unique opportunity for this evaluation, with multiple sensors, 250 m away of TARA, the profiling ARM mobile facility (pointing direction of TARA) and the airplanes collecting in-situ cloud data. The spectral polarimetric processing has been tested on study cases in The Netherlands and therefore has reached a final stage. It is otherwise for the challenging retrievals of two Particle Size Distributions within clouds, where a large effort of validation is necessary. Concerning wind profiling, we still need to verify individual profiles acquired with the time resolution 3 s, especially in the case of heterogeneous situations with cells of different wind speed or direction. Averaged wind profiles give so far satisfying results.

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REFERENCES

[1] Unal C. M. H., 2009: Spectral polarimetric radar clutter suppression technique to enhance atmospheric echoes, accepted for publication in *J. Atmos. Oceanic Technol.*

[2] Spek A. L. J., C. M. H. Unal, D. N. Moisseev, H. W. J. Russchenberg, V. Chandrasekar, Y. Dufournet, 2008: A new technique to categorize and retrieve the microphysical properties of ice particles above the melting layer using radar dual-polarization spectral analysis, *J. Atmos. Oceanic Technol.*, **25**, pp. 482-497.

[3] Unal C. M. H., 2008: High resolution 3D wind profiling using an S-band polarimetric FM-CW radar: clutter reduction techniques, *Proc., 5th European Conf. on Radar in Meteorology and Hydrology (CDROM)*, Helsinki, Finland.

[4] Dufournet Y., C.M.H. Unal, H.W.J. Russchenberg, Retrieval of the microphysical properties of mixed-phase clouds using Doppler polarimetric tools, *extended abstract submitted to ISTP 2009.*