Estimation of differential and specific differential phase with the IDRA X-band Doppler polarimetric radar for improving rain rate retrieval

S. Georgiou, C. M. H. Unal, J. Figueras i Ventura, T. Otto, and H.W.J. Russchenberg

IRCTR, Delft University of Technology, S.Georgiou@student.tudelft.nl, C.M.H.Unal@tudelft.nl

ABSTRACT

For studying atmospheric phenomena and monitoring climate change, radar has been proven to be an indispensable and dependable tool. A Doppler radar also allows for the observation of particle velocities and filtering of the received signal in the frequency domain. A polarimetric radar exploits the anisotropy of the precipitation medium by employing pulses of different polarizations. A Doppler polarimetric radar not only combines both aforementioned advantages, but also offers the possibility to interpret the radar observables as functions of the particle velocities instead of single, integrated values. This option of finely partitioning the radar resolution volume results in abounding information which seems attractive; however, careful consideration should be placed on how to process it in order to access its content and avoid pitfalls.

This paper presents rain measurements carried out by the IDRA X-band Doppler polarimetric radar located in Cabauw, the Netherlands [1]. The focus is on the estimation of differential propagation phase (Φ_{dp}) and specific differential phase (K_{dp}), from a spectral polarimetric point of view. With an adequate spectral polarimetric processing, it is expected to improve the estimates of Φ_{dp} and K_{dp}. Comparison with the established time-domain technique will be carried out. K_{dp} is challenging to estimate because it is a phase-related observable and the phase of radar signal presents rapid variations, necessitating careful processing and filtering. Yet, it is valuable, as it has been sufficiently supported in literature that it results in advantageous rain rate retrieval and classification algorithms.

1. BACKGROUND

K_{dp} is the first range derivative of the differential propagation phase (Φ_{dp}). Φ_{dp} expresses the difference in propagation constants between the horizontally and vertically polarized wave originating from the anisotropy of the precipitation particles. In practice, Φ_{dp} can only be estimated with the differential scattering phase (δ_{co}) superimposed on it:

$$\Psi_{dp} = \Phi_{dp} + \delta_{co} \tag{1}$$

This results in the total differential phase (Ψ_{dp}) instead of the desired Φ_{dp}. It may be possible to filter out δ_{co} since it is not range cumulative in contrast to Φ_{dp}, so it will appear as 'bumps' on top of the slow-varying Φ_{dp}. However if these bumps extend over a long range they could be masked inside the mean trend of Φ_{dp}. Also, δ_{co} is due to non-Rayleigh scattering which is expected in X-band even for moderate rain paths. For these reasons, it would be useful to test the performance of an $\delta_{co}(Z_{dr})$ estimator on the physical basis that both originate from the non-sphericity of particles. Rain rate estimators based on K_{dp} have been shown to be advantageous due to its immunity to hail contamination, attenuation effects since it is a phase-based observable, absolute calibration errors etc [2].

2. SPECTRAL POLARIMETRIC ESTIMATION OF Ψ_{DP}

The essence of the spectral polarimetry is that the radar observables are no longer considered to be single values, but functions with respect to the Doppler velocities of the precipitation particles, v ([3]). In other words, particles of a certain velocity are grouped together and their contribution to a certain radar observable[1] is separated from the whole. So far, Ψ_{dp} has been estimated in the time domain implying the use of a pulse radar with a polarization switching scheme. IDRA is an FM-CW radar, so it emits a series of chirp pulses of duration DT each. The received waveform after quadrature demodulation is then sampled within each chirp duration DT, so it can be represented as a two-variable funtion $s(t_k, t_n)$ where t_k denotes the samples within DT and t_n a certain chirp and its corresponding DT. By taking its Fourier Transform with respect to t_k we obtain $s(f_k, t_n)$ where the frequencies f_k can be translated into rangebins since this is the principle of FM-CW radars. With a subsequent Fourier Transform with respect to t_n (in practice after a number of consecutive sweeps) we obtain $s(f_k, f_n)$ where the frequencies f_n can be translated into the Doppler velocities of the particles thus forming the Doppler spectrum for a certain rangebin. In discrete notation, the result is a $S[k, n]$ 512x512 matrix where index k denotes a rangebin and index n denotes a Doppler velocity. Polarization can be taken into account as well so we end up with S_{hh}, S_{vh}, S_{vv} and S_{hv} matrices conceptually corresponding to V_{hh}, V_{vh},

[1] thus named spectral

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

V_{vv} and V_{hv} return signals. Essentially, considering the difference of the phases of their elements gives rise to Ψ_{dp}, however some extra steps have to be applied as well. These are:

- obtain Ψ_{dp} as $arg(S_{hh}[k,n]S^*_{vv}[k,n])$
- apply system circuitry phase offset
- compensate for non-simultaneity of copolar measurements: this was implemented with a phase compensation as discussed in [4].
- de-aliasing [4]
- spectrum smoothing
- zero Doppler bin suppression
- spectral polarimetric filtering

Eventually, the result is a Ψ_{dp}[k,n] matrix. In order to arrive to a single value for each rangebin and thus converge in the time domain approach, an integration has to occur along the Doppler velocity bins. Two approaches are available:

- Averaging over all Doppler velocity bins which are considered equally.
- Weighting each Doppler velocity bin by the magnitude of the respective $S_{hh}[k,n]$ elements before averaging then, the idea being to suppress the influence of weak echoes which are more likely to be governed by noise and promote the influence of strong, atmospheric echoes instead.

In practice, it was observed that both approaches produce similar results but weighting by the spectral reflectivity results in less variance in the resulting Ψ_{dp} range profile, hence it was favoured. In Fig. 1 and Fig. 2 some example results are shown. They are from a rain event observed by IDRA on 26 May 2008, 0430UTC (the Z and Z_{dr} profiles are shown later in Fig. 5). It is noticed that by applying a pulse-pair processing algorithm, the equivalent time domain Ψ_{dp} can also be obtained.

3. ASSESSMENT OF RESULTS

Although the systematic agreement between the time domain and the spectral polarimetric approach regarding Ψ_{dp} estimation is a positive indication, a way to check the correctness of the estimation seemed necessary. It is noticed that eventually the only way for reliable validation of results is correlation with a reference such as rain gauge measurements. In the following, the objective was merely to assess the correctness of the estimation by comparison against the expected Ψ_{dp} and Φ_{dp} profiles.

3.1. Self-consistency approach

The concept of the self-consistency [5] is that all the radar observables are interrelated through the drop size distribution (dsd). Therefore, they reside in a confined space and relationships can be formulated that express one in terms of the others in a best-fit sense. Following a simulation approach base on the Fredholm Integral

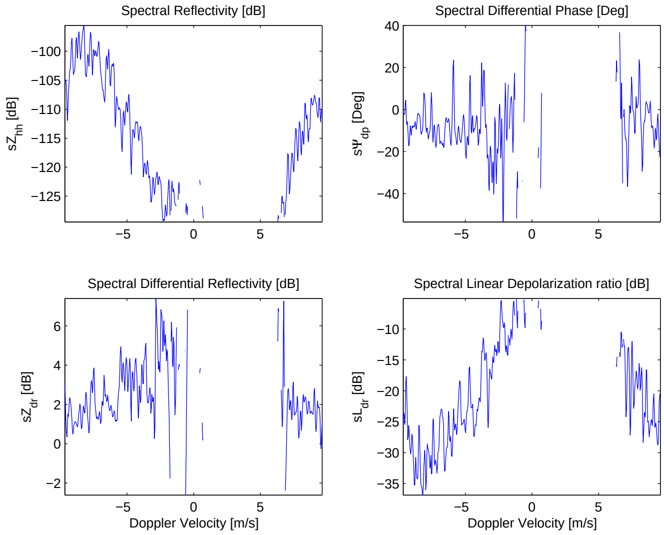

Figure 1. The spectral Z, Z_{dr}, L_{dr} and Ψ_{dp} for a certain rangebin: they are not integrated single values, but functions over the particle Doppler velocities.

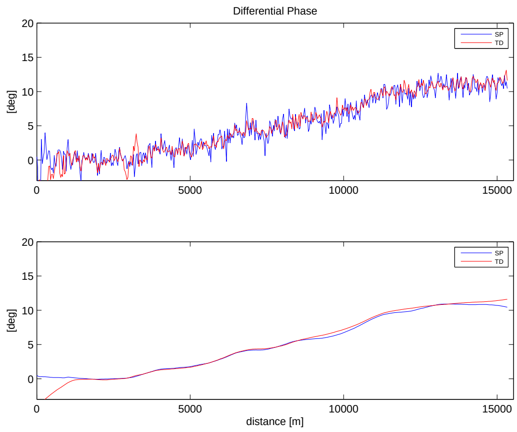

Figure 2. The estimated Ψ_{dp} profiles for the time domain and spectral polarimetry approach (upper part), 320^0 azimuth sector. Agreeement is observed although the spectral polarimetry approach results in more variance. However, after the necessary smoothing (lower part) this effect becomes negligible and the curves almost coincide.

Method, a variety of gamma dsd were generated resulting in a dataset for the radar observables. By applying regression, the following estimators were obtained (Z is in linear scale and Z_{dr} in dB):

$$K_{dp}^{sc} = 0.0005 Z^{0.9751} 10^{-0.398 Z_{dr}} \; (MSE = 6.7\%) \quad (2)$$

$$\delta_{co}^{sc} = 0.3719 {Z_{dr}}^{2.8291} \; (MSE = 14.1)\% \quad (3)$$

By using these estimators reconstructed Φ_{dp} and Ψ_{dp} profiles can be obtained, along with K_{dp}. Also, various rain rate estimators can be formulated. It was found that the most accurate one was the R(K_{dp},Z_{dr}) followed by R(Z,Z_{dr}) and R(K_{dp}). Although in practice the accuracy of estimation of the radar observables does affect the overall performance, these results are indicative of the applicability of the K_{dp} for rain rate estimation. It is noticed that the dataset was filtered so that only dsd corresponding to rain rate less that 20mm/hr (the estimated maximum for the considered rain event based on reflectivity values) were taken into account. The reasoning was that the resulting estimators should be based on a dataset which corresponds as closely as possible to the observed meteorological conditions so that they are correct on a physical basis as well.

3.2. Drop size distribution retrieval

Since the gamma dsd model contains three parameters, they can be retrieved having three independent measurements. If a value is assumed for μ, then based on the measured Z and Z_{dr} the dsd can be retrieved and thus all the radar observables can be computed. In the end, reconstructed profiles of Φ_{dp} and Ψ_{dp} can be obtained, as before. The results are given in Fig. 3, where agreement is observed between the two approaches. Therefore, the respective Ψ_{dp} and Φ_{dp} profiles will be almost identical. For this reason, in the following only the dsd retrieval approach is mentioned since they both give the same expected values. Regarding the choice of μ, small values were selected since higher values tend to relate to more intense rain events, unlike the one considered. However, more detailed analysis seems more appropriate. As seen in Fig. 4, the reconstructed Ψ_{dp}, Φ_{dp} and K_{dp} profiles agree well with the estimated ones up to a certain range, after which deviation occurs which was thought to be due to attenuation effects which are usually non-negligible for X-band.

4. ATTENUATION

As mentioned before, there is disagreement between the expected and estimated Ψ_{dp}, Φ_{dp}. Initially, there is agreement but after about 6km there is a growing deviation so that at the end of the range the expected Φ_{dp} value is almost 3.5^o less then the measured one. This behavior was observed in other sectors as well and was attributed to attenuation effects: specific and differential attenuation result in attenuated Z and Z_{dr} values respectively, which means that the expected K_{dp} based on these attenuated values is less than in reality, therefore the expected Φ_{dp} has lower rate of increase and its curve stays under the measured one. This takes affect

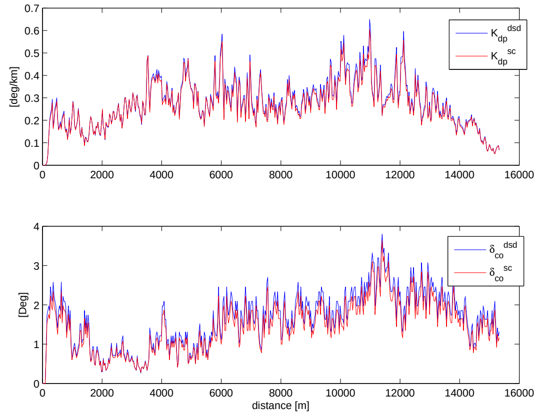

Figure 3. Expected K_{dp} and δ_{co} according to the self-consistency and dsd retrieval method. They closely agree and so do the resulting expected Ψ_{dp} and Φ_{dp} range profiles.

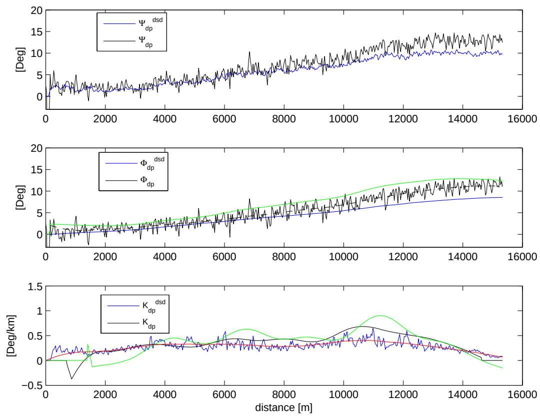

Figure 4. Reconstructed Ψ_{dp},Φ_{dp} and K_{dp} profiles from dsd retrieval (blue) and comparison with the estimated ones (black). For Φ_{dp}, the black dashed line represents the smoothed profile (MA filter of 48 range bins spaced 30m apart) based on the solid one which is simply Ψ_{dp}-δ_{co}^{dsd}. The green curve is obtained directly by smoothing Ψ_{dp}, so without δ_{co} removal. For K_{dp}, the red curve is simply the blue (K_{dp} from dsd retrieval) after smoothing with the same filter. The estimated Kdp (black curve) should be compared against that one since the K_{dp} estimator used implies smoothing. The green K_{dp} curve presents non-negligible bias at segments where δ_{co} is not steady (10-12km most prominently). That means that a δ_{co} removal approach is needed. It is noticed that for δ_{co} removal, using a self-consistent relationship is less complicated (no need for dsd retrieval) and gives similar results (Fig. 3). Agreement in Φ_{dp} is indicative of efficient δ_{co} estimator and successful removal of it from Ψ_{dp}. Finally, it is mentioned that the K_{dp} estimator operates by considering segments of Φ_{dp} around a certain rangebin and computing their slope by applying a linear fit. Therefore, a loss of resolution is implied so the estimated K_{dp} curves do not have many peaks.

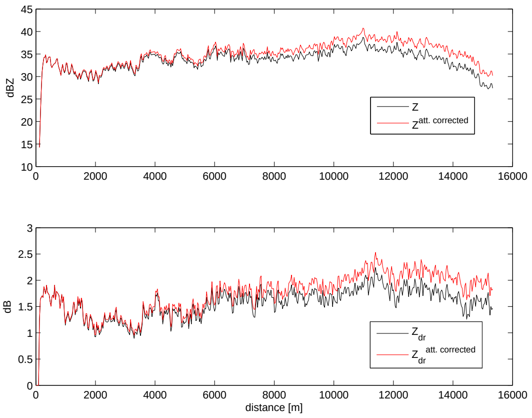

Figure 5. Attenuation correction for the Z and Z_{dr} range profiles.

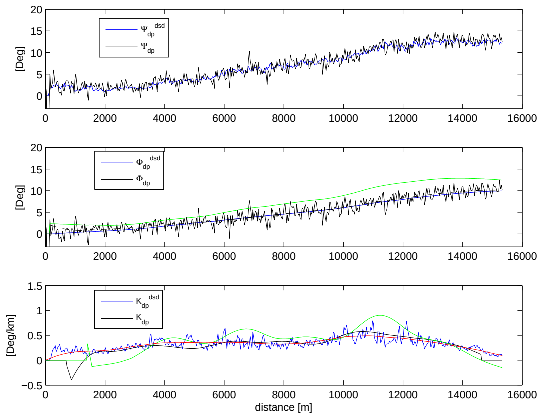

Figure 6. Same as Fig. 4, but based on Z and Z_{dr} range profiles compensated for attenuation: now there is agreement between the expected and measured Ψ_{dp}, Φ_{dp} and K_{dp} over the whole radar range in contrast to Fig. 4. It is interesting to notice that the estimated black Φ_{dp} curve now is brought down a little, because correcting for differential attenuation results in increased estimated values of δ_{co}, and Φ_{dp}=Ψ_{dp}-δ_{co}^{dsd}; on the other hand the expected blue Φ_{dp} curve is brought even more up and in total they meet. Similar behavior is observed for the K_{dp} curves.

only after some distance (about 6km) since the attenuation is cumulative hence negligible for shorter distances. In order to check the validity of this assumption, the attenuation correction approach of [6] was followed. The corrected Z and Z_{dr} profiles are given in Fig. 5 and if we are based on these corrected profiles for reconstructing the expected Φ_{dp} profile, agreement is reached with the estimated one all over the radar range (Fig. 6). As an additional check, sectors where considered were the expected and estimated Φ_{dp} happened to agree over the whole range in the first place; applying the attenuation correction algorithm resulted in negligible correction for Z and Z_{dr} implying that the effect of attenuation was insignificant, due to less intense precipitation medium.

5. CONCLUSIONS

A method for estimating Ψ_{dp} under a spectral polarimetry approach was presented. After estimation of Ψ_{dp}, estimation of K_{dp} is possible. The results agree well with the typical time domain method especially after applying a smoothing filter. A potential advantage of the spectral polarimetry formulation is the possibility to use spectral polarimetric filtering to efficiently remove clutter. For IDRA, clutter does not pose a very serious problem due to the open location; however for other cases this may not be the case and the spectral polarimetry approach may prove to be beneficial.

The correctness of the estimation was assessed qualitatively by comparison against the expected values. Good agreement was observed after taking into account attenuation effects and compensating for them. These results allow us to have confidence in the estimation of Ψ_{dp} and Φ_{dp}. It is also possible to apply successfully a simple $\delta_{co}(Z_{dr})$ estimator or compute it by first retrieving the dsd. Still, correlation of K_{dp} rain rate estimation with rain gauge measurements is necessary. In general, it is believed that a correctly estimated Ψ_{dp} and δ_{co} make it possible to use the full potential of the advantageous rain rate estimators involving K_{dp}.

REFERENCES

[1] J. Figueras i Ventura, H.W.J. Russchenberg, IDRA: a new instrument for drizzle monitoring, International Geoscience and Remote Sensing Symposium, IGARSS 2007, Barcelona 23-27 July 07.

[2] Zrnić, D., and A. Ryzhkov, 1996: Advantages of Rain Measurements Using Specific Differential Phase. J. Atmos. Oceanic Technol., 13, 454-464.

[3] Russchenberg, HWJ, Spek, L, Moisseev, D, Unal, CMH, Dufournet, Y Chandrasekar, V (2008): On the use of spectral polarimetry to observe ice cloud microphysics with radar. Precipitation: Advances in Measurement, Estimation and Prediction (pp. 285–312), Springer Berlin Heidelberg

[4] Unal, C.M.H., and D.N. Moisseev, 2004: Combined Doppler and Polarimetric Radar Measurements: Correction for Spectrum Aliasing and Nonsimultaneous Polarimetric Measurements. J. Atmos. Oceanic Technol., 21, 443-456.

[5] Scarchilli G., E. Gorgucci, V. Chandrasekar, and A. Dobaie, 1996: Self-consistency of polarization diversity measurement of rainfall. IEEE Trans. Geosci. Remote Sens., 34, 22–26.

[6] T. Otto, J. Figueras i Ventura, H.W.J. Russchenberg: Drop-size distribution retrieval of precipitation using a high-resolution polarimetric X-band weather radar, Proceedings of ISTP 2009, Delft, The Netherlands