Propagation Effects in the Application of Weather Radar – Positive and Negative Impact

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***Abstract*—Propagation effects play in important role in the application of weather radar. Attenuation and depolarization have negative effects on the quality of radar data and hinder rainfall estimation, whereas the differential propagation phase can be used for the quantification of precipitation and even correction of attenuation effects.**

***Index Terms*—weather radar, propagation, measurement.**

I. Introduction

Weather radar is used in Meteorology for the identification and quantification of precipitation systems like thunderstorms or weather fronts. Weather radars operate with centimeter wavelength. In order to observe non-precipitating clouds millimeter-wave radars are used.

The propagation of electromagnetic waves through the atmosphere and clouds or precipitation is affected by the respective media. While the primary objective of weather radar is the measurement of properties of precipitation like rain rate of hydrometeor type, propagation effects often hinder such measurements. For example, especially at short wavelength there is considerable attenuation in rainy situations. On the other hand, propagation effects are used to derive properties of clouds and precipitation.

In this paper we discuss common effects of propagation like attenuation, depolarization, and the usage of differential phase measurements for rain estimation or auto-calibration.

II. Weather Radar

Weather radars are pulsed radars operating at centimeter waves, typical characteristics are shown in Tab. I and Tab. II. In contrast to aviation surveillance radar systems a volume filled with targets is observed and besides localization of the target a quantification of the target is aimed. More about weather radar can be found in [1], [2], and [3]. Advanced applications are outlined in [4].

Typically modern dual-polarization Doppler weather radar generate in near real-time a number of products which are normally displayed either in a geo-referenced PPI (plan position indicator), or interpolated to a constant altitude CAPPI (constant altitude plan position indicator). Often the reflectivity or rain rate product is composed to national or international radar composites.

TABLE I. Frequency bands used for weather radar in Europe

Band	Frequency *f* (GHz)	Wavelength λ (cm)
X	9.3 - 9.5	3.1 – 3.2
C	5.6 – 5.65	5.3 – 5.4
S	2.7 – 2.9	1.0 – 1.1

TABLE II. Characteristics of weather radar

Parameter	Value
pulse peak power	10 – 1000 kW
pulse duration	0.6 – 2 µs
pulse repetition frequency	300 – 2500 Hz
half-power beam width	1 – 3°
maximum range	100 – 300 km
range resolution	90 – 300 m
antenna rotation speed	2 – 6 rpm

A. Reflectivity

Radar reflectivity factor or shortly called reflectivity is the standard product for weather radars [1][2]. Reflectivity factor z is defined as

$$z = \sum_{Vol} D_i^6 \qquad (1)$$

where D is the diameter of the scattering particles and the sum is over a unit volume of 1 m^3. Thus the unit is mm^6/m^3. Commonly the logarithmic presentation in dB is used relative to 1 mm^6/m^3. The respective unit is then dBz. Reflectivity is used to locate precipitation systems.

B. Rain Rate

For meteorological usage reflectivity factor z is converted to rain rate R. Rain rate is defined as the flux of liquid water through a unit plane and normally expressed in mm/h or liter per hour per square meter. Since z and R are different moments of the a priori unknown rain drop size distribution, a linear conversion from z to R is not possible. Normally empirical $z – R$ relations in the form of

$$z = aR^b \qquad (2)$$

are used [1]. a is in the order of 100 to 300, and b in the order of 1.2 to 1.6, depending on the kind of precipitation, the climatology and the location [1]. Due to the non-linear relation, the uncertainty in rain rate estimation is in the order of 10 – 50%.

C. Differential Reflectivity

Weather radar use linear polarized waves. Modern weather radar use linear horizontal and vertical polarized waves, either simultaneous transmitted and received (STAR mode), or alternating from pulse to pulse (AHV mode). Differential reflectivity Z_{DR} is defined as the logarithmic ratio between the reflectivity at linear horizontal polarization z_H and reflectivity at linear vertical polarization z_V

$$Z_{DR} = 10 \log_{10}(z_H/z_V) \tag{3}$$

Since raindrops larger than 1 mm in diameter have an oblate shape, Z_{DR} will be positive in rain. Differential reflectivity is used to improve rain rate estimation [5] and for the identification of hydrometeor type.

D. Linear Depolarization Ratio

In case of elongated scattering particles which are not aligned with the polarization plane, i.e. the minor axis elements S_{HV} and S_{VH} of the scattering matrix are non-zero, depolarization of the linear polarized wave takes place and the wave becomes elliptical and contains also a cross-polar component. The linear depolarization ratio LDR is defined as

$$LDR = 10 \log_{10}(z_{VH}/z_{HH}) \tag{4}$$

with z_{HH} the co-polar and z_{VH} the cross-polar reflectivity. In precipitation, LDR is strong when ice particles are melting and start tumbling during fall. LDR is a good indicator for hail shafts and the melting layer (*bright band*).

E. Doppler Velocity

If there is a relative motion between the radar and the target, the frequency of the received wave is changed by the Doppler Effect. Weather radar typically measures the phase difference between two consecutive pulses and estimate Doppler frequency which is then related to the radial motion of the precipitation particles. In general it is assumed that precipitation particles follow with the wind and have a known terminal fall velocity. Thus it is possible to estimate the wind field using measurements of Doppler velocity. Phase measurements, i.e. Doppler velocity are basically immune to propagation effects.

F. Differential propagation phase

When electromagnetic waves pass through precipitation particles, their propagation speed is delayed according the index of refraction. Depending on the shape and mass of the particle the propagation speed of the horizontal and vertical polarized wave will be different e.g. in case of oblate rain drops [6]. Differential propagation ϕ_{DP} phase is defined as

$$\phi_{DP} = \phi_H - \phi_V \tag{5}$$

The specific differential propagation K_{DP} phase is the range derivative of ϕ_{DP}

$$K_{DP} = \frac{\phi_{DP}(r_2) - \phi_{DP}(r_1)}{2(r_2 - r_1)} \tag{6}$$

with r as the range to the target volume. The unit is °/km. It is assumed that the scattering process itself does not introduce a differential phase shift. This is true as long the scattering particles are small compared to the wave length. Differential phase is used for attenuation correction and rain rate estimation.

III. Propagation Effects

Propagation effects play an important role in the application of weather radar. Commonly known is the attenuation of the signal during the passage of rain cells. This negative effect on reflectivity measurements can be corrected to some degree using reflectivity. On the other hand the differential propagation phase is a well suited parameter to correct for attenuation or to estimate rain rate and LDR helps the identification of hydrometeors.

A. Negative Propagation Effects

Negative propagation effects are those effects hindering or contaminating weather radar measurements.

1) Attenuation

Attenuation is the reduction of the transmitted energy during the passage through a media. The forward transmitted energy is reduced by the back and sideward scattered energy and the absorption of energy by the scattering particles. No attenuation will occur in vacuum.

Here we will concentrate on the attenuation in rain since the scattering processes of rain drops can be described quite easily. Absorption is proportional to D^3, whereas reflectivity is $\propto D^6$. Consequently, absorption cannot be estimated directly form reflectivity measurements. A number of empirical relations have been proposed for weather radar.

The following example (Fig. 1) shows the effect of

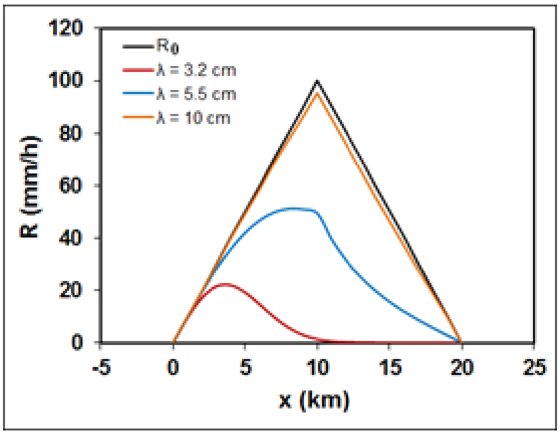

Fig. 1. Simulated effect of attenuation on rain rate measurements by weather radar.

attenuation on the estimation of the rain rate using a *z-R* relation. A simulated thunderstorm cell with a maximum rain rate of 100 m/h at the center and a width of 20 km cannot be resolved with C and X band weather radars. Even the position of the core is incorrectly located with a X-band radar. Almost no attenuation takes place for S-band radars. The maximum precipitation is considerable underestimated with X and C-band radars. Short-term forecasting for hydrological purpose might fail when using radars with short wavelengths λ.

Additionally, differential attenuation is observed in measurements of Z_{DR} when the wave passes through heavy precipitation with large oblate raindrops. In this situation the horizontal wave is much more attenuated than the vertical polarized wave. Thus resulting in a weaker horizontal signal at the end of the precipitation core and leading to negative Z_{DR} in weak precipitation beyond the cell. Note, that particles with negative Z_{DR} do not occur in nature.

Due to the non-linear relation between reflectivity and attenuation, a direct correction for attenuation is not possible. The application of simple empirical relations can lead to an unstable behavior introducing large errors [7]. Certain filtering of data is necessary before attenuation correction can be applied.

2) Depolarization

As shown above, *LDR* is a measure for depolarization of the linear transmitted wave. However, it was found that also Z_{DR} is affected by depolarization in case the radar operates in the STAR mode. The basic assumption for measurements in STAR mode is that the linear horizontal and linear vertical polarized waves (with same frequency) propagate without any interaction. This is not true anymore in case of depolarization where cross-talk between the two polarizations take place. A further assumption is that the waves are transmitted with equal phase, i.e. the resulting wave is a linear polarized wave with 45° orientation. In case a 90° phase shift is between the horizontal and vertical wave, the resulting wave is circular polarized. In the past radar manufacturers did not respect the phase difference between the two channels and their cross-coupling. However, the coupling of the cross-polar terms with the co-polar terms depends on the phase between the two channels.

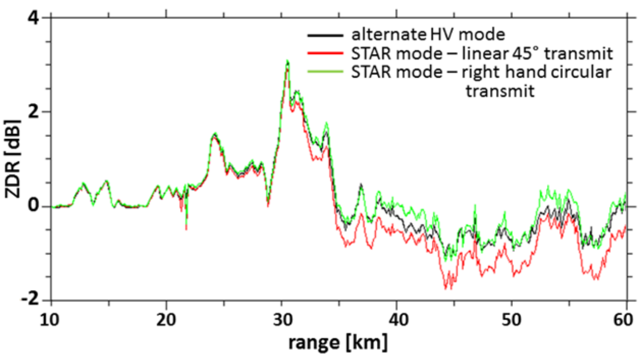

Fig. 2. Profile of Z_{DR} measurements with POLDIRAD on 2012-06-04 at 15:46 using three diferent polarization modes. For details see text.

With the DLR research radar POLDIRAD [8] it is possible to measure the STAR mode with different phase offsets simultaneous with the AHV mode [9]. In AHV mode the complete scattering matrix can be measured, whereas in STAR mode only the major axis elements possible contaminated by the minor axis elements can be measured.

Fig. 2 shows a single ray through a convective cell embedded in stratiform precipitation. Z_{DR} was measured in three different ways: a) using the STAR mode with an initial phase offset of 0°, i.e. linear 45°orientation; b) using the STAR mode with an initial phase offset of 90°, i.e. circular polarization; c) using the AHV mode avoiding cross-channel contamination. While the offset-corrected profile of Z_{DR} of all three methods overlap prior to the convective cell at range 30 km, distinct offset in the order of up to 1 dB can be observed on the rear side of the cell. This is caused by the change of the phase between the two measurements in STAR mode. AHV mode is immune to phase changes along the propagation phase. Note that rain rate estimation proposed by [5] requires high quality Z_{DR} measurements within 0.1 dB accuracy.

B. Positive Propagation Effects

Positive effects are considered as those effects which help to measure properties of precipitation.

1) Rain rate estimation using K_{DP}

As shown by [6] and others, K_{DP} can be used to estimate rain rate with higher precision than it is possible with Z alone. The reason is that K_{DP} is nearly proportional to the mass of the raindrops, thus less sensitive on the raindrop size distribution. For C-band an empirical relation

$$R = 19.8\, K_{DP} \tag{7}$$

was found by [10]. The linear relation shows the independence of the raindrop size distribution. However, the coefficient of 19.8 shows that K_{DP} has to be estimated with high precision in order to retrieve low rain rates. Common practice is to smooth measured ϕ_{DP} over a range of a few kilometers to improve accuracy of K_{DP}. Since K_{DP} is immune to attenuation effects it is well suited even for high precipitation rates.

2) Attenuation correction using K_{DP}

Attenuation is proportional to the mass of precipitation ($\propto D^3$) and K_{DP} is roughly proportional to D^4. Therefore, a nearly linear relation between K_{DP} and attenuation of reflectivity α_H and differential attenuation α_D of Z_{DR} can be found [11]. Using attenuation correction to Z and Z_{DR}, both parameters can be used further for rain rate estimation with high spatial resolution or for the identification of hydrometeors.

Fig. 3 shows one example of a radar ray through a strong convective cell. Using α_H = 0.12 and α_D = 0.04 a corrected profile of Z and Z_{DR} can be estimated. With this correction a more realistic positive Z_{DR} is obtained at the rear side of the convective cell. Z is increased by more than 10 dB within the

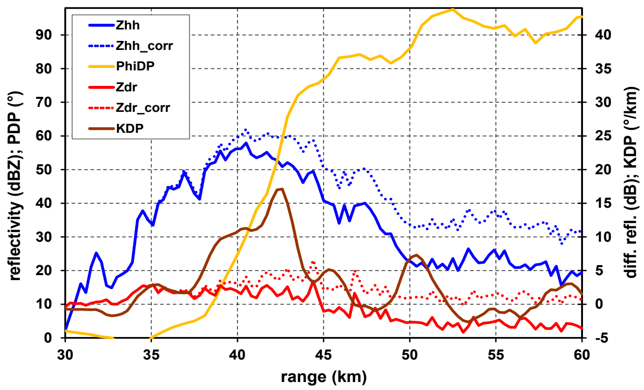

Fig. 3. Range profile measured with POLDIRAD on 2007-08-15 at 18:21.

convective cell; this certainly has a considerable impact for hydrological applications: 40 dBz at range 45 km corresponds roughly to 13 mm/h rainfall, whereas 50 dBz corresponds to about 67 mm/h rainfall. With this heavy rainfall, flooding in the vicinity of small rivers can occur; uncorrected radar data would not raise a warning level in this situation.

3) Self-consistency check using Z, Z_{DR}, and ϕ_{DP}

Self-consistency or auto-calibration of radar parameters is a further application of differential phases. It was proposed by [11] and [12] to use the observed values of Z and Z_{DR} to predict K_{DP} at each range bin. The estimated K_{DP} values are then used to construct the total differential phase ϕ_{DP} along the radar beam. Comparing the measured profile of ϕ_{DP} with the reconstructed profile of ϕ_{DP} allows identifying miss-calibration of reflectivity and Z can be adjusted accordingly. It has to be assured that Z_{DR} is properly calibrated, this is normally checked with a vertically pointing antenna in light rain where Z_{DR} should be zero.

IV. Summary and Conclusions

In weather radar applications, propagation effects are often considered only in case of attenuation for X-band radars. However, this is only one aspect. Attenuation occurs at all wavelengths, even though it is of minor importance for S-band radars. The application of attenuation correction procedures using differential phase measurements allow for a successful correction of attenuation at least for rain. Other hydrometeors like hail or graupel can have a large variety of shapes and will have also different scattering properties in case they are coated with a thin water layer. Depolarization of linear waves propagating through non-spherical hydrometeors, or hydrometeors which are not within the Rayleigh regime ($D << \lambda$) has an impact on the accuracy of Z_{DR} measurements with weather radar systems operating in STAR mode.

In summary, propagation effects do contaminate power measurements like Z and Z_{DR}, but on the on the other hand, modern dual-polarization Doppler weather radar systems benefit from applications using the differential propagation phase.

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