RainGain Conference,
08-09 June 2015, Paris, France

Dual-Polarimetric X-Band Weather Radar: Accurate Rainfall Estimation and Storm Observation

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Abstract

Weather observations are conventionally performed by single-polarimetric C-band weather radars with temporal and spatial resolutions of 5 min and 1 km, respectively. However, in recent years, weather radars have been upgraded from single to dual-polarimetric for improved weather measurements. For example, the dual-polarimetric capabilities might lead to more accurate rainfall estimation than that of single-polarimetric. Still, these spatial and temporal resolutions might be undesirable for the detection of localized heavy rainfall which is usually required to model fast rainfall-runoff processes in urbanized areas. Moreover, small but threatening patterns associated with severe weather might be unseen. In this work, a dual-polarimetric X-band weather radar, IDRA hereafter, located in the Netherlands (NL) is used to obtain accurate rainfall estimation and observe and derive physical processes of storms, at high temporal and spatial resolutions. In this work, rainfall estimation was based on the specific differential phase (K_{dp}), for moderate and convective storms. In addition, an advanced method to estimate K_{dp} from pure rain at X-band frequencies is proposed. To analyse the impact of resolution quality on the variability of rainfall intensities, estimates of rainfall intensities by IDRA were used to simulate rainfall intensities at coarse resolutions. Preliminary results have shown significant variability in rainfall intensities when the spatial resolution was decreased from 30 m to 1000 m. Observations of multiple storms by IDRA were compared with those of the operational C-band radars of the NL. High resolutions observations by IDRA were able to capture essential patterns, such as the hook-like echo, associated with non-supercell storms which were difficult to detect by the C-band radars.

Part I: Specific Differential Phase (K_{dp}) and Rainfall (R) Estimators

Why K_{dp}?

- Independent to radar calibration and attenuation.
- Independent of rain/hail mixtures.
- Low sensitivity to variability of raindrop size distribution.
- High sensitivity to raindrop shape and liquid water content.
- Suitable candidate to estimate R.

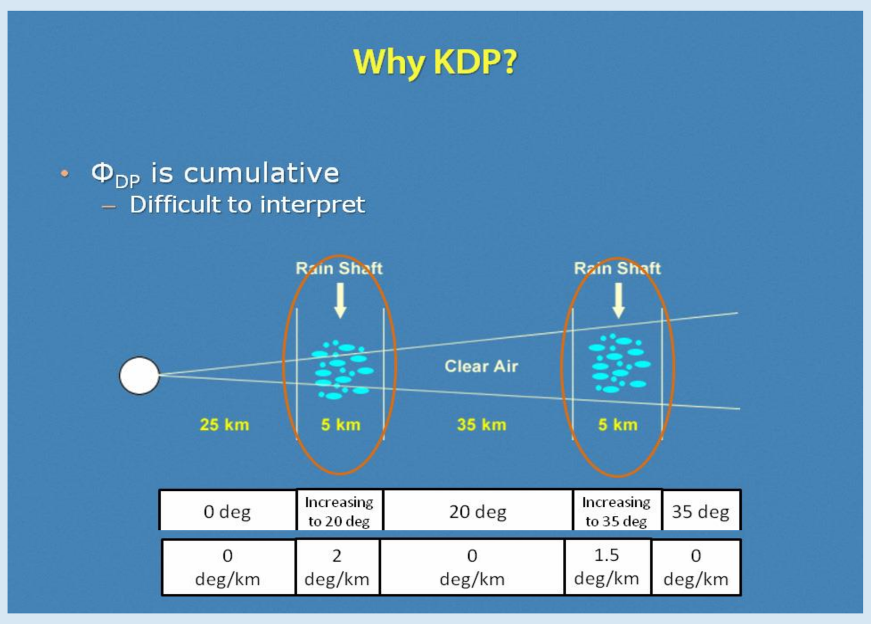

Fig.1: Illustration of differential phase (Ψ_{dp}) and specific differential phase (K_{dp}). *Adapted from* http://www.wdtb.noaa.gov/courses/ *- Clark Payne*

$$\Psi_{dp}(r) = \Phi_{dp}(r) + \delta(r)$$

$$\Phi_{dp}(r) = 2\int_0^r K_{dp}(s)ds$$

$$\frac{\Delta\Psi_{dp}}{2(r_b - r_a)} = \frac{\Delta\Phi_{dp}}{2(r_b - r_a)} + \frac{\Delta\delta}{2(r_b - r_a)}$$

δ-Z_{dr} Relation: [1]

$$\delta = Z_{dr}^{\ 1.8} \Rightarrow Z_{dr}(r_a) - Z_{dr}(r_b) \cong 0$$

$$\Delta\delta \cong 0$$

K_{dp} Estimator:

$$\widehat{K}_{dp} = \frac{L}{M\Delta r}\sum_{j=1}^{M}\frac{\Delta\Psi^{(j)} + \Delta\epsilon^{(j)}}{2L}w^{(j)}$$

- ***L*** is the interval length in km
- ***M*** is the number of intervals
- **Δr** is the range resolution
- ***w^(j)*** is the weight obtained from the Self-Consist. (SC) Method

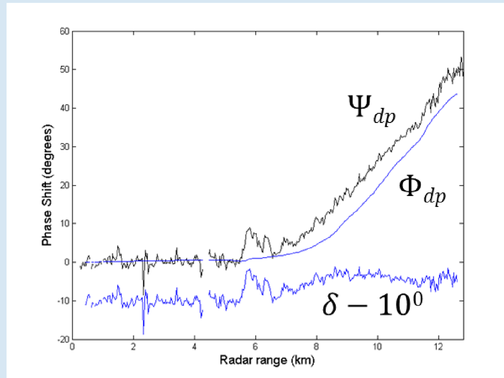

Fig.2: Phase shifts: Ψ = Φ + δ.

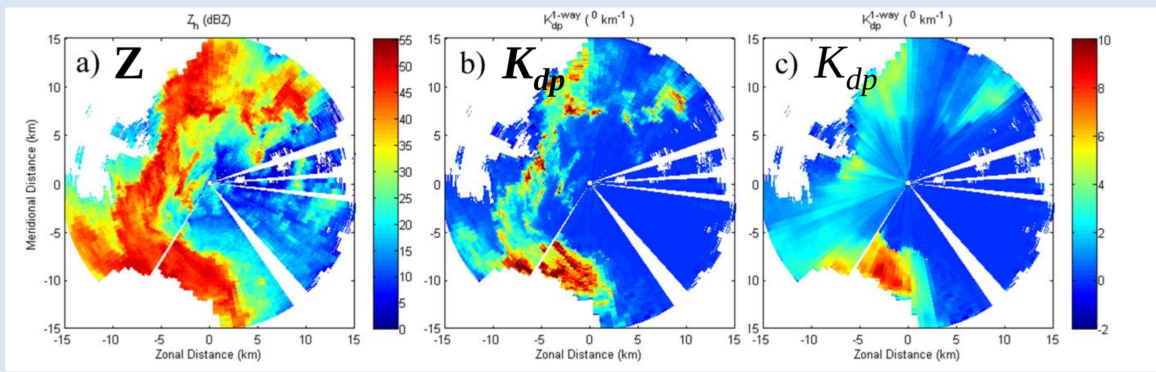

Fig.3: a) Reflectivity, b) Specific Differential Phase (K_{dp}) using the SC method, and c) K_{dp} no using SC. September 10 2011 observed by X-band IDRA.

K_{dp} Precision:

$$\sigma(\widehat{K}_{dp}) = \frac{1}{L}\sqrt{\frac{\sigma^2(\Psi) + \sigma^2(\Delta\epsilon)}{2M}}$$

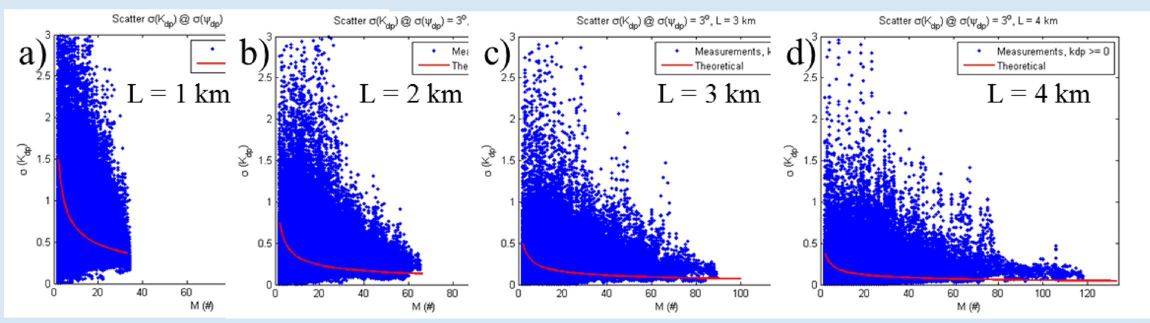

Fig.4: Scatter plots of the estimated σ(K_{dp}) vs the number of intervals (M) for different length intervals (L), using SC. Theoretical σ(K_{dp})'s were indicated by red curves.

K_{dp} Analysis:

- L = 4 km and averaged σ(K_{dp}) = 0.25 ⁰ km^{-1}
- Low computational time
- High spatial resolution of 30 m
- High K_{dp}'s values

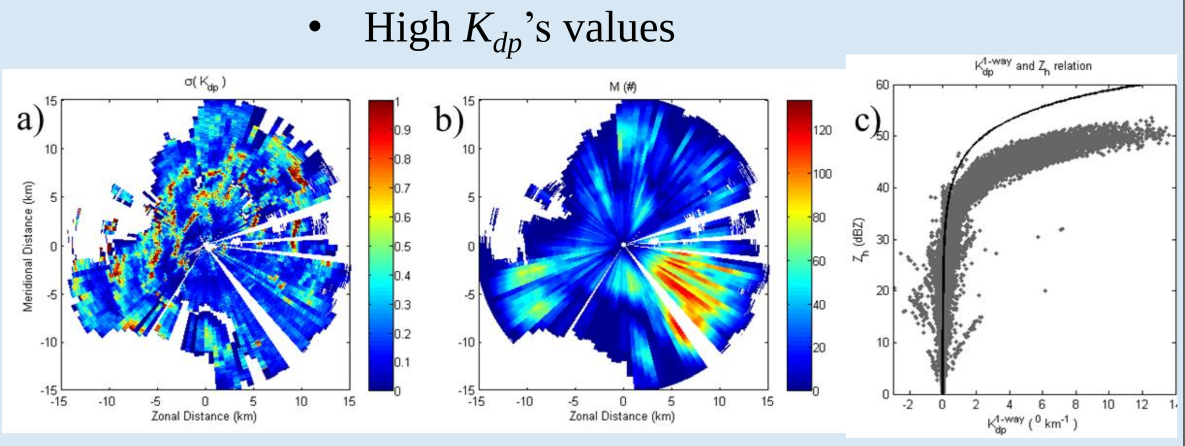

Fig.5: K_{dp} analysis: a) standard deviation of K_{dp}, b) number of intervals used to estimate K_{dp}, and c) scatter plot of Z vs K_{dp}.

Estimator and Precision of R: [2]

$$R = 13K_{dp}^{\ 0.75} \qquad \frac{\sigma(R)}{R} = 0.75\frac{\sigma(K_{dp})}{K_{dp}}$$

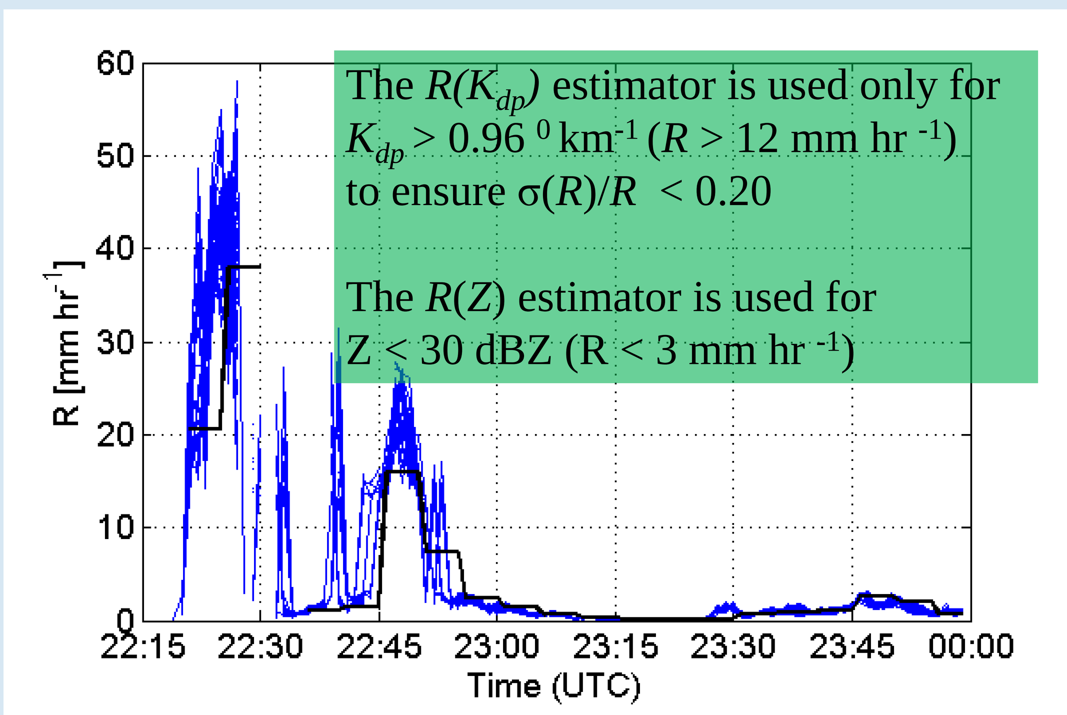

Fig.6: Rainfall rate (R) estimation using K_{dp} and Z on June 28 2011. R at 30 m and 1 min (blue lines) and simulated R at 1000 m and 5 min (black line).

Part II: Storm Observations

Quasi-Linear Convective System: [3]

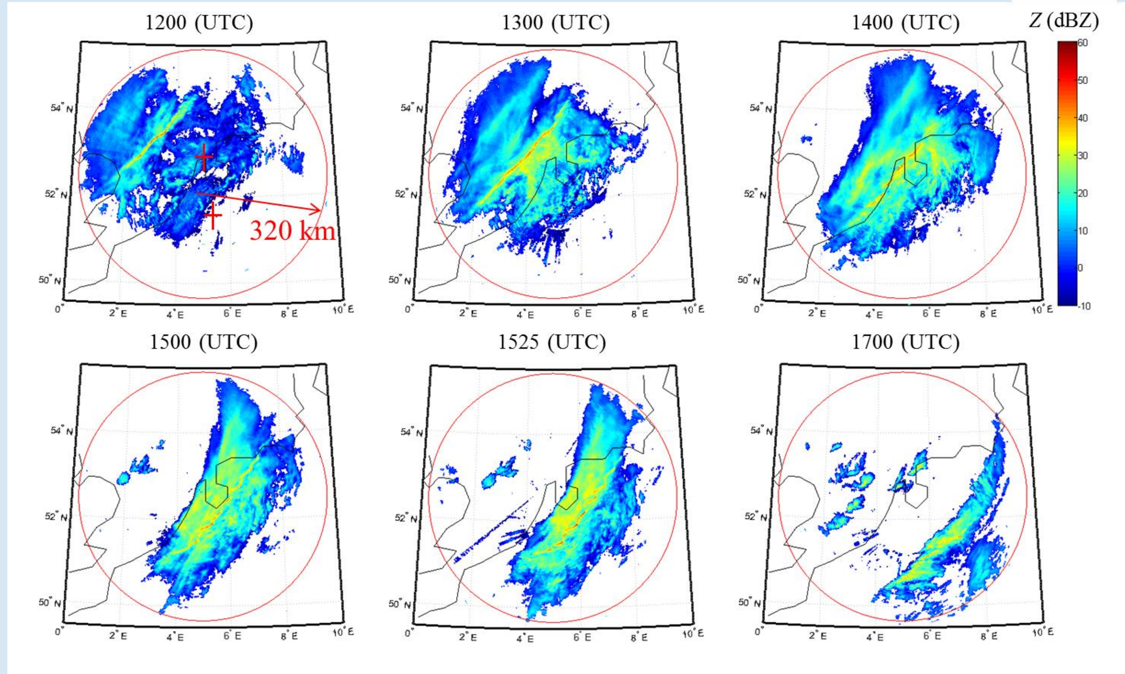

Fig.7: Composite reflectivity at 1500 m height using two C-band radars. A line echo wave pattern (**LEWP**) was observed as the convective system moves over the NL on January 03 2012.

Reflectivity Observations at C and X Bands:

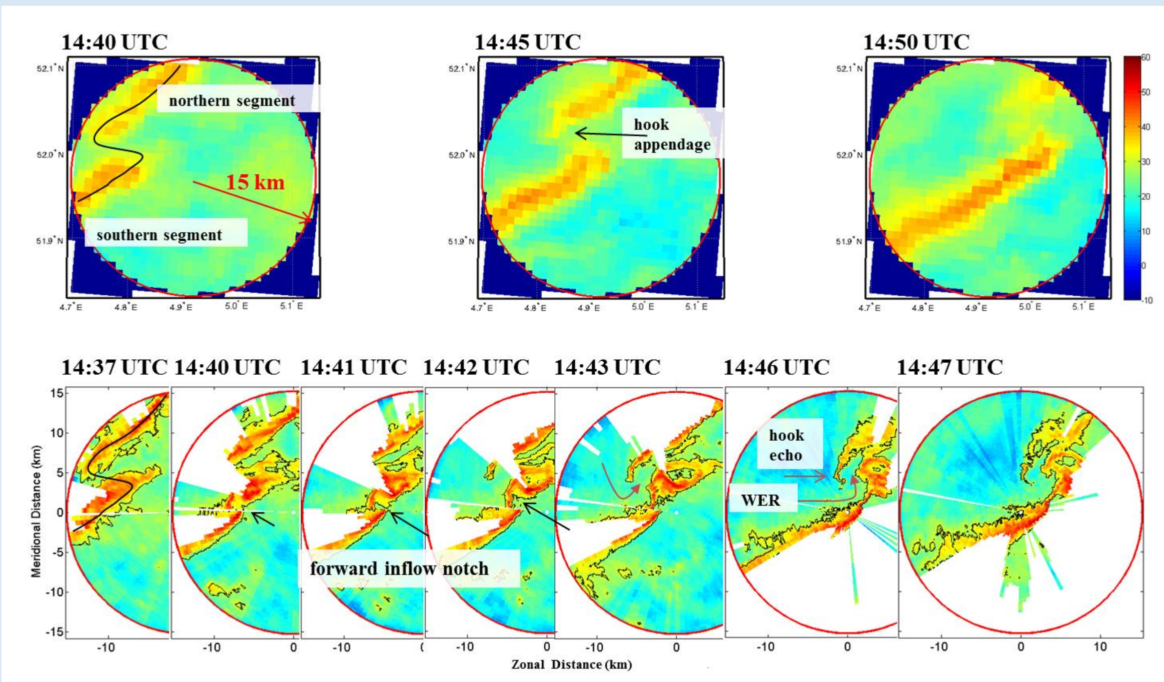

Fig.8: Reflectivity signatures associated with the **S-broken pattern**.
Top row: C-band observations showing a hook appendage in the south-end of the northern segment. Bottom row: X-band observations exhibiting a forward inflow notch (southern segment) and both, weak echo region (WER) and hook echo (northern segment).

Comparison of Rainfall Accumulation:

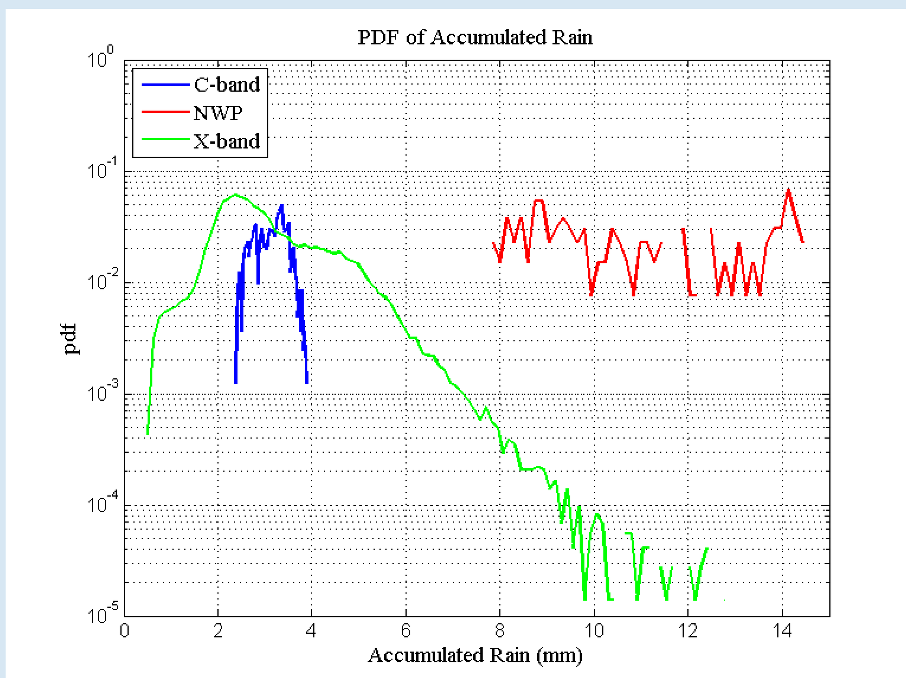

Fig.9: Distribution of rainfall accumulation of the Quasi-Linear Convective System using C-band (blue), X-band (green), and the HORMONIE NWP (red).

Conclusions

- An advanced method to estimate K_{dp} from pure rain at X-band frequencies was proposed. The method aims to obtain high spatial resolution of K_{dp} estimators while controlling their inherent bias-variance dilemma. Results shown that K_{dp} was able to retain the spatial variability of storms, few tens of meters, and produce a variance similar to or less than those of conventional approaches.
- It is foreseen that weather surveillance performed by dual-polarimetric X-band radars would lead to early detection of crucial storm patterns and improve the quality of radar-based rainfall estimation as recommended by both, weather-forecast and urban-hydrology communities.

References:

[1] Otto, T., and Russchenberg H. (2011), Estimation of the specific differential phase and differential backscatter phase from polarimetric weather radar measurements of rain. *IEEE Geoscience and Remote Sensing Letters*, **8**, 988 – 992.

[2] Otto, T., and Russchenberg H. (2012): Rainfall rate retrieval with IDRA, the polarimetric X-band radar at Cabauw, Netherlands. *6th European Conference on Radar in Meteorology and Hydrology*, Toulouse, France.

[3] Reinoso-Rondinel, R., and Russchenberg H. (2014): Polarimetric weather signatures and Doppler spectral analysis of a convective squall line. *8th European Conference on Radar in Meteorology and Hydrology*, G-P, Germany.