What is the Max RhoHV of Your Radar? What is the Min LDR of Your Radar? …

Why These and Other Questions Matter When Considering Acquisition of a Dual Polarimetric Weather Radar

With all the benefits weather radar provides to a community, measuring the amount and location of precipitation is unequivocally the most important worldwide. It is generally accepted that dual polarization weather radar provides significant improvement over conventional radar in measuring actual rainfall and quality comparisons of data. What is less understood but becoming more apparent, is the importance of systematic errors within the dual polarimetric weather radar system and how these errors impact the quantitative measurements of rainfall. These system errors can grow to such an extreme that the dual polarization weather radar can no longer be used for quantitative analysis and reverts back to being slightly better than a conventional radar.

The introduction of dual polarimetric research radars in the 1980s and 90s focused on capturing the entire spectrum of dual polarimetric data. In order to accomplish this task, research quality radars achieved dual polarization measurements by alternating the transmitted polarization from pulse to pulse. This is generally referred to as the alternating polarization mode. Commercialization of dual polarimetric radars brought the economic, simplicity, and reliability factors into consideration that researchers tend to give a lower priority. Today, all commercial manufacturers achieve dual polarization using the simultaneous transmission and reception (STAR mode) of the two polarizations states.

The STAR mode has the specific advantage of taking the horizontal and vertical data sample at the exact same moment in time. While in the traditional alternating mode, there is a slight time shift between the sampling of the horizontal and vertical pulses. Therefore STAR mode radars have the capability to achieve higher correlations observed in rainfall between polarizations and thus more precise measurements of the dual polarimetric data (Bringi et al, 2001: see figure 6.30)

The STAR method also poses challenges to the manufacturer of dual polarization weather radars in order to retain its specific advantage over the alternating mode. High isolation between the two polarization channels must be achieved. This is sometimes referred as the cross-polar isolation or cross-coupling in the engineering world. When isolation is not high the polarization data moments may be biased by systematic errors within the radar system. Also the two polarization channels must be intrinsically matched throughout the hardware/software architecture of the radar system.

In the 1980's and 90's dual polarimetric research era these types of systematic errors where known but generally ignored because of having the alternating transmission capability. Therefore quantitizing the affect of these errors to the data measurement was neglected. However, with the introduction of commercial dual polarization radars in the 2000's the impact of these systematic errors have been studied. Several recent articles have been published on this topic. During the early development cycle of Vaisala weather radar systems, the impact of antenna performances was understood. Vaisala focused on keeping this consideration an important design goal in its radar product line. Established weather radar manufacturers have been relying on antenna designs from the 1990s, or even 1980s. At these earlier points in history the practical importance of the antenna characteristics within the system were less understood, and still affecting their products today.

It All Starts with the Antenna

The antenna system plays a key role in matching the power of the beams between the two polarizations while retaining isolation. Thus the antenna largely determines the quality of the dual polarization radar precipitation measurements. The antenna performance is dependent on how well the beam pattern of the two polarizations are matched and how effectively the dual-port feed horn can keep these polarizations isolated from each other. In the next sections we visualize what the effects of matched polarization beams and isolation mean to data measurements. How do these engineer-type specifications show up in data? How do they impact the measurement value?

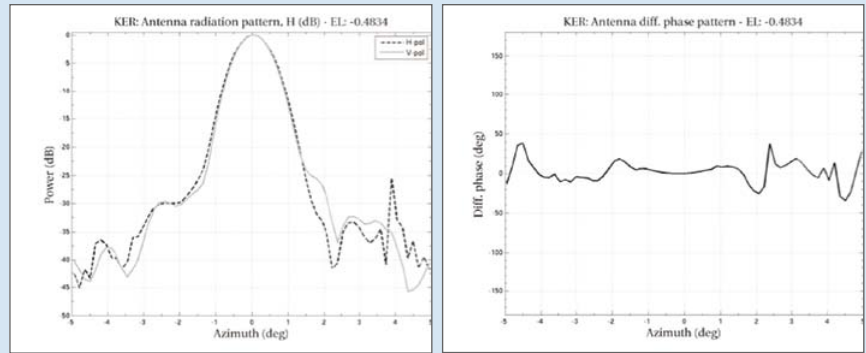## Impact of Matched Horizontal and Vertical Beam Pattern

Figure 1. *H and V beam pattern and differential phase pattern from Vaisala's Kerava radar.*

The beam pattern from Vaisala's WRM200 shown in Figure 1 reveals the H and V polarizations are well matched down to -20dB. Furthermore, the differential phase patterns are relatively flat over the main lobe of the antenna. However, one must realize Figure 1 is a one-dimensional slice and the entire three dimensional beam pattern is most important. A more complete view of the antenna characteristics would be stated as 'integrated co-polar matching' and 'integrated cross-polar isolation' specifications. Vaisala has been using these specifications for many years to differentiate the WRM/WRK product line to our customers. It is also a specification competing manufacturers have been refusing to make, instead relying on main polarization plane data as in figure 1, which is simpler to explain but easier to hide problems. What do such terms as integrated co-polar beam matching and a cross-polar isolation terminology mean? How do these engineer-type specifications show up in data?

The co-polar correlation function, RhoHV, is data type produced by how well the magnitude and phase measurments between the horizontal and vertical channels are matched, or correlated. It is a value normalized between 0 and 1. Perfect correlation of the two channels would have a value of 1 and perfect de-correlation a value of 0. In light stratiform rainfall RhoHV appears to approach one without a limit, except set by the radar intrinsic measurement capability, in particular defined by the antenna performance [Mudukutore at al, 1995]. If a dual polarimetric radar system introduces errors in the form of imperfect beam matching or lower isolation between channels, measured RhoHV values in light rainfall will peak at lower values. These systematic errors will introduce some mismatch, or de-correlation, of the H and V magnitude and phase measurements and affect the quality of other data types. Thus maximum RhoHV measurable can be used to define the quality of the antenna.

The close correspondence between the measured antenna co-polar characteristics and the RhoHV data has been observed with Vaisala WRK200 radar, as well as in the prototype models, see Figure 2. Traditionally an acceptable system maximum value of RhoHV from the 1990's research community was a value >0.98. This is when considering the alternating polarization mode where the horizontal and vertical polarization measurements are made at slightly different times, as discussed earlier. It is now understood that 0.98 is no longer a suitable data specification with STAR mode radars, and in fact, this value is sub-optimal. For Vaisala's WRK200 dual polarimetric radar operated by the University of Helsinki the RhoHV measurements generally fall between 0.992 to 0.998.
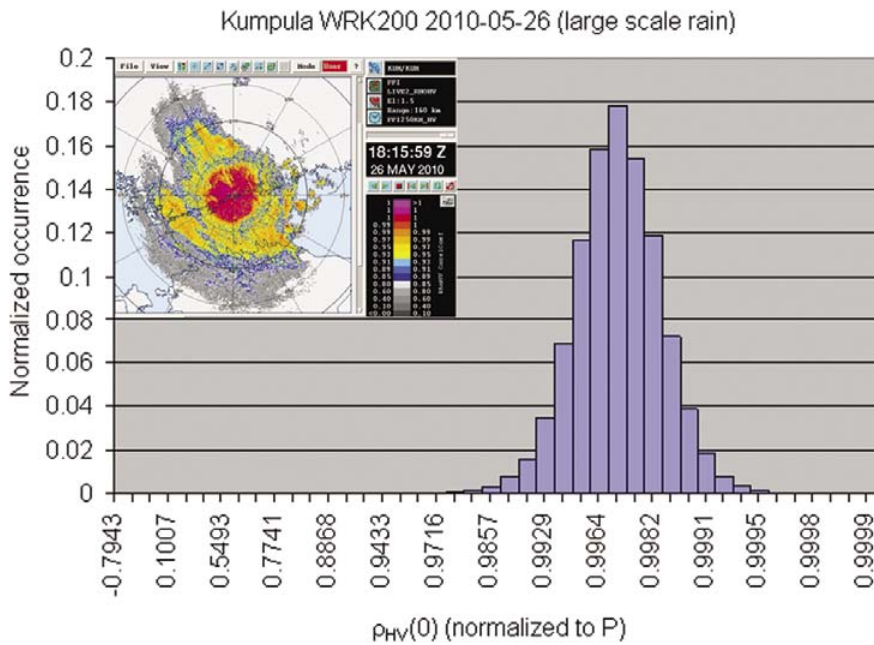
Figure 2. *RhoHV of light rainfall event capured by Vaisala's WRK200 radar located at the University of Helsinki Kumpula campus. The RhoHV observed measurement 1st standard deviation fall between 0.995 to 0.998*

(a few mm/hr). This range represents the max distance that conscious customers aim at making quantitative measurements in their radar networks

In plain words, relatively minor imperfections in the antenna quality can degrade the radar performance such that transmitter powers ten or hundred times higher (20 dB) would be needed to compensate the loss in performance. It is obviously impractical to move from the common power levels of 250 kW to operating transmitters at tens of MW, while high performance antennas are practical - in Vaisala's weather radar.

In the light of this discussion, this challenge can be converted into an engineering question: "What is the max RhoHV of the radar system?" With the STAR mode transmission radars, high values of RhoHV (> 0.99) are feasible, which allows the simple polarimetric rainfall estimates of R(KDP) to be useful down to modest rain intensities. This allows robust cross-checks and large scale merging with traditional reflectivity estimates - for the merit of both. Things degrade by factor of four when radar can deliver performances at the level of RhoHV = 0.98 or less, creating measurement gaps both in radar range and in rain fall intensity - 0.98 is just not good enough!
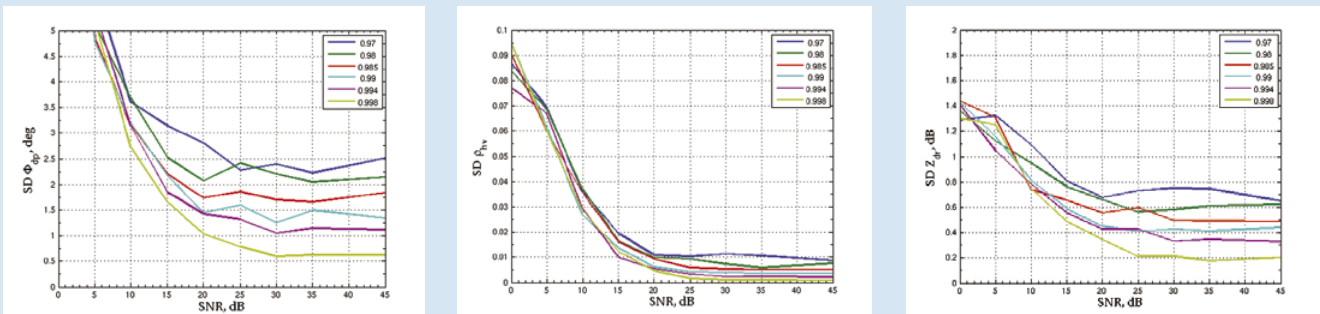
To analyze how antenna dual polarization performance measured by the max RhoHV metric affects the quantitative rainfall measurement, a simulation was conducted with results shown in Figure 3 (Moisseev et al, 2010). For small to moderate signal to noise values (SNR<20dB) degradation of the RhoHV from 0.998 to 0.985 is equivalent to a reduction in SNR by 3 to 6 dB. For high SNR values this degradation is equivalent to 10 – 20 dB reduction in SNR. From the view point of practical meteorological applications it is useful to realize that a 20 dB SNR corresponds to weak rain of 0.1 mm/hr at 50km distance from the radar site. However at 250km from the radar site 20 dB SNR is modest rain

Figure 3. *Simulation of dual polarimetric moment standard deviations for different values of co-polar correlation coefficients (RhoHV) and signal to noise ratio's (SNR).*

Significance of Isolation between polarization

The amount of cross-polar isolation of the radar system can also be effectively answered by asking the question "What is the minimum LDR which can be measured?" Linear Depolarization Ratio (LDR) is a data type produced when a single horizontal polarization is transmitted through the antenna and horizontal and vertical polarizations are received. As all the transmitted energy was horizontally polarized the energy being received should also be horizontal. Any vertical polarization energy being received is thought to be from atmospheric effects. But if there is poor cross-polar isolation within the radar system depolarization can also be introduced by the hardware.

Simulation studies of the amount of depolarization for light stratiform rainfall has been shown to be < -45 dB. There have been very few types of radar even approaching making measurements at this value. Thus the limiting factor of measuring LDR in liquid rainfall is strictly the hardware limitations. Figure 4 shows typical LDR data gathered by the Vaisala WRK200 dual polarimetric radar installed at Kumpula. The 1st standard deviation of minimum LDR measured is approximately -35 dB. This value can be used as the system limit due to hardware.
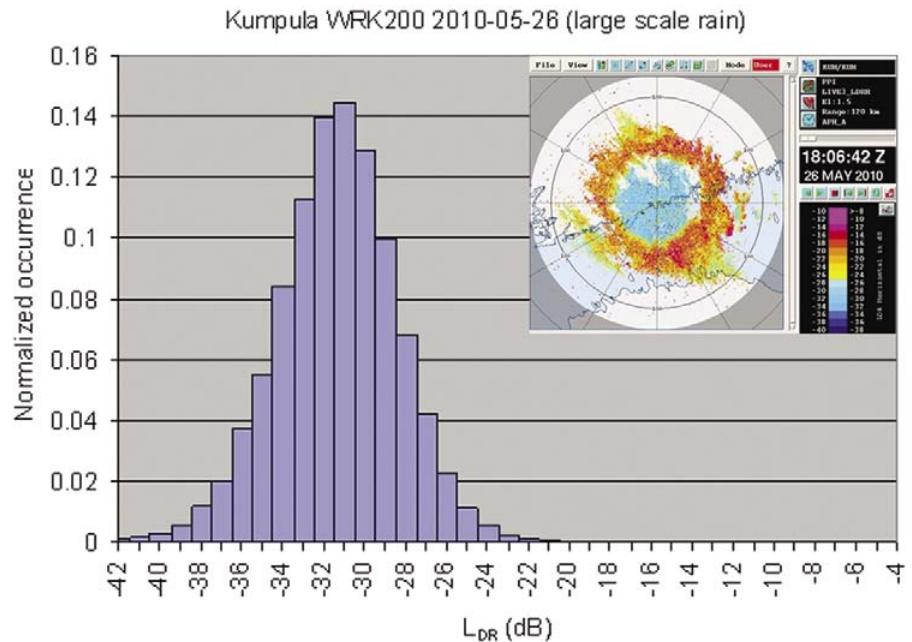

Figure 4. *LDR of light rainfall event capured by Vaisala's WRK200 radar located at the University of Helsinki Kumpula campus. The LDR observed measurement 1st standard deviation fall between -28 to -35 dB*

In STAR mode we are assuming to have true horizontal (0 degree) and vertical polarization (90 degree) transmit and receive states. But small errors in these angles plus cross-coupling within the radar system will always result in errors from true horizontal and vertical polarizations. The LDR system limit measurement can be directly quantized into differential reflectivity (ZDR) biases, see Figure 5 (Hubbert et al 2010).

Recall that to quantitatively measured rainfall with an accuracy much better the ± 25% the accuracy of ZDR must be known within 0.2 dB for rain rates of 10 mm/hr and 0.1 dB for rain rates of 3 mm/hr (Illingworth et al 2004). Again looking at Figure 5, it can be seen that LDR system limits of -35 dB would have ZDR bias of ± 0.15 dB and could be considered good for light to moderate rainfall. If we really want to measure rain fall accurately for rain rates of 1 mm/hr using ZDR, a great weather radar system should be able to measure minimum LDR down to at least -40 dB. The only weather radars having that type of performance are newer offset feed style where the antenna itself costs more than 1 million U.S. dollars.
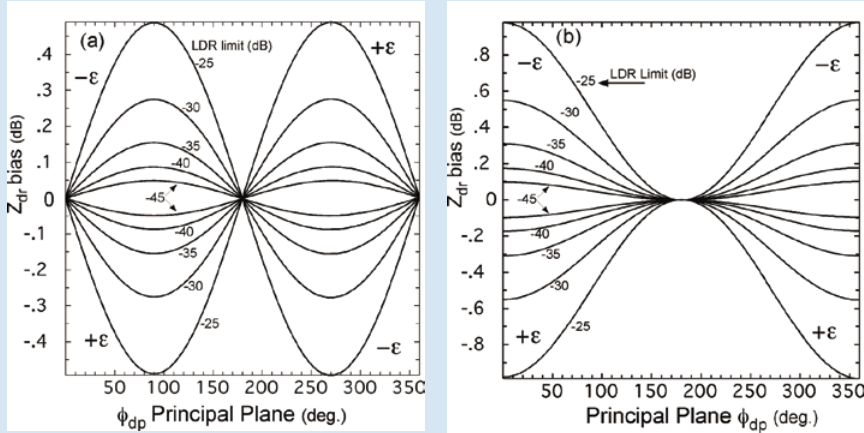
Figure 5. *STAR mode ZDR bias as a function of PhiDP with LDR system limit as a parameter.*

This described effect which is exclusive to STAR mode dual polarization radars is far beyond simulation driven. Figure 6 shows data from NCAR's SPOL dual polarimetric radar system which is capable of operating in both the alternating polarization mode and STAR mode (Hubbert et al 2010). The left-hand side of the figure shows the polarimetric data in alternating mode while the right-hand side shows the data in STAR mode. Clearly there is a ZDR bias introduced in STAR mode. The SPOL LDR system limit is assumed to be somewhere between -30 to -35 dB.
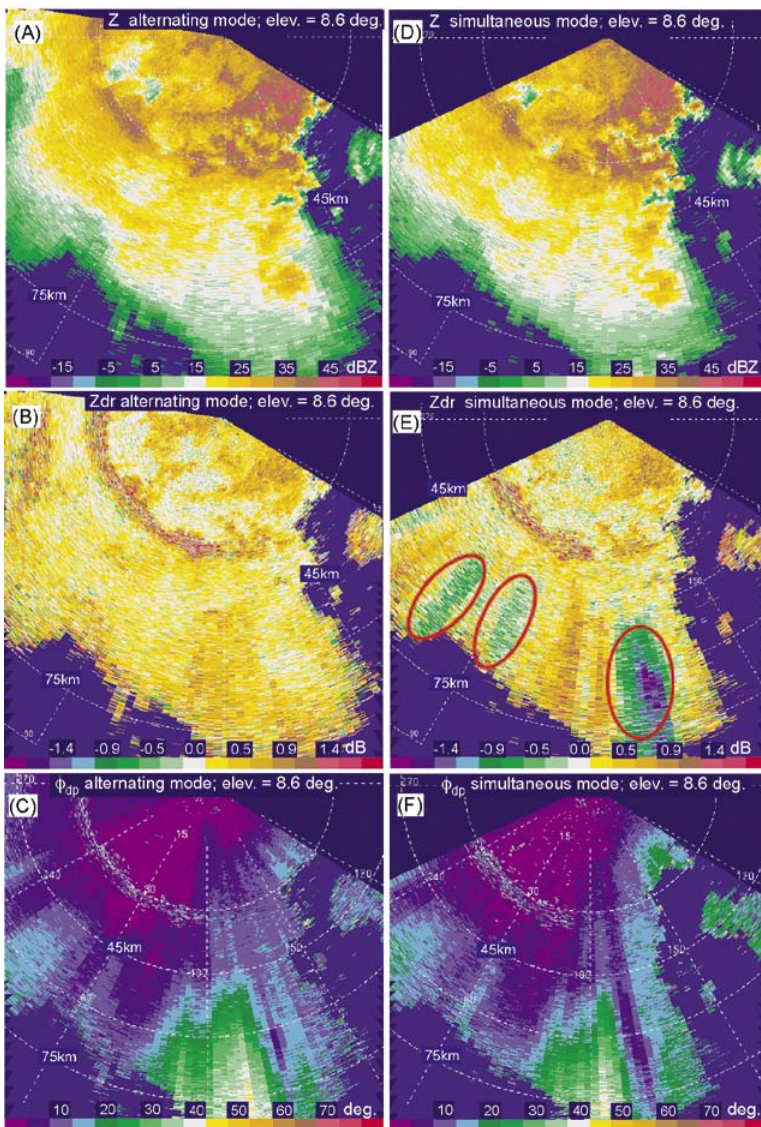

Figure 6. *NCAR SPOL dual polarization scans on 2 June 2008. Alternating polarization mode on the right and STAR mode on the left. The red circles indicate Zdr bias introduced by system cross-coupling in STAR mode. This is sometimes mistaken as a differential attenuation effect.*

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