9A.5 Z_{dr} CALIBRATION FOR RADARS THAT TRANSMIT SIMULTANEOUS HORIZONTAL AND VERTICAL POLARIZATIONS

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1. INTRODUCTION

The calibration of radar differential reflectivity (Z_{dr}) to an uncertainty of 0.1 dB is desirable for accurate rainfall estimates. However, determination of the Z_{dr} calibration figure and maintenance of the that calibration is difficult. Three Z_{dr} calibration techniques were investigated and compared in Hubbert et al. (2008, 2007): 1) vertical pointing, 2) crosspolar power, and 3) engineering techniques. Probably the mostly widely accepted technique is (1), using vertical pointing data in light rain. It works well since it is an "end-to-end" method that exercises the full transmit and receiver paths as they would be for meteorological measurements. Engineering techniques attempt to estimate the Z_{dr} calibration factor by injecting test signals and using passive measurements of solar radiation. Because of the uncertainties introduced by the calibration test equipment, the uncertainty of the engineering Z_{dr} calibration technique is 0.25 dB at best, at least for the engineering techniques investigated by Hubbert et al. (2008). This is confirmed by the experience of both the NCAR/EOL staff (using S-Pol) and CSU-CHILLL staff (using CSU-CHILL). Both use engineering calibrations for Z_{dr} but routinely find that the final Z_{dr} calibration number must be determined from vertical pointing (VP) data. The third method, the crosspolar power technique, uses solar scan data plus crosspolar power data to calibrate Z_{dr} (Hubbert and Bringi 2003). This technique is similar to the VP technique in that no obtrusive calibration test equipment is used. The crosspolar power (CP) technique uses the principle of radar reciprocity that states that the two crosspolar powers, (1) transmit horizontal (H) polarization, receive vertical (V) polarization and 2) transmit vertical polarization, receive horizontal polarization), are equal, assuming that the H and V transmit powers are equal. It has been shown that the CP technique can calibrate Z_{dr} to a similar uncertainty (< 0.1dB) as is possible with the VP technique (Hubbert et al. 2008). An advantage of the CP technique is that crosspolar power from ground clutter targets, which are nearly always available, can be used for calibration. Light rain, necessary for the VP technique, may infrequently fall at the radar.

Both S-Pol and CSU-CHILL achieve dual polarization measurement by transmitting fast alternating pulses of H and V power. This is convenient for the CP technique since both crosspolar powers are separated in time by the PRT (pulse repetition time) of the radar. Over such a short time interval, the backscatter targets vary little so that the correlation between the crosspolar powers is high. Thus, S-Pol and CSU-CHILL can use both precipitation targets as well as ground clutter targets for CP calibrations.

Operationally, the NEXRADs will transmit H and V polarizations simultaneously and thus the CP method will not work directly as it has on S-Pol and CSU-CHILL, i.e., near simultaneous samples of the two crosspolar powers are not available as is the case for fast H and V alternating polarization transmission. However, the average crosspolar powers from stationary ground clutter targets (e.g., from consecutive PPI surveillance scans at H and V polarization if indexed beams are used) can be measured by employing a slow mechanical switch to alternate H and V transmit polarizations. This is possible since the backscatter cross sections of stationary ground clutter targets are invariant (ground clutter targets such as trees that can move with the wind are exceptions).

Currently, the CP technique is being investigated and tested for use on the NEXRADs. This paper describes how the CP technique is being used for NEXRAD and shows data examples.

2. THE CROSSPOLAR POWER TECHNIQUE FOR NEXRAD

The CP method has been successfully applied to CSU-CHILL radar data to calibrate Z_{dr} (Hubbert et al. 2003). The technique uses the property of radar reciprocity (Saxon, D.S. 1955) which states that the off diagonal terms of the radar scattering matrix, S_{hv}, S_{vh}, are equal (Bringi and Chandrasekar 2001). Using this fact the Z_{dr} calibration equation can be derived:

$$Z_{dr}^{cal} = Z_{dr}^{m} S^2 \overline{\left(\frac{P_{XV}}{P_{XH}}\right)} \qquad (1)$$

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where Z_{dr}^{cal} is calibrated Z_{dr}, Z_{dr}^m is measured Z_{dr}, S is the ratio of the V and H powers from sun measurements, and $\overline{(P_{XH}/P_{XV})}$ is the average crosspolar power ratio for reciprocal transmit H and transmit V polarization pairs. The crosspolar power ratios may be averaged over a few rays or an entire volume of radar data. Both precipitation as well as ground clutter targets may be used. If precipitation targets are used, fast alternating H and V transmit polarizations must be used. The CP Z_{dr} calibration approach is like the VP technique in that neither require waveguide couplers, signal sources nor power meters and thus the associated uncertainty related to such RF measurements is eliminated.

Both CSU-CHILL and S-Pol employ a copolar and crosspolar receiver design in contrast to H and V receivers. To accomplish this, CSU-CHILL uses a switch after the low noise LNAs of the receivers whereas S-Pol uses a switch at the IF (intermediate frequency) stage. Having copolar and crosspolar receivers reduces the variance and drift of the Z_{dr} measurement but this also slightly changes the Z_{dr} calibration equation to:

$$Z_{dr}^{cal} = Z_{dr}^m S_1 S_2 \overline{\left(\frac{P_{XV}}{P_{XH}}\right)} \tag{2}$$

where S_1 is the ratio of V-copolar to H-copolar sun radiation and S_2 is the ratio of V crosspolar to H crosspolar sun radiation (See Hubbert and Bringi (2003) for details).

As mentioned before, the NEXRAD dual polarization system uses simultaneous H and V transmission and reception and thus, near simultaneous samples of H and V crosspolar returns are not available. However, if two slow waveguide switches are used then the NEXRADs will be able to measure both crosspolar powers. One technique for the evaluation of $\overline{P_{XV}/P_{XH}}$ is to alternate between only H and only V transmission on a PPI to PPI basis. If the beams are indexed, crosspolar powers from the same resolution volumes (but from different PPI scans) can be paired and used for the CP calibration.

In the CP technique, for fast alternating H and V transmission, the crosspolar power calibration signals follow the same electrical paths as do the meteorological measurements. However, NEXRAD will transmit both H and V signals (SHV mode) simultaneously to achieve dual polarization. Thus, when using the SHV mode, the crosspolar powers are not measured. To measure the crosspolar powers for the CP technique, the radar needs to be designed so that transmit only H polarization and transmit only V polarization is possible. The power division network that allows this should be designed so that the H(V) only transmit paths are identical to the SHV paths. For example, Fig. 1 shows a block diagram of S-Pol's high power front end. This circuit topology allows for SHV mode, FHV mode, transmit H only, and trans-

mit V only. The transmitter signal (TX) goes to circulator (A) which directs the power either to the fast switch (FHV mode) or to the Magic-T (SHV mode) which is a 3 dB power divider with excellent isolation between the ports. Circulators B (C) direct the power either down the H(V) waveguide to the antenna or into dummy loads that absorb the transmit power. As can be seen the B(C) circulators can be set to either SHV mode, H transmit only or V transmit only modes such that the H and V signal paths for SHV mode are identical to the H only and V only paths. The CSU-CHILL radar avoids the power division and high speed switching network that S-Pol uses by employing both H and V transmitters. However, the power of the transmitters needs to be controlled and monitored for good calibrations.

Figure 2 shows a block diagram of the NEXRAD SHV dual polarized system. The system appears similar to S-Pol; however, instead of employing a Magic-T and wave guide switches to allow for SHV, H and V only transmit modes, NEXRAD uses two 90 degree hybrid couplers with a ferrite phase shifter. Consequently, the H and and V only paths are electrically distinct from the H and V paths in SHV mode. This complicates the CP technique. The result is that $P_H^S \neq P_H^{only}$ and $P_V^S \neq P_V^{only}$ so that these powers do not cancel in the Z_{dr} CP calibration equation. $P_{H,V}^S$ are the H and V transmit powers for SHV mode and $P_{H,V}^{only}$ are the H and V for the H only and V only transmit modes. Thus they must be measured for the NEXRAD Z_{dr} calibration. It can be shown that the calibration equation becomes biased,

$$Z_{dr}^{cal} = Z_{dr}^m S^2 \overline{\left(\frac{P_{XV}}{P_{XH}}\right)} = Z_{dr} \frac{P_H^S P_V^{only}}{P_V^S P_H^{only}} \tag{3}$$

where Z_{dr} is the intrinsic Z_{dr}. The correction of this bias can be problematic since the introduction of test and measurement equipment to measure these transmit powers can introduce additional uncertainties to the calibration figure (Hubbert et al. 2008).

Shown in Fig. 3 is a symplified block diagram of the NEXRAD system. A coupler is shown with a red box at the test or reference plane. The power measurement equipment is part of the permanent NEXRAD BITE (Built in Test Equipment). Since ratios of transmit powers are being measured (i.e, P_H^S/P_H^{only} and P_V^{only}/P_V^S) the uncertainties of the power measurement equipment cancel. Importantly, since all measurements are transmit power measurements, the impedance seen by the coupler looking into the waveguide is the same for each measurement and thus ratios of power measurements will have the uncertainty introduced by impedance mismatches cancel. Unknown impedances are a significant source of uncertainty for engineering calibrations (Hubbert et al. 2008).

Thus, if P_H^S/P_H^{only} and P_V^{only}/P_V^S can be measured during the the CP calibration procedure, then intrinsic

Z_{dr} on the right hand side of Eq.(3) can be isolated.

3. EXPERIMENTAL DATA

To calibrate Z_{dr} for NEXRAD the following measurements are needed:

1. solar scans

2. crosspolar power scans

3. receiver gain (injecting signals above the LNAs)

4. transmit powers (i.e, P_H^S, P_H^{only}, P_V^{only}, P_V^S)

These measurements should be made over a short a time period as possible so that gain variations due to thermal effects are as small as possible.

3.1. *Solar Measurements*

The sun is scanned passively (no transmit signal) so that extraneous clutter signals are eliminated. To reduce the sun integration errors, sun data points are first interpolated to a uniform rectangular 0.1^o X 0.1^o grid. In order to determine the location of the solar disk center (considered the maximum power point), data along each of the vertical and horizontal grid lines are fitted to a Gaussian shaped curve. The data is then integrated over different annuli corresponding to different solid angles. It has also been found that by using 3 consecutive solar scans to construct the grid of data, lower variance of S (see Eq.(1)) is obtained. Before gridding the data, the sun's movement and elevation angle distortion must be accounted for.

Shown in Fig. 4 are the H copolar antenna pattern (top panel) and a H-copolar/V-copolar antenna patterns calculated from solar scan data collected on 22 Feb. 2011 using KOUN, NSSL's (National Severe Storm Laboratory) S-band research radar. KOUN was used to prototype the NEXRAD dual polarization upgrade. The H-power pattern is not calibrated. As can be seen the H-power/V-power pattern is not constant across the one degree solid angle marked by the larger white line circle. Therefore, the S calibration term should be averaged across this one degree solid angle and not just calculated from boresight data (maximum power point). Table 1 shows KOUN solar scan data. S^2 is evaluated 8 times with an average of 1.924 dB and a standard deviation of $\sigma = 0.009$dB. This indicated that S^2 can be estimated well within the 0.1 dB uncertainty requirement for NEXRAD. This is an uncertainty estimate for the *random errors*. Systematic errors could possibly be present that this analysis would not uncover.

Table 1: KOUN solar scan data.

Time (UTC)	S^2 (dB)
19:45	1.926
20:20	1.924
20:45	1.907
21:20	1.914
21:55	1.925
22:30	1.934
23:00	1.935
Mean	**1.924**
S.Dev.	**0.009**

3.2. *Crosspolar Power Measurements*

The principle of reciprocity states that the two crosspolar power measurement (transmit H receive V (P_{XV}) and transmit V receive H (P_{XH}) are equal. Since NEXRAD used SHV mode the P_{XH} is measured for one low level PPI scan (in clutter) and then P_{XV} is measured the next PPI. The two crosspolar power can then be compared and used to estimate the average ratio $\overline{P_{XH}/P_{XV}}$ as required by the CP technique. Figure 5 shows a 2-D histogram of these (P_{XH}, P_{XV}) pairs from several PPI scans. The regression line is shown and the scatter is fairly symmetric about it. The mean value of P_{XH}/P_{XV} for this data set is 0.113 dB. The scatter seen in Fig. 5 is quite broad. For example, Fig. 6 shows similar 2-D crosspolar power histograms for S-Pol data. The top panel is for FHV mode (i.e., the crosspolar power pairs are separated by about 1 ms) and the bottom panel compares crosspolar powers from consecutive PPIs of H only transmit data and V only transmit data. Thus, the two crosspolar powers are separated by approximately one minute. The scatter in the top panel is quite tight while the scatter in the bottom panel is more spread. However, the scatter in the bottom panel is still tighter than the comparable KOUN 2-D histogram of Fig. 5. One cause for this is that the hybrid coupler that the KOUN uses to split the transmit power for the H and V channels had only 20 dB isolation for this data set. This has been corrected and more KOUN data is being analyzed. Still, if the number of data points is large, the mean crosspolar power ratio of Fig. 5 should yield a good estimate of the mean. The scatter histograms of S-Pol data in Fig. 6 result from the same data set. The bottom panel simply compares the P_{XH} crosspolar power from one PPI scan the P_{XV} of the next PPI scan. The mean ratio for the top panel is 0.043 dB while the average ratio for the bottom panel is 0.022 dB, a difference of only 0.021 dB.

3.3. *Transmit Powers*

The transmit powers for KOUN were measured on 2011/03/10 from 18:15 UTC to 19:45 UTC, in various modes. The mean powers for this period were:

P_H^S: 82.029 dBm

P_H^S: 81.854 dBm

P_H^{only}: 84.253 dBm

P_V^{only}: 84.668 dBm

Since the transmit power data come from 10 March while the sun scan and crosspolar power data come from 22 February, the resulting Z_{dr} calibration figure will only be approximate, i.e., various system parameters likely changed between the those data. In order for the CP technique to calibrate Z_{dr} to within a tenth of a dB, all calibration data should be gathered in very close time proximity. Nevertheless, we can illustrate the CP technique with the data at hand. Beginning with Eq.(3), the calibration equation can be rewritten to correct for the transmit power bias as,

$$Z_{dr}^{cal} = Z_{dr}^m C = Z_{dr}^m S^2 \overline{\left(\frac{P_{XV}}{P_{XH}}\right)} \frac{P_V^S P_H^{only}}{P_H^S P_V^{only}} = Z_{dr} \quad (4)$$

Calculating the correction factor C in Eq.(4) in dB scale yields

$$
\begin{aligned}
C &= 1.924 + 0.113 + (81.854 - 82.029) \\
&+ (84.253 - 84.668) = 1.447\,dB. \quad (5)
\end{aligned}
$$

so that

$$Z_{dr}^{cal} = Z_{dr} + 1.447\,dB \quad (6)$$

3.4. *Calibration Monitoring*

The calibration in Eq.(6) remains valid as long as the gains and the transmit powers are constant. This will not be the case as the electronic components will be affected by temperature changes, for example. At the time of the initial CP calibration measurements, the transmit powers need to be recorded along with the gains of the two receiver paths. These receive path gains can be measured by injecting test signals above the LNAs and recording the resulting received power. Call these receiver gains G_{H_0} and G_{V_0} and call the transmit powers at calibration $P_{H_0}^S$ and $P_{V_0}^S$ where the "0" subscript denotes a measurement at the initial calibration time. As time passes these 4 quantities need to continually monitored (say once per volume scan or more). Call these measurements at time τ, G_{H_τ}, G_{V_τ}, $P_{H_\tau}^S$ and $P_{V_\tau}^S$. As the ratios G_{H_τ}/G_{V_τ} and $P_{H_\tau}^S/P_{V_\tau}^S$ vary from the corresponding ratios at time "0", the Z_{dr} correction factor needs to be adjusted.

4. EVALUATING THE Z_{dr} CALIBRATION

After the radar is calibrated using the CP method, how does one determine if the calibration factor is accurate? This issue was addressed in Hubbert et al. (2008) where the CP technique was compared to VP calibrations (considered as truth). They found that the CP and VP calibration techniques agreed well (well within a tenth of a dB). However, the NEXRAD antennas can not point vertically so that the VP technique can not be executed. Another way to check the CP calibration number is to examine scatter histogram plots of Z_{dr} versus Z and such plots are shown in Fig. 7 for KOUN data for elevation angles of 2.4^o (top panel) and 3.1^o (bottom panel). The idea is that as the reflectivity becomes smaller (in pure rain) the rain drops become smaller and more spherical and thus Z_{dr} approaches 0 dB. Simulations show that for equilibrium shaped rain drops and raindrop size distribution, Z_{dr} is about 0.25 dB when $Z = 20$ dBZ and about 0 dB when $Z = 10$ dBZ or less (Illingworth and Caylor 1989). The black solid line in Fig. 7 is the mean of Z_{dr} and the red solid line is the median of Z_{dr}. The two plots are from the same scan volume and are the 2.4^o and 3.1^o elevation PPI scans. The mean Z_{dr} at a reflectivity value of 20 dBZ for the 2 scans are:

$$
\begin{aligned}
Z_{dr}(2.4^o) &= 0.585\,dB \\
Z_{dr}(3.1^o) &= 0.584\,dB. \quad (7)
\end{aligned}
$$

These scatter plots then indicate that the Z_{dr} is biased high by about $0.58 - 0.25 = 0.33$ dB. Unfortunately, all measurements needed for the CP method were not made in close time proximity to this data so that a comparison of calibration figures is difficult. The Z_{dr}–Z scatter plot technique does assume a equilibrium drop size distribution which is impossible to verify experimentally. Only a few larger drops in the radar resolution volume can increase Z_{dr}. Other sources of biases are ground clutter, attenuation, noise and noise correction so that there is a significant uncertainty associated with this technique. Still this technique provides for a good comparison for the CP calibration if calculated carefully.

5. CONCLUSIONS

The crosspolar power (CP) technique for calibrating Z_{dr} has been demonstrated previously to compare well with calibrations from vertical pointing data in light rain. Currently the CP technique is being investigated for possible use on the NEXRADs. More data sets need to be gathered and analyzed for several of the NEXRADs.

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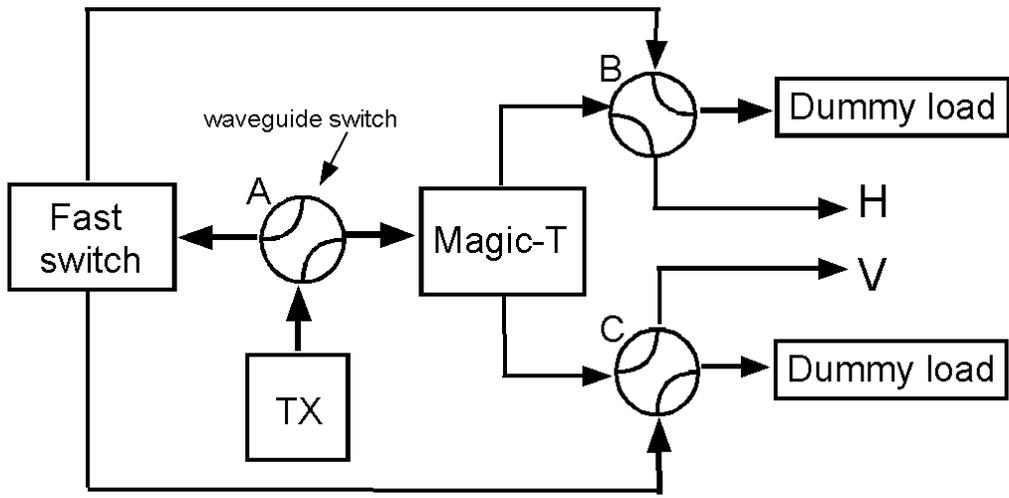
Figure 1: *S-Pol high power front end.*
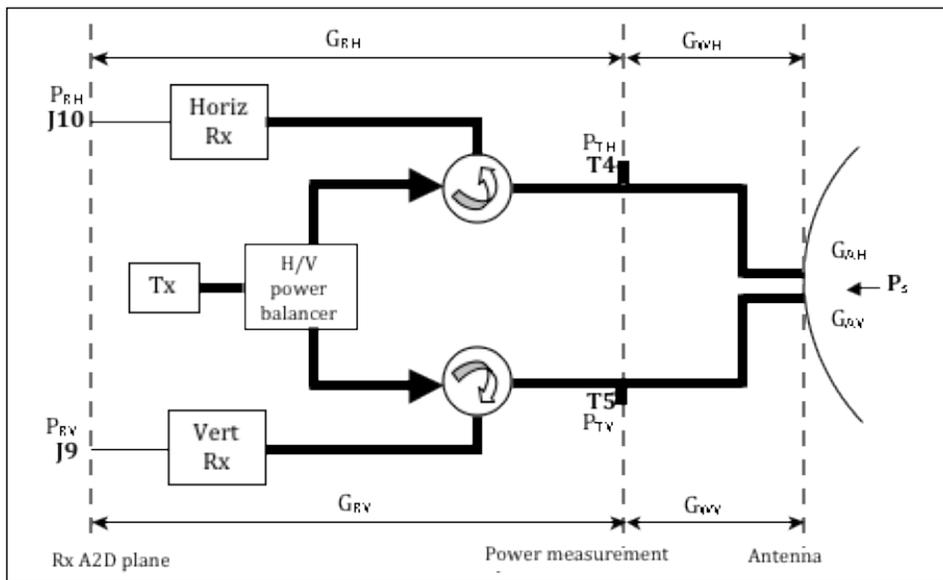
Figure 2: *NEXRAD block diagram.*
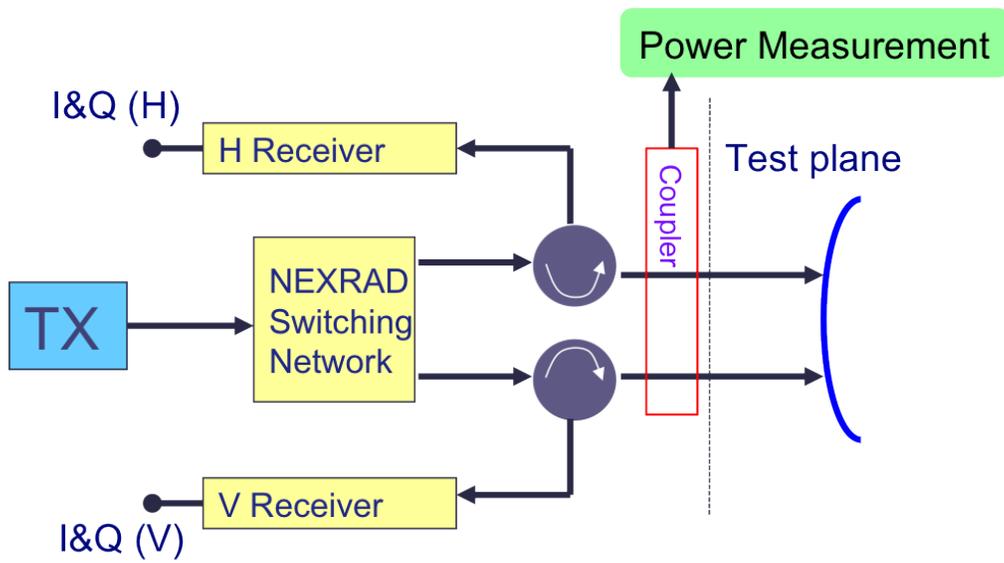
Figure 3: *NEXRAD transmit power measurement.*
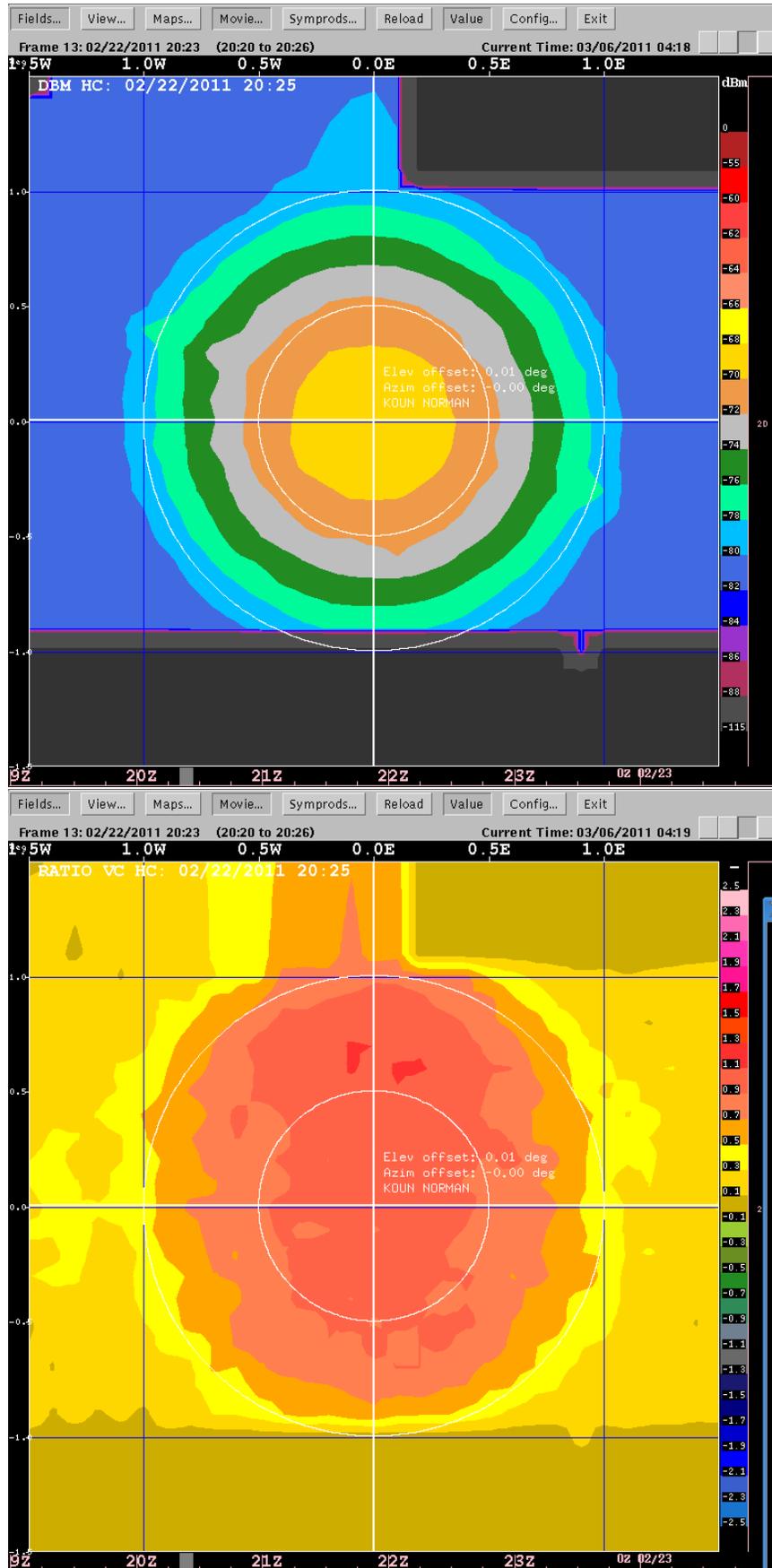
Figure 4: *KOUN (top) H-power antenna pattern and (bottom) H/V antenna pattern.*
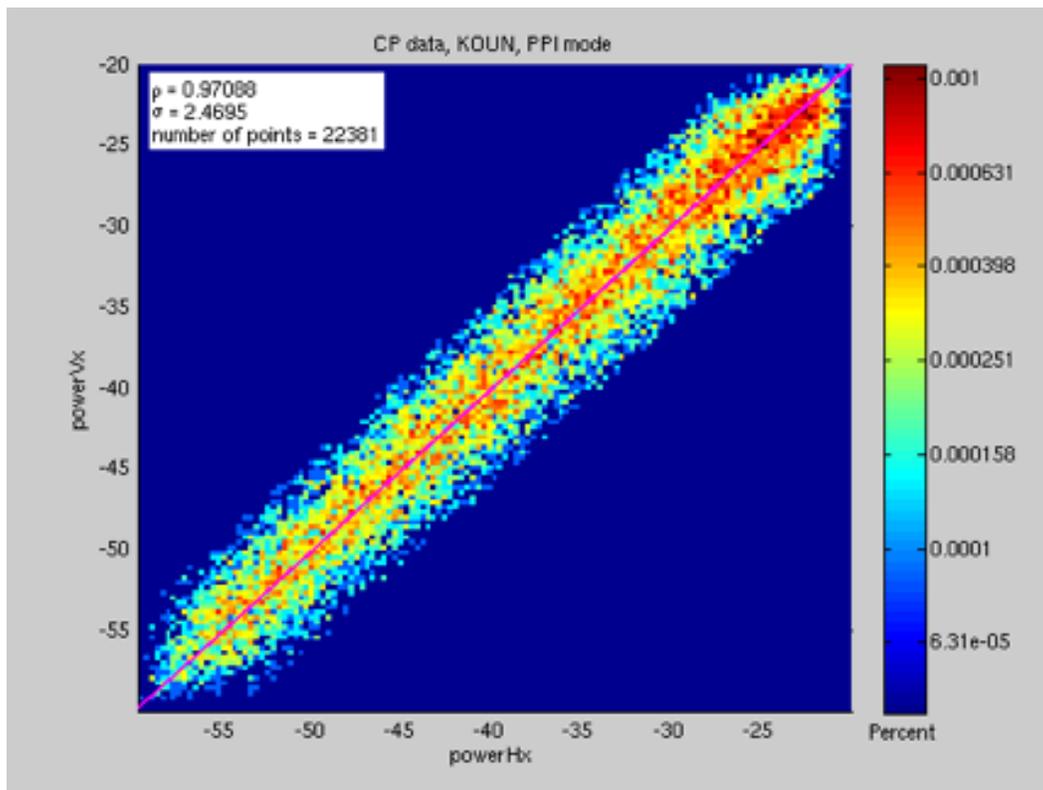
Figure 5: *Crosspolar power 2-D histogram plot for KOUN data.*
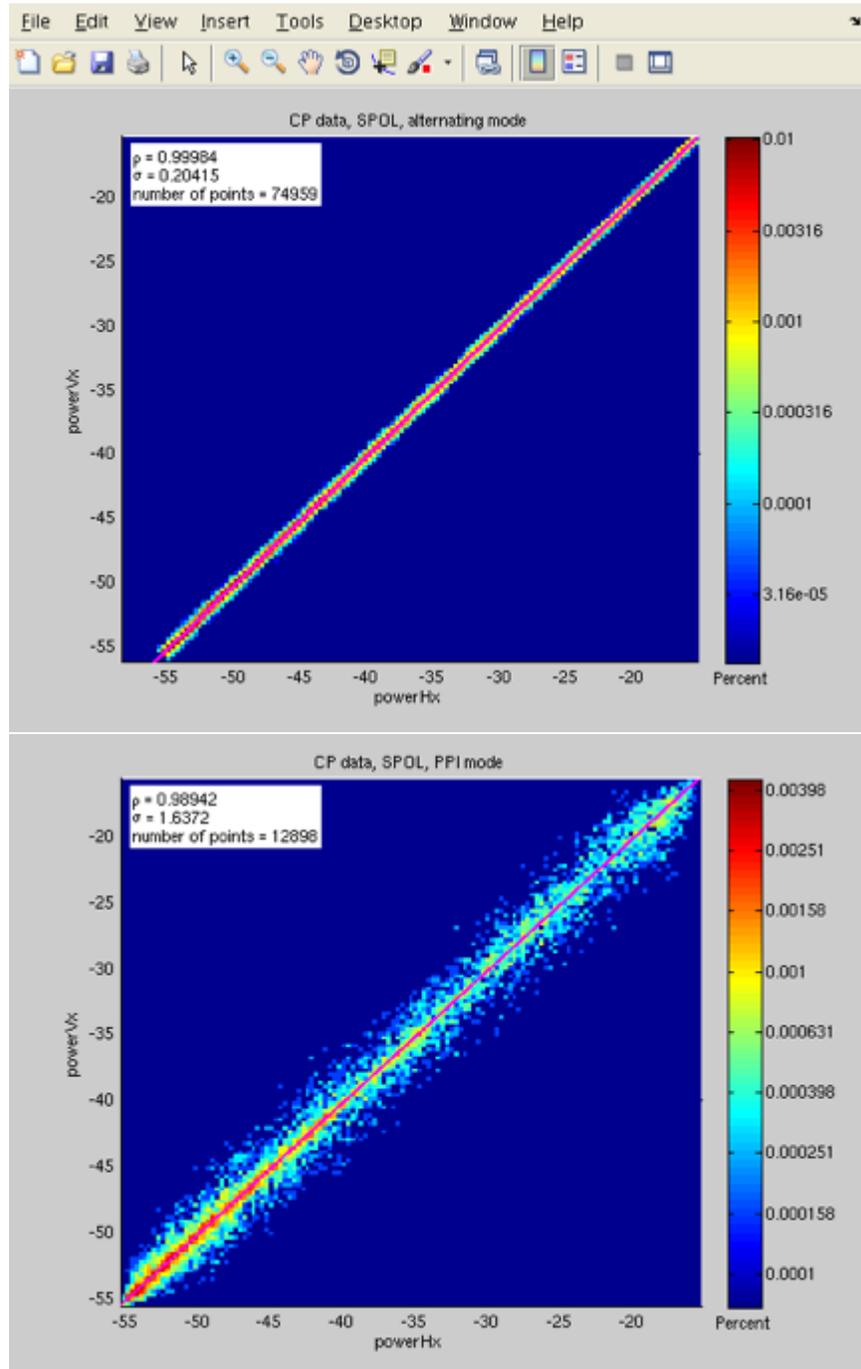
Figure 6: *2-D histograms of S-Pol crosspolar powers: Top panel: for fast alternating H and V transmission; Bottom panel: for only H and only V transmission. The crosspolar powers from consecutive only H transmission then only V transmission are paired via indexed beams.*
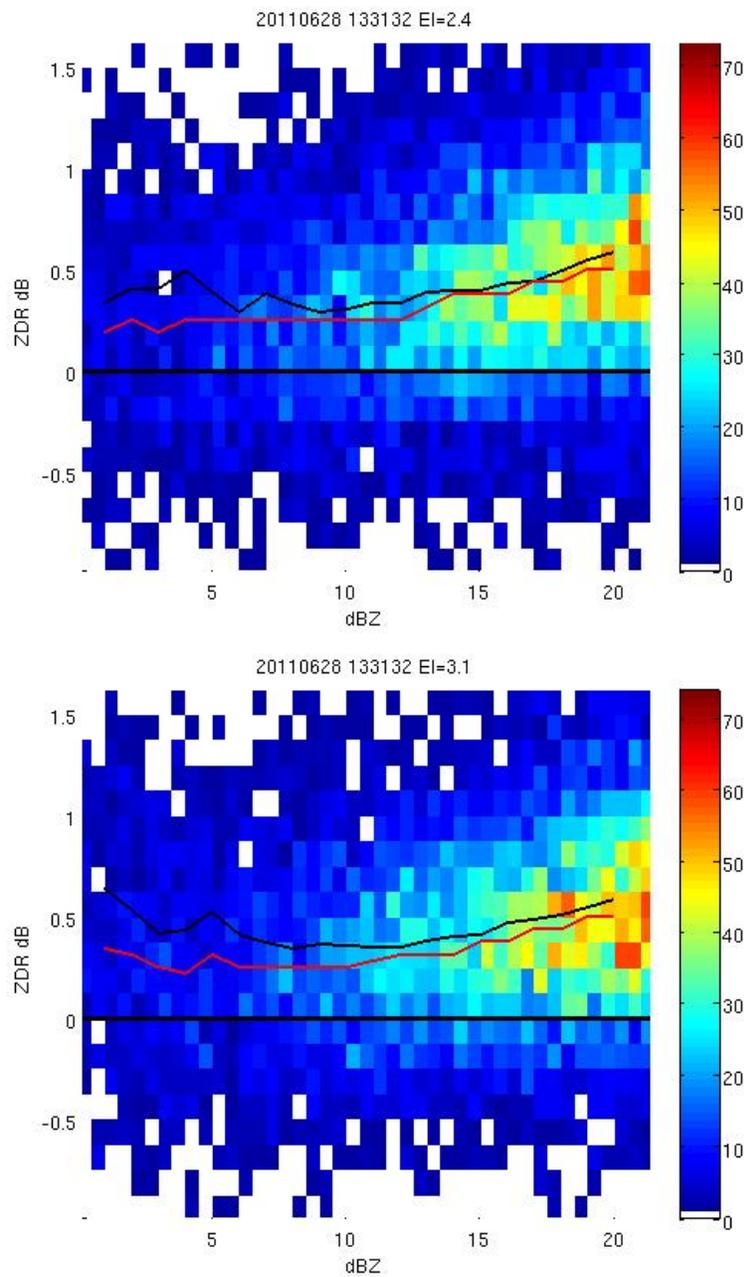
Figure 7: *2-D histograms of Z_{dr} vesus Z for KOUN data (SHV mode). Top panel: elevation angle of 2.4^o; Bottom panel: elevation angle of 3.1^o.*