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Differential Reflectivity Calibration For Simultaneous Horizontal and Vertical Transmit Radars

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27 June 2012

1. Introduction

The accurate calibration of radar differential reflectivity (Z_{dr}) continues to be a challenge for weather radars especially to an uncertainty of 0.1 dB which 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. (2008b, 2007): 1) vertical pointing, 2) crosspolar power, and 3) engineering techniques. Probably the mostly widely accepted technique is 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. However, there can be complications: 1) no rain at the radar 2) accumulation of rain in the radar dish, 3) wetting of the radome, and 3) receiver saturation if the the rain is too heavy. Another technique for Z_{dr} calibration is also "end-to-end" and it uses passive solar scans and gathered radar data from scatterers. Since it relies on radar reciprocity (i.e., the crosspolar powers from H (horizontal) and V (vertical) polarization transmission are equal) it is called the crosspolar power (CP) technique (Hubbert et al. 2003, 2008a; Hubbert and Dixon 2012). The CP technique has been shown to work well for radars that employ fast alternating H and V transmit polarizations (FHV, also referred to as ATSR (Alternate Transmit Simultaneous Receive) mode), for example, S-Pol and CSU-CHILL radars. For FHV operations, the two crosspolar power measurements are separated by the PRT (Pulse Repetition Time) so that the crosspolar powers are well correlated. This means that echo from precipitation as well as ground clutter can be used. An advantage of the CP technique is that crosspolar power from ground clutter targets and solar measurements , which are nearly always available, can be used for calibration.

Achieving dual polarization measurements by simultaneously transmitting H and V polarizations (referred to as SHV here and sometimes referred to as STSR (simultaneous transmit simultaneous receive)) has become very popular and this paper examines issues for using the CP technique with such radars. Data from S-Pol and KOUN (NSSL's S-Band dual polarization research radar) are given to illustrate the concepts.

2. The Crosspolar Power Technique

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:

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

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 solar 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 ratio may be averaged over a few rays or an entire volume of radar data, however, more averaging usually produces superior results. 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.

For SHV dual polarization systems, near simultaneous samples of H and V crosspolar returns are not available. To employ the CP technique SHV radars must be able to transmit only H and only V polarizations and this can be accomplished if slow waveguide switches are used. However, the two measured crosspolar powers for a particular resolution volume will likely be separated in time by seconds if not 10s of seconds. This means that precipitation

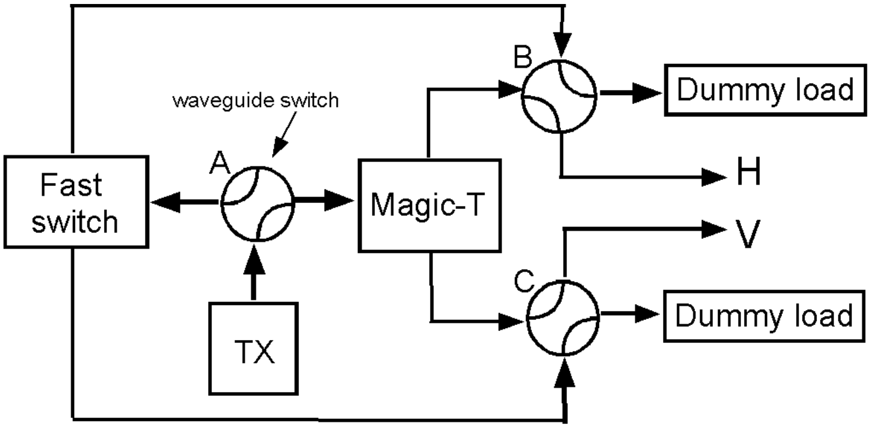

Figure 1: *S-Pol high power front end.*

targets will be decorrelated and thus the two crosspolar powers will not be equal. This is easily overcome by using ground clutter targets.

One technique for the measurement 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 to calculate the crosspolar power ratio.

In the CP technique for FHV operations, the crosspolar power calibration signals follow the same electrical paths as do the meteorological measurements. However, for SHV radars this is not necessarily true unless care is taken in the radar design. To use the CP technique for SHV radars, the radar needs to be designed so that 1) transmit only H polarization and transmit only V polarization is possible, and 2) 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 transmit 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.

Next we give an example of a radar where the CP calibration paths (i.e., the crosspolar power paths) are not identical to the SHV paths. 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 waveguide 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 transmit powers 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,

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

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. 2008b).

Shown in Fig. 3 is a simplified 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

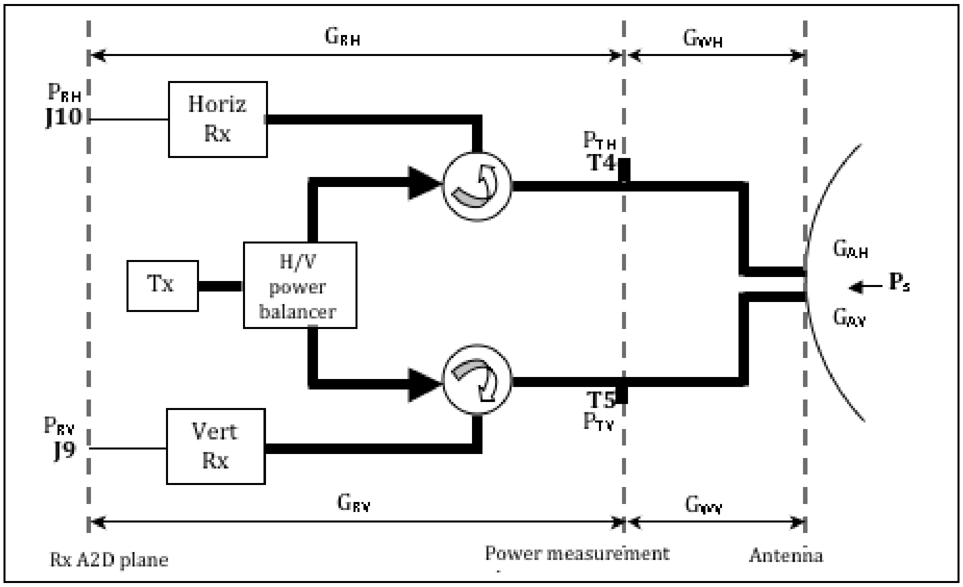

Figure 2: *NEXRAD block diagram.*

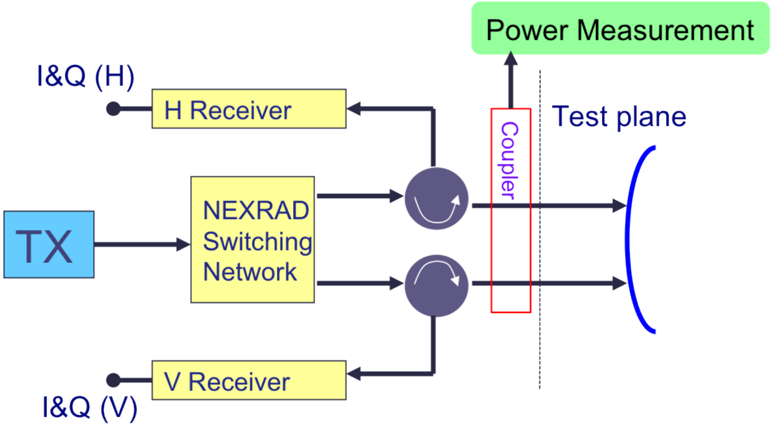

Figure 3: *NEXRAD transmit power measurement.*

(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. 2008b).

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.(2) can be isolated. The Z_{dr} calibration equation then becomes,

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

3. Experimental Data

To calibrate Z_{dr} for SHV radars, such as 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.

a. *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° X 0.1° 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. Since there are inevitably mismatch between the H and V copolar antenna patterns, the S calibration term should be averaged across about a one degree solid angle and not just calculated from boresight data (maximum power point). Table 1 shows KOUN (NSSL's (National Severe Storm Laboratory) S-band research radar) solar scan data collected on 22 Feb. 2011. 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.

b. *Crosspolar Power Measurements*

The principle of reciprocity states that the two crosspolar power measurements (transmit H receive V (P_{XV}) and transmit V receive H (P_{XH}) are equal. In order to use the CP technique for SHV operations, crosspolar data from a H-transmit PPI needs to be compared to V-transmit PPI data. This typically mean that the H and V crosspolar data is separated by about 30 to 60 seconds. Also, the H and V transmit data need to come from the same resolution volumes. This requires indexed beams. SHV data can be simulated from FHV data. The H-polarization data from one FHV PPI scan can be compared to the V-polarization data from the next FHV PPI scan.

Fig. 4 shows a 2-D crosspolar power histogram for FHV S-Pol data. The left panel is for "FHV mode" (i.e., the crosspolar power pairs are separated by about 1 ms) and the right panel shows crosspolar power pairs from consecutive PPIs of FHV 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 can still be used to calculate the mean crosspolar power ratio. The mean ratio for the top panel is 0.043 dB while the mean ratio for the bottom panel is 0.022 dB, a difference of only 0.021 dB. One does need to be careful of how the ground clutter targets are selected. They should 1) not vary much in time (i.e., stationary targets) 2) have a15 dB SNR, and 3) not saturate the receivers. To avoid saturation, the powers should be more than 10 dB from the maximum power limit of the receivers.

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**

c. *Data from DYNAMO*

From 1 Oct. to 15 Jan. S-Pol collected data for the field experiment DYNAMO (Dynamics of the Madden-Julian Oscillation) on the Addu Atoll, Maldives in the Indian ocean. Even though very little ground clutter was available, the CP technique was successfully performed using the limited clutter echo. Both the VP technique and the CP technique were executed together on 5 days. The Z_{dr} bias are in (CP,VP) dB pairs: (0.315, 0.284), (0.273, 0.291), (0.319, 0.307), (0.298. 0.304), (0.327, 0.013) which give a RMS difference of 0.018 dB. Thus the VP and CP techniques again show very good agreement. This is for FHV crosspolar power pairs separated by 1 ms.

As mentioned above, the CP technique for SHV radars with can be "simulated" using FHV data by simply comparing H-crosspolar powers form one PPI scan to V-crosspolar power from the next PPI scan. This experiment was done during DYNAMO on 8 January 2012 which was a very dry period. S-Pol was executing PPI volume scans every 15 minutes. Thus the "simulated" SHV data came from PPIs that were separated by 15 minutes. Data from 0.5, 1.5, 2.5, 3.5, 4.5 and 5.5 deg. elevations were used (obviously side lobe clutter signal was used for the higher elevation angles). The Z_{dr} (dB) bias pairs for the FHV data and consecutive PPI data for each elevation angle are: (-0.022, 0.00), (-0.001, 0.011), (0.002, 0.009), (0.002, -0.016) and (0.001, 0.016) which yields an RMS difference of 0.0 17dB. Because of the very limited amount of clutter targets available, the average crosspolar power ratios were calculate over 96 volume scans. Figure 5 shows a 2-D histogram of the crosspolar power pairs. The data is symmetrically distributed around the regression line.

4. Calibration Monitoring

The initial calibration of Z_{dr} can be considered as a "snapshot" of the radar system. Due to outside influences (primarily temperature) the gains of the radar system will be a function of time and need to be monitored. Passive sections of the signal path should have constant, non-time varying gains; gains of the active portions of the signal path will vary and need to be monitored regularly. This mean 1) injecting test signals above the LNAs (Low Noise Amplifier) of the receiver path and 2) measuring the transmit powers. 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 (according to the injected signal measurements). Call these receiver gains G_{H_0} and G_{V_0} and call the transmit powers at calibration $P^S_{H_0}$ and $P^S_{V_0}$ where the "0" subscript denotes a measurement at the initial calibration time. As time passes these 4 quantities need to be continually monitored (say once per volume scan or more). Call these measurements at time τ, G_{H_τ}, G_{V_τ}, $P^S_{H_\tau}$ and $P^S_{V_\tau}$. As the ratios G_{H_τ}/G_{V_τ} and $P^S_{H_\tau}/P^S_{V_\tau}$ vary from the corresponding ratios at time "0", the Z_{dr} correction factor needs to be correspondingly adjusted.

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.

Acknowledgment
This research was supported in part by the ROC (Radar Operations Center) of Norman OK. The NCAR S-Pol radar is supported by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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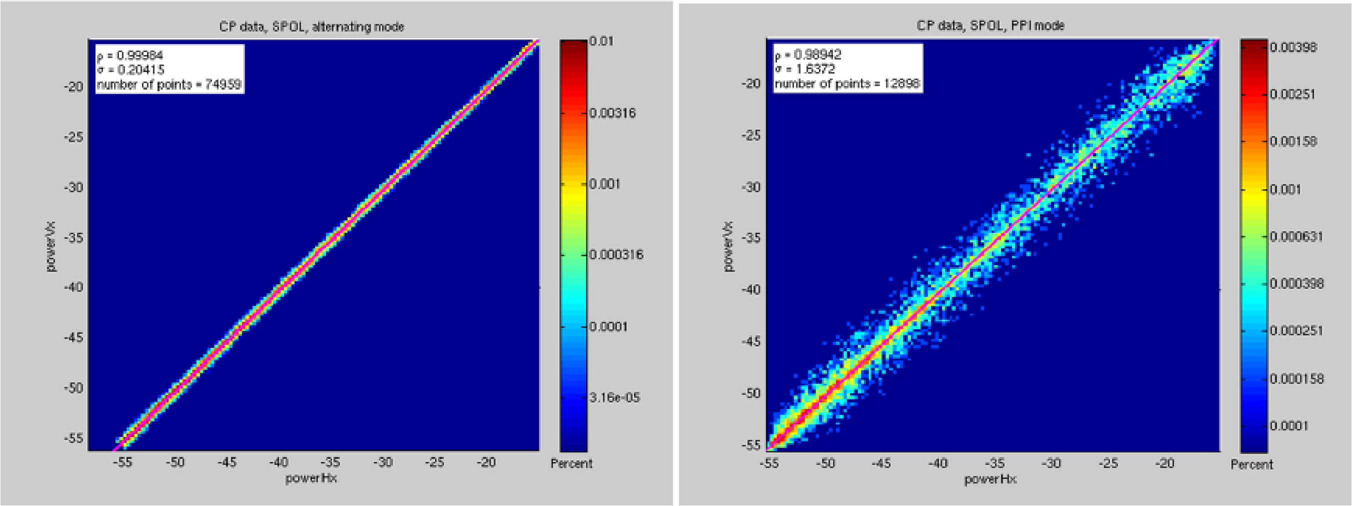

Figure 4: *2-D histograms of S-Pol crosspolar powers: Left panel: for fast alternating H and V transmission; Right panel: for only H and only V transmission. The crosspolar powers from consecutive only H transmission then only V transmission are paired via indexed beams.*

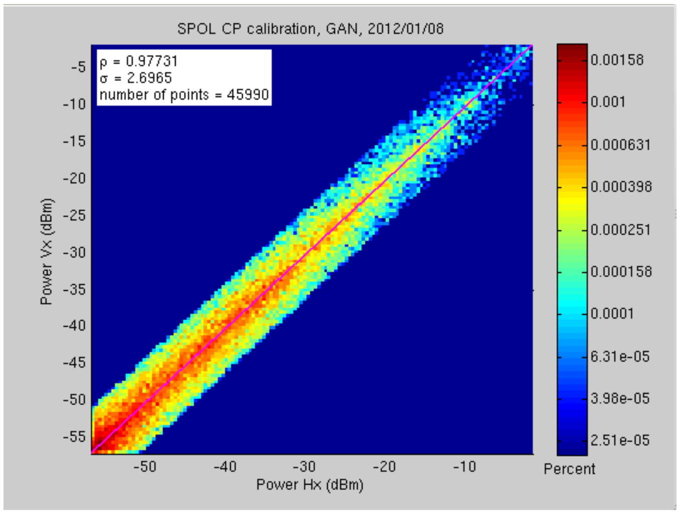

Figure 5: *2-D histogram of S-Pol crosspolar powers from DYNAMO. Crosspolar power pairs are separated by 15 minutes.*