P1.8 **CALIBRATION OF $Z_{DR}$ FOR AN S-BAND POLARIMETRIC RADAR**

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## 1. INTRODUCTION

The polarimetric radar variable of differential reflectivity is an estimate of the axial asymmetry of a population of hydrometeors (Seliga and Bringi,1976). Differential reflectivity is defined as the ratio of the horizontally polarized radar reflectivity (horizontally polarized transmit pulse, horizontal received signal, $Z_{HH}$) to the vertically polarized reflectivity ($Z_{VV}$); when expressed in decibel units of reflectivity, we have (Illingworth and Caylor, 1989):

$$Z_{DR} = 10\log_{10}( Z_{HH} / Z_{VV} )$$

Or:

$$Z_{DR} = dBZ_{HH} - dBZ_{VV}$$

For reflective particles that are wider than they are high, $Z_{DR}$ will have positive values. Liquid precipitation particles are deformed as they fall through the atmosphere, and have positive values of $Z_{DR}$. The ratio of axial deformation increases as the volume of a droplet increases, providing a relationship between $Z_{DR}$ and droplet size, and therefore, rain rate (*Ibid.*).

$Z_{DR}$ has demonstrated application for increasing the accuracy of radar rainfall estimates (Seliga and Bringi, 1976; Illingworth and Caylor, 1989), for providing information on hydrometeor identification (Vivekanandan, et al., 1999), and for clutter discrimination (Guili, et al., 1991). However, $Z_{DR}$ is a difference between two large quantities, each of limited absolute accuracy, creating a problem of compounded numerical error. An error of as little as .3 dB in $Z_{DR}$ can lead to precipitation estimate errors of about 17%, reducing benefits that might be realized through the use of this parameter.

Elimination of any error in $Z_{DR}$ has received considerable recent attention from NCAR's radar systems group during the evolution of the NCAR S-band Polarimetric radar, **S-Pol** (Keeler, et al., 2000). Improvements in $Z_{DR}$ accuracy have resulted from 1) a more complete consideration of hardware issues such as dual receiver and dual transmit/receive (T/R) tube configurations 2) refinements to episodic vertical pointing methodology for $Z_{DR}$ bias correction, 3) use of the sun for routine, periodic monitoring of differential changes in system gains, and 4) the use of continuous monitoring of $Z_{DR}$ stability by means of a system test pulse. It is fundamentally realized that even a carefully engineered and maintained radar system has components that change their response over time, and that the monitoring of those variations is required. The techniques for monitoring of $Z_{DR}$ error are summarized, with results provided from a recent field campaign. The examples indicate that these techniques can provide $Z_{DR}$ with an accuracy of about +/- 0.1dB. Many of these procedures can be automated, and several of these may be applied directly to any ZDR-capable system, including the WSR-88D, when made polarization capable.

## 2. TECHNIQUES

Calibration of $Z_{DR}$ is reduced to a two-part problem: 1) removal of the residual error (bias) between calibrations of the horizontal and vertical co-polar system gains (used to determine $Z_{HH}$ and $Z_{VV}$, respectively), and 2) ensuring that the calibrations and bias estimate remain stable over time.

### 2.1 ***Vertical Pointing***

Nature provides a well-characterized, non-biased, system-independent data set for analysis of $Z_{DR}$ bias: rainfall viewed at vertical incidence. $Z_{DR}$ is essentially an estimator of particle axial asymmetry, and there is no consistent axial asymmetry in raindrop shape when viewed from directly below. Therefore, pointing the radar straight up through rain, $Z_{DR}$ should be zero (this is also generally true for ice particles). In the case of a strongly sheared environment, there might arguably be preferred orientation of a collection of hydrometeors, and therefore, a non-zero ZDR. Preferential orientation effects are removed by rotating the vertically pointing antenna in azimuth, and averaging results over several rotations; this has the added practical benefit of reducing false bias due to side lobe effects.

Vertical-pointing data collection is considered when two (subjective) criteria are met: 1) there is light precipitation at the radar (low to moderate reflectivities above the radar) and 2) hydrometeors extend vertically for sufficient range to provide a large collection of data points. Other practical considerations related to the physics of radar, or the engineering design of a particular radar system, lead to quantified conditions for exclusion of individual gates of radar data. Table 1 details criteria used in the automatic vertical pointing analysis routines at S-Pol.

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| Description | Exclusion Condition | Reason |
|---|---|---|
| Eliminate data when received power is too high | Pwr > 45dBm | Avoid regions of non-linear receiver response |
| Eliminate regions of weak signal | Pwr <100dBm | Limit variability due to poor signal statistics |
| Eliminate radar bright band | $L_{DR}$ > -13 dB | $Z_{DR}$ varies widely in such regions |
| Avoid regions close to radar | Range < 3 km | Limit to far field; Eliminate regions of **differential** T/R tube recovery |
| Remove data above the atmosphere | Range > 14 km | Eliminate statistical noise & test pulse |

**Table 1**: Objective vertical pointing data filter criteria for S-Pol. Pwr refers to uncalibrated, raw power returned to the radar, in dBm; $L_{DR}$ is another polarization variable, used in this case to diagnose the bright band.

S-Pol is a dual receiver system, but uses the same receiver for estimates of the two components of ZDR. This eliminates potential problems caused by uncorrelated calibration drift of two receivers. However, each component of $Z_{DR}$ is affected by use of different T/R tubes[3], and care must be taken to avoid near-range effects due to different rates of recovery in the two tubes. This is done with the fourth criteria, by ignoring data closer than 3 km to the radar.

### *2.2 Solar Gain Estimates*

Consistency of $Z_{DR}$ calibration can be monitored through vertical pointing techniques, but this may require operator intervention, and is done only when precipitation is present at the radar. At S-Pol, a solar calibration technique (Pratte, et al., 1995) is used routinely in conjunction with vertical pointing, to monitor for changes in either the horizontal or vertical system gains that would impact ZDR. Solar calibration is likely somewhat less accurate than vertical pointing, but can be performed when no echoes are present. Even when the absolute accuracy of a given solar calibration may be doubtful (say, due to uncertainties in solar energy flux), the difference between the horizontal and vertical system gains can still be used to monitor $Z_{DR}$ bias.

The NCAR Radar Systems Group is also in the process of extending the capability of solar calibrations to provide approximate information about S-Pol antenna patterns. Since S-Pol is a moveable radar system, there are concerns about horizontal and vertical beam alignments whenever the system is reassembled. Further progress on "solar beam alignment" will be reported, as available.

A summary of solar calibration information for the STEPS (Weisman and Miller, 2000) field deployment is provided in Table 2. Similar results are obtained for other S-Pol field projects.

| Date | System Gain, H | System Gain, V | Gain Differenc | Residual Difference From Mean |
|---|---|---|---|---|
| 13May00 | 44.82 | 44.44 | .38 | .12 |
| 24May00 | 45.18 | 44.91 | .27 | .01 |
| 27May00 | 44.49 | 44.29 | .20 | -.06 |
| 11Jun00 | 45.17 | 44.91 | .26 | -.00 |
| 16Jun00 | 44.98 | 44.71 | .27 | .01 |
| 04Jul00 | 45.06 | 44.89 | .17 | -.09 |
| | | | Mean: .26 | |

**Table 2**: Solar Calibrations, S-Pol in STEPS. Values are in dB.

### *2.3 Test Pulse monitoring*

An injected test signal is used at S-Pol to continuously monitor stability of the receiver systems. Test signals of known power are injected into both the dual S-Pol receivers, and are timed to appear at maximum radar range. The test signals are subjected to full system data processing, and create reference information for most of the S-Pol parameters. However, the ZDR test pulse currently in use at S-Pol does not accurately reflect variations in $Z_{DR}$ bias (as compared to vertical pointing bias estimates). This is likely due to inappropriate application of a transmit power correction in deriving the horizontal and vertical reflectivities from the test pulse powers. This issue will receive further attention.

### *2.4 Sphere Calibrations for $Z_{DR}$ Bias Estimation*

System calibration and $Z_{DR}$ bias estimates have been attempted through the use of small (30 cm) metalized spheres attached to balloons. Results have been variable, and somewhat unsatisfactory; of three sphere calibration attempts for S-Pol, satisfactory, but noisy results were obtained from one (not shown). Sphere calibrations are time and labor intensive, limiting their routine application. However, a sphere calibration can be matched to theoretical expectations of radar signals, and provides a backup test of the full transmit/receive process of the radar.

## 3. RESULTS

The combined results for $Z_{DR}$ calibration/bias estimation are presented in Table 3 for S-Pol in the STEPS 2000 experiment. An entry is included in Table 3 for dates when there 1) were any significant radar echoes (and therefore, might be scientific interest), 2) a solar calibration was performed, or 3) was a vertical pointing data set obtained. Generally, the vertical pointing estimates could be done quickly upon targets of opportunity during daily operations; solar gain estimates

[3] The T/R (transmit/receive) tubes are used to protect sensitive receiver components from the high-power transmit pulse of the radar. The tubes contain a gas that is quickly ionized by the transmit pulse, blocking passage of energy. The tube then returns to full transparency with a characteristic relaxation time, which is translated into a range effect for the radar. Different tubes recover at different rates. S-Pol uses a different tube for each transmit polarization.

required more time, and were only performed when they would not interfere with operations during weather events. This made the two sets of measurements mutually exclusive. The system test pulse was present at all times, except during solar calibrations (the nearest-in-time test pulse value was selected for most solar calibrations). For S-Pol, a nominal, non-zero value of the test pulse was targeted to have a value of about .6 dB.

| Date | Vertical Pointing Bias Estimate | Solar Gain Bias Estimate | $Z_{DR}$ Test Pulse Value |
|---|---|---|---|
| 13May00 | | +.12 | n/a |
| 24May00 | | +.01 | -.53 |
| 25May00 | | | -.60 |
| 26May00 | -.02 | | -.58 |
| 27May00 | | -.06 | n/a |
| 29May00 | | | -.62 |
| 31May00 | | | -.52 |
| 03Jun00 | | | -.46 |
| 06Jun00 | | | -.62 |
| 07Jun00 | -.04 | | -.57 |
| 09Jun00 | | | -.63 |
| 11Jun00 | -.00 | +.00 | -.59 |
| 12Jun00 | | | -.60 |
| 16Jun00 | | +.01 | -.67 |
| 17Jun00 | +.02 | | -.60 |
| 19Jun00 | | | -.67 |
| 22Jun00 | | | -.61 |
| 23Jun00 | | | -.64 |
| 24Jun00 | | | -.65 |
| 25Jun00 | | | -.61 |
| 26Jun00 | +.05 | | -.63 |
| 27Jun00 | +.09 | | -.62 |
| 29Jun00 | | | -.64 |
| 01Jul00 | | | -.66 |
| 02Jul00 | -.08 | | -.64 |
| 04Jul00 | | -.09 | n/a |
| 05Jul00 | | | -.64 |
| 09Jul00 | | | -.68 |
| 10Jul00 | | | -.67 |
| 12Jul00 | | | -.64 |
| 16Jul00 | +.03 | | -.64 |

**Table 3**. Results of $Z_{DR}$ calibration monitoring for the STEPS field campaign.

The following are evident from Table 3:

- $Z_{DR}$ bias changes with time
- $Z_{DR}$ bias estimates range from -.08 to +.09 (value of 13May preceded system adjustment)
- Bias estimates from vertical pointing closely track estimates from solar calibrations
- The $Z_{DR}$ test pulse is stable to better than .2 dB, but there is little correlation between the test pulse and the two other bias estimators.

**4. SUMMARY**

$Z_{DR}$ bias/calibration for the S-Pol radar system changes slightly with time. This is likely due to relatively minor changes in system components, perhaps due to changes in component temperature. Regardless of the reason for the changes, without a routine program for monitoring $Z_{DR}$ bias, the utility of this parameter would become suspect. For S-Pol, monitoring the calibration is done primarily through analysis of vertical pointing data sets and through special solar calibrations. The two techniques produce reliably similar results, and may be interchangeable. Absolute accuracy of S-Pol $Z_{DR}$ measurements is +/- .10 dB, sufficient to meet the design goals of S-Pol, and to provide required accuracy for precipitation estimation.

Future work will include further automation of both the vertical pointing and solar calibration procedures, and application of the vertical pointing information to beam alignment issues. Semi-automatic tracking and analysis of system test pulse components will be explored, with emphasis on developing a better indicator of $Z_{DR}$ stability than the current $Z_{DR}$ test pulse.

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**References**

Giuli, D., M. Gherardelli, A. Freni, T.A. Seliga, and K. Aydin, 1991: Rainfall and clutter discrimination by means of dual-linear polarization radar measurements. *J. Atmos. Oceanic Tech*., **8**, 777-789.

Illingworth, A.J., and I.J. Caylor, 1989: Polarization radar estimates of raindrop size spectra and rainfall rates. *J. Atmos. Oceanic Tech*., **6**, 939-949.

Keeler, R.J., J. Lutz, and J. Vivekanandan, 2000: S-Pol: NCAR's polarimetric Doppler research radar. IGARRS-2000, IEEE, Honolulu, HI, 24-28 July, 2000, 4pp.

Pratte, F., D. Ferraro, and C. Frush, 1995: System calibration of the WSR-88D network. Final Report, Data Quality Optimization Interagency MOU between WSR-88D Operational Support Facility and Forecast Systems Laboratory.

Seliga, T.A., and V.N. Bringi, 1976: Potential use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation. *J. Appl. Meteor.*, **15**, 69-76.

Vivekanandan, J., D.S. Zrnic, S.M. Ellis, R. Oye, A.V. Ryzhkov, and J. Straka, 1999: Cloud microphysics retrieval using S-band dual-polarization radar measurements. *Bull. Amer. Met. Soc*., **80**, 381-388.

Weisman, M.L., and L.J. Miller, 2000: An overview of the Severe Thunderstorm Electrification and Precipitation Study (STEPS). Preprints, 20th Conference on Severe Local Storms, AMS, Orlando, Florida. 11-14 Sep, 2000.