The uncertainty of Zdr calibration

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1. Introduction

Three techniques for the calibration of Z_{dr} are investigated 1) the vertical pointing (VP) technique, 2) the engineering calibration (EC) technique and 3) the crosspolar power (CP) technique (Hubbert et al. 2003). Uncertainty of measurements is a way to quantify the probability that a measurement (in the present case a calculated calibration factor) lies within some error bound. Thus, the goal of this this paper is to quantify the uncertainty of the estimated Z_{dr} calibration factors determined by each method.

One widely accepted way to calibrate Z_{dr} is to point the radar dish vertically in light rain and measure Z_{dr} while turning the dish 360 degrees. Since raindrops have no preferred orientation (i.e., distributed uniform randomly in the plane of polarization) 360-degree-integrated, intrinsic Z_{dr} is zero dB. Thus, any measured non-zero dB Z_{dr} yields the radar system Z_{dr} offset.

A second way to calibrate Z_{dr} is with an EC approach based on engineering measurements (Zrnić et al. 2006). The radar transmit and receive paths are divided into "active" and "passive" parts. The gains and losses of the "passive" or "static" parts, i.e. the waveguides and antenna, are measured by using test signals and radiation from the sun. The gain of the active signal path (i.e., receiver chain) is monitored via test signal injection on a continuous basis. Transmit powers are also monitored. By combining the passive and active calibration measurements, the Z_{dr} bias can be estimated.

The CP method has been successfully applied to the CSU-CHILL radar data to calibrate Z_{dr} (Hubbert et al. 2003). The technique uses the property of radar reciprocity (Saxon 1955) which means 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:

$$Z_{dr}^{cal} = Z_{dr}^{m} S^2 \frac{\overline{P_{xv}}}{\overline{P_{xh}}} \quad (1)$$

where Z_{dr}^{cal} is calibrated Z_{dr}, Z_{dr}^{m} is measured Z_{dr}, S is the ratio of the V and H power from sun measurements, and $\overline{P_{xh}}$, $\overline{P_{xv}}$ are the average crosspolar powers for transmit H and transmit V polarization, respectively. The crosspolar powers 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.

S-Pol employs a copolar and crosspolar receiver design in contrast to H and V receivers. This is done to reduce the variance and drift of the Z_{dr} measurement but this also slightly changes the Z_{dr} calibration equation to:

$$Z_{dr}^{cal} = Z_{dr}^{m} S_1 S_2 \frac{\overline{P_{xv}}}{\overline{P_{xh}}} \quad (2)$$

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 et al. 2003 for details). In this paper estimated uncertainty of the three Z_{dr} calibration techniques are given. Issues affecting the uncertainty budgets are discussed. Experimental data from NCAR's S-Pol (S-band Polarimetric Radar) are given that indicate the uncertainty of each method.

2. Uncertainty measurement concepts

Uncertainty can be categorized as either Type A or Type B. Type A uncertainty is represented by the standard deviation of a set of measurements and is primarily quantified by repetition under controlled test conditions. Type B uncertainty is any other non-measured uncertainty (e.g., manufacturer specifications). Type B uncertainty can also be represented by the standard deviation of an assumed Normal Distribution but is not quantified through measurement.

An uncertainty specification is incomplete without a confidence interval (Taylor and Kuyatt 1994). The 2σ coverage standard is used in this paper since this is the coverage value typically used by manufactures of RF devices. It also seems reasonable that meteorologist/hydrologists would like to use Z_{dr} measurements that are calibrated to within 0.1 dB with 95% confidence (i.e., 2σ coverage). In fact, the NEXRAD Technical Advisory Committee recently recommended (in March 2007) that Z_{dr} be calibrated to within 0.1 dB with 95% confidence (i.e., 2σ coverage).

The desired Z_{dr} calibration goal can be expressed as

$$Z_{dr}^{cal} = Z_{dr}^{m} + Z_{dr}^{bias} \pm \delta \quad (3)$$

where Z_{dr}^{cal} is the corrected or calibrated Z_{dr}, Z_{dr}^{m} is the measured Z_{dr} estimated from radar data, Z_{dr}^{bias} is the Z_{dr} bias calculated via one of the calibration techniques and δ is the 2σ uncertainty of the bias estimate.

Use of automated test equipment for calibration measurements permits more complete decomposition of Z_{dr} uncertainty and reduces human error and variance in measurement due to repeated connects and disconnects of RF measurement equipment. Mechanical processes and procedures such as attaching and re-attaching cables, couplers and meters introduce variability to the EC approach. To reduce these effects, Automatic Test Equipment (ATE) has now been built into S-Pol to measure test point signals, inject test signals and monitor environmental variables such as temperature along the signal path using fixed cable attachments and electronic switches.

The ATE consists of a control computer, wideband power meter, signal generator, noise sources, attenuators and an RF switching matrix all of quality necessary to achieve overall 0.1 dB measurement uncertainty.

3. Engineering calibration approach

The essence of the EC method can be understood via Fig. 1. The blue lines represent measurements planes where signal can be either injected or measured by the ATE. The principle behind all of the calibration techniques is to measure the differential path losses 1) from the transmitter out through the antenna and 2) from outside the antenna back through to the received I and Q samples. Note that the path from the circulators through the antenna is common to both transmit and receive paths. It can be shown that the following calibration

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equation accounts for the entire electrical transmit and receive paths. The EC Z_{dr} calibration equation is,

$$Z_{dr}^{bias} = \Delta(1,2)_{pulse} + 2\Delta(S,4) - \Delta(2,4)_{noise}. \quad (4)$$

where the terms are in dB and the number pairs (and the letter S) correspond to the measurement planes shown in Fig. 1. The $\Delta(1,2)_{pulse}$ term is a measurement of the differential path loss from the transmitter to measurement plane 2. Physically, the radar transmit pulses are monitored at measurement plane 1 and RF power measurements are made at plane 2 via a waveguide coupler. The term $\Delta(S,4)$ determines the differential gain from outside the antenna to the I and Q samples using the sun as an unpolarized RF source (i.e., the H and V power from the sun are equal, a very good assumption (Tapping 2001)). The $\Delta(2,4)_{noise}$ term is measured by injecting noise at measurement plane 2 and measuring the resulting differential power at measurement plane 4 via the I and Q samples. In this way, the system Z_{dr}^{bias} is measured. Thus, to determine the uncertainty of this Z_{dr} bias estimate is tantamount to determining the Z_{dr} uncertainty of each term on the right hand side of Eq. (4) in conjunction with each other.

The Type A uncertainty of a particular repeated RF power measurement (i.e., simply repeating an RF power measurement while the circuit topology and components are constant) can be very low, perhaps on the order of a hundredth of a dB; however, as explained above, there are systematic errors (typically Type B) that must be taken into consideration: for example the uncertainty of the waveguide coupling factor, impedance mismatches and other systematic biases. These types of errors cannot be reduced with repeated trials and averaging.

3.1 An engineering calibration uncertainty estimate

In this section the uncertainties of making waveguide power measurements are discussed and applied to the uncertainty budget for Eq. (4). Figure 2 shows a block diagram for a differential power measurement. In this setup (modeled after the ATE) a switch is used to select either the H or V waveguide for measurement. Shown also are circles that indicate some of the various uncertainties that affect power measurement. Table 1 gives a description of the uncertainties and typical values (2σ coverage, for high quality, well calibrated test equipment).

The estimated uncertainty of a single power measurement can be expressed

$$U_m^H = f\big(U_c^H, U_{w,c}^H, U_{w,s}^H, U_s, U_{s,a}, U_a, U_{a,p}, U_p, U_m\big). \quad (5)$$

Using the values given in Table 1, the 2σ uncertainty is 0.195 dB.

For differential power measurements, some of the uncertainties will cancel, e.g., the uncertainties due to the attenuator, power sensor and power meter are common to both the H and V measurements and thus cancel in the ratio of H and V power measurement. The uncertainty of the differential waveguide power measurement can be expressed,

$$U_m^D = f\left(U_c^H, U_{w,c}^H, U_{w,s}^H, U_c^V, U_{w,c}^V, U_{w,s}^V\right) \quad (6)$$

where U_m^D is the differential power measurement uncertainty. Again, the uncertainties are assumed independent and are combined in quadrature to yield a total uncertainty of 0.183 dB.

This uncertainty can be regarded as an estimate of the uncertainty of the $\Delta(1,2)$ term in the EC calibration Eq. (4) where the transmit pulse power is measured at test plane 2. If the same waveguide couplers are used to inject signals for the purpose of determining $\Delta(2,4)$, more of these uncertainty terms in Eq. (6) will cancel when calculating the overall uncertainty of Eq. (4). Specifically, the uncertainty of the waveguide coupling factor, U_c, will cancel. However, additional uncertainty terms due to impedance mismatches are added.

- *An important observation is that the coupling factor for a waveguide coupler is bi-directional or reciprocal where as the associated impedance mismatch factors are not.*

Thus, the direction of the RF signal is accounted for with the superscripts "inj" for inject a signal into the waveguide while "out" denotes that a signal is extracted from the waveguide. The total uncertainty of Eq. (4) can be expressed

$$U_m^T = f\big(U_{w,c}^{H_{inj}}, U_{w,s}^{H_{inj}}, U_{w,c}^{V_{inj}}, U_{w,s}^{V_{inj}}, U_{w,c}^{H_{out}}, U_{w,s}^{H_{out}}, U_{w,c}^{V_{out}}, U_{w,s}^{Vout}, U_s, U_{gn}, U_{g,s}, U_{sun}, U_{tx}\big) \quad (7)$$

where the "inj" is associated with the impedance mismatch at the waveguide coupler interfaces when signal is being injected into the waveguide, the "out" is associated with the impedance mismatch at the waveguide coupler interfaces when signal is being sampled from the waveguide. As can be seen from Eq. (7), the uncertainty of making a Z_{dr} bias estimate via Eq. (4) is due in large part to impedance mismatches. Other uncertainties are U_{gn} the signal generator, U_s switch jitter, U_{sun} sun variability and processing procedures (0.05 dB), and U_{tx} the power injection uncertainty for the measurement $\Delta(1,2)$ (0.05dB). The impedance mismatches are quite significant and the 2σ uncertainty estimate due to just just the 8 waveguide impedance mismatch terms is 0.186 dB (i.e., adding the 8 individual uncertainty estimates of 0.06 dB in quadrature). Adding the rest of the uncertainties yields $U_m^T = 0.192\,dB$. The uncertainties used are taken from Table 1 where we assume $U_{w,c}^{H_{inj}} = U_{w,c}^{H_{out}} = U_{w,c}^H$ and similarly for the other impedance mismatches.

For the uncertainty budgets presented here, we have estimated the the uncertainty due to impedance mismatch to be 0.06 dB. For more details on impedance mismatch see Hubbert et al. (2007) and Kearn and Beatty (1967).

4. Experimental results

In this section we present experimental results that are indicative of the uncertainty of the measurements that are required for the three Z_{dr} calibration techniques.

4.1 Sun measurement statistics

Both the EC and CP calibration techniques require sun measurements. The sun radiation at S-Band is assumed unpolarized (Tapping 2001) and thus the H and V powers are equal. Typically the sun is scanned with one tenth degree elevation steps at about one degree per second rate.

To reduce the sun integration errors, sun data points are first interpolated to a uniform rectangular $0.1° \times 0.1°$ grid. In order to determine the location of the sun 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 sun scans to construct the grid of data, lower variance of S_1S_2 is obtained. Before gridding the data, the sun's movement and elevation angle distortion must be accounted for.

On 21 June 2007, an entire day of sun box scans were made. Fig. 3 shows the S_1S_2 values for various integration annuli. The horizontal axis is labeled in "UNIX days". S_1S_2 values are calculated by combining consecutive sets of 3 sun box scans. For an annulus of 1.25°, smallest variances are achieved and this variance is about 0.01 dB over a short period of time (say about 0.5 hours) which gives a 2σ uncertainty of about 0.02 dB. However, there is also a significant drift over the of nearly 0.1 dB. This indicates that the Z_{dr} bias should be monitored and corrected over a day's measurements. More about Z_{dr} bias correction is discussed later.

Such grided solar scan data can be used to construct pseudo antenna patterns. See Hubbert et al. (2007) for more details.

4.2 Vertical pointing measurements

Vertical pointing measurements in rain have an intrinsic Z_{dr} of 0 dB when data is averaged over a 360° rotation of the radar dish (Bringi and Chandrasekar 2000). A measured non-zero value is considered the system Z_{dr} bias. To evaluate the uncertainty of the VP Z_{dr} bias estimate, 90 consecutive 360° vertical point scans were made in light rain on 23 May 2007. Each measurement results from integrating measured Z_{dr} over one 360° antenna revolution and using the following thresholds: range > 2.7km, 30 dB$<$ SNR $<$60 dB, $\rho_{hv} > 0.95$ and $LDR > 20$ dB. Each 360° revolution takes about 1 minute. Fig. 4 shows the 90 Z_{dr} bias values in dB scale. The total extent of the vertical axis is 0.045 dB. There appears to be a mean increasing trend to the data set. If this trend is eliminated, the the standard deviation of the de-trended data is about 0.01 dB which gives a 2σ uncertainty of the Z_{dr} bias estimate of 0.02 dB. However, the trend in the data set again points to the necessity of monitoring the Z_{dr} bias.

4.3 Crosspolar power data

In addition to the sun measurements, the CP technique for Z_{dr} calibration requires the measurement of the mean crosspolar power ratio, $\overline{P_{xv}/P_{xh}}$. The CP technique takes advantage of the principle of radar reciprocity which dictates that the two crosspolar powers must be equal

The NEXRAD dual polarization system will use simultaneous H and V transmission and reception and thus, near simultaneous samples of H and V crosspolar returns will not be 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. Another viable technique is to simply point the radar along a radial where there are good clutter targets. The slow waveguide switch can alternated H and V transmit polarization that illuminate the same clutter targets.

On 18 October 2006 the PPI measurement technique was tested using RVP8 data. PPI scan data were collected in fast alternating transmit H and V mode, followed shortly by H-only transmit, and then V-only transmit modes. The crosspolar power ratios were calculated from both sets of data. For 22 H and V PPI pairs, the mean crosspolar power ratio is $\overline{P_{xv}/P_{xh}} = 0.373$ dB with a 2σ uncertainty of 0.032 dB. Similarly, for the fast alternating mode, the mean $\overline{P_{xv}/P_{xh}} = 0.404$ dB and the 2σ uncertainty is 0.002 dB. The uncertainty of $\overline{P_{xv}/P_{xh}}$ for the fast alternating method is much lower than that for the alternate H and V PPI method; however, these results show that the cross polarization approach is amenable to NEXRAD.

4.4 Comparison of calibration techniques

The Z_{dr} calibration factor or bias of the S-Pol system should be the same whether using the VP, the CP or EC techniques. The following data were gathered on 31 August 31 2006 but are representative, in general, of our calibration measurements. The Z_{dr} bias calculated from VP data is 0.712 dB$\pm$0.019 dB. The Z_{dr} bias is calculated via the CP technique using Eq.(2) from sun measurements and crosspolar power measurements, also gathered on 31 August 2006. S_1S_2 is -1.051 dB$\pm$0.013 dB while the crosspolar power ratio was -0.323 dB$\pm$0.014 dB. This yields a Z_{dr} bias of $(-0.323) - (-1.051) = 0.728$ dB$\pm$0.027 dB which is in excellent agreement with the VP bias estimate 0.712 dB$\pm$0.019 dB. Both of these uncertainties are derived from Type A evaluations. There are likely other systematic errors that we have neglected for both techniques. For the VP we estimate these neglected errors to contribute an uncertainty of 0.05 dB. For the CP technique, we estimate an uncertainty of 0.05 dB for both the crosspolar power ratio $\overline{P_{xv}/P_{xh}}$ and the sun ratio measurement S_1S_2. These neglected Type B errors could arise from the data processing techniques, sun scan anomalies or other unidentified influence factors. An example of such anomalies is given in the next section. This then changes the VP bias estimate to 0.712 dB$\pm$0.053 dB and the the CP estimate to 0.728 dB$\pm$0.075 dB. Both 2σ uncertainties are still under the 0.1 dB requirement. The results from the EC approach indicate Z_{dr} measurement bias is 0.80 dB with a total uncertainty of about 0.25 dB (other uncertainties are included in this estimate that were not included in Section 4.1 above). The EC bias number of 0.80 dB was estimated from data taken over several days so that a direct comparison of the EC bias to the CP and VP biases is not warranted. The uncertainty estimate of the EC bias, 0.25 dB, however, more importantly indicates that the EC Z_{dr} bias may not be estimated to within the 0.1 dB requirement.

7. $\mathbf{Z_{dr}}$ bias monitoring

As indicated by the above data, the Z_{dr} bias is very likely to drift significantly during the course of a day. These drifts, though small, are on the order of a tenth of a dB, for the S-Pol system, and thus the Z_{dr} bias needs to be monitored and the Z_{dr} bias adjusted. The components most prone to gain drift are the active components, i.e., the LNAs and the receiver. This active portion of the receiver path can be monitored for gain drifts by 1) injecting test pulses at test plane 3 (see Fig. 1) and measuring the resulting differential power at the I&Q samples and 2) scanning the sun. In the following two data sets, the sun scan data are compared to test pulse injection data.

Fig. 5 shows S_1S_2 sun scan numbers (in purple) versus time in Unix days for 17 July 2007. The horizontal axis extent is 14.4 hours and the vertical axis is in dB. The sun scan numbers are calculated from a single sun box scan. The blue markers show the drift in S_1S_2 as measured via test pulse injected at measurement plane 2. Both data sets show the same trends with the test pulse measurements showing less variance. The sun scan measurement variance could be reduced if 3 box scans were used to calculate S_1S_2. At the beginning of the plot, the average difference between the two data sets is about 0.03 dB whereas the average difference grows to about 0.08 dB at Unix time 37818.75. This discrepancy could be due to 1) the processing algorithm of the sun data, 2) unaccounted variations in the sun as an unpolarized source 3) other unaccounted variances in the electrical path. Consider the third alternative. The test pulses only monitor the gain drifts from measurement plane 3 to the I&Q samples. The sun measurement plane take into account the entire receive path from outside the antenna to the I&Q samples. Thus, there could be gain fluctuations cause by the electrical path from the antenna to measurement plane 3 that could account for the differences seen in Fig. 5. Such discrepancy illustrate the difficulty in making RF power measurements accurate to sub tenth of a dB levels and to the realistic evaluation of RF power measurement uncertainty at these levels.

Fig. 6 shows similar S_1S_2 data as shown in Fig. 5 for 21

June 2007. Again there is a differential discrepancy of about 0.08 dB between the curves from the beginning of the data set to Unix time 37792.7. This is of the same magnitude and direction as seen in Fig. 5. Thus it is unlikely that the sun processing algorithm is responsible for the observed discrepancy. One explanation is that via heating by the sun, the electrical path from the antenna to measurement plane 3 is altered via expansion. This then appears to point to another RF power measurement uncertainty source. Further measurements and investigation are needed.

8. CONCLUSIONS

Three Z_{dr} calibration techniques were investigated for the WSR-88Ds using S-Pol, NCAR's S-band polarimetric radar: 1) vertical pointing (VP) data in light rain, 2) engineering calibration technique (EC) and 3) the crosspolar power technique (CP). A main conclusion of this study is that the 2 σ uncertainty of the EC Z_{dr} bias measurement is approximately 0.25 dB which exceeds the 0.1 dB specification requirement. The uncertainty is dominated by impedance mismatches. Reduced uncertainty could be achieved if meticulous vector power measurements were made that could quantify the inevitable impedance mismatches that occur but this is deemed to be impractical for operational radars. To estimate Z_{dr} bias to within 0.1 dB uncertainty, some sort of "end-to-end" measurement technique is needed such as vertical pointing data in light rain or the crosspolar power technique which uses sun measurement in conjunction with crosspolar power measurements. No power meters or other RF sources are required which give rise to unacceptable uncertainty levels.

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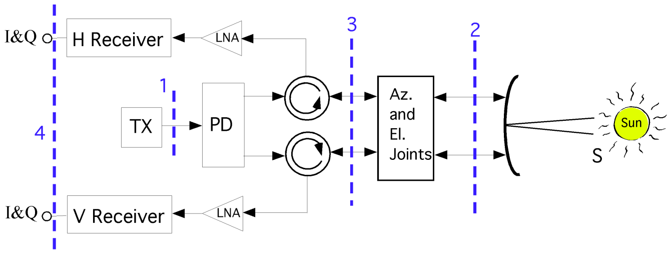

Figure 1: *A block diagram of a radar system for the EC method.*

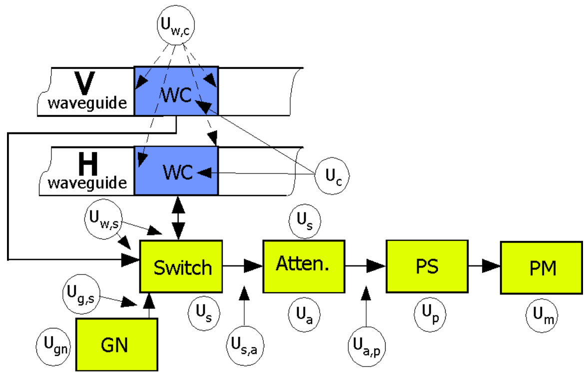

Figure 2: *A block diagram of a differential waveguide power measurement. "WC" is waveguide coupler, "Atten." is an attenuator, "PS" is a power sensor, "PM" is a power meter and "GN" is a generator. The circles represent the various uncertainties. The double subscripted uncertainties are various impedance mismatches between the devices. A list of the uncertainties with definitions is given in Table 1*

Unc.	Description	dB
U_s	Waveguide coupling factor	0.1
U_s	Switch	0.01
U_a	Attenuator	0.08
U_p	Power sensor (RF to DC)	0.09
U_m	Power meter	0.05
$U_{w,c}$	Impedance mismatch between waveguide coupler and waveguide	0.06
$U_{c,s}$	Impedance mismatch between waveguide coupler and switch	0.06
$U_{s,a}$	Impedance mismatch between switch and attenuator	0.06
$U_{g,s}$	Impedance mismatch between generator and switch	0.06
U_{gn}	generator noise	0.02
U_{gn}	Sun source & processing	0.05

Table 1: *A list of 2σuncertainties for the differential power measurement shown in Fig. 2 .*

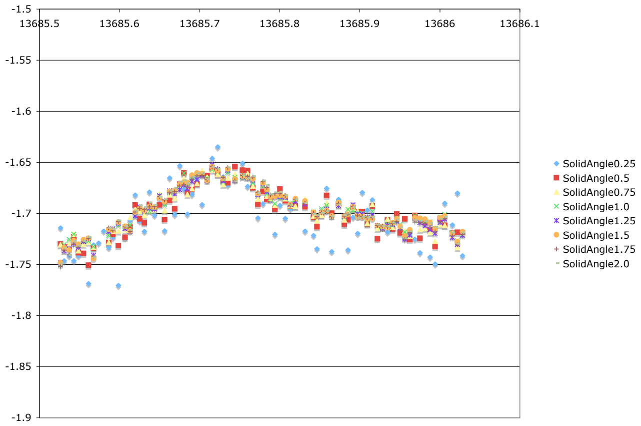

Figure 3: *S_1S2 sun scan measurements over an entire day for various solid angles of integration.*

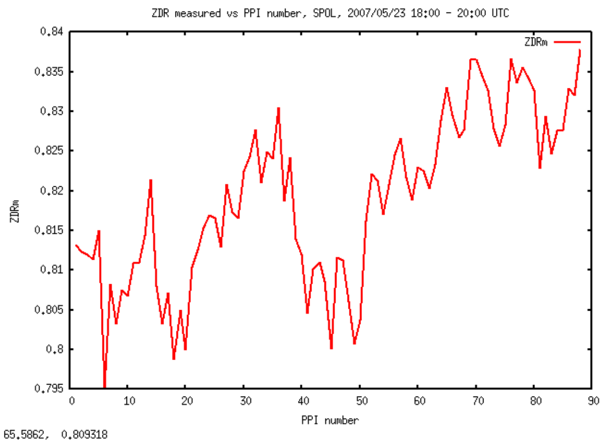

Figure 4: *Z_{dr} biases calculated from 90 consecutive 360° vertical pointing scans. There is one estimated bias per 360° scan.*

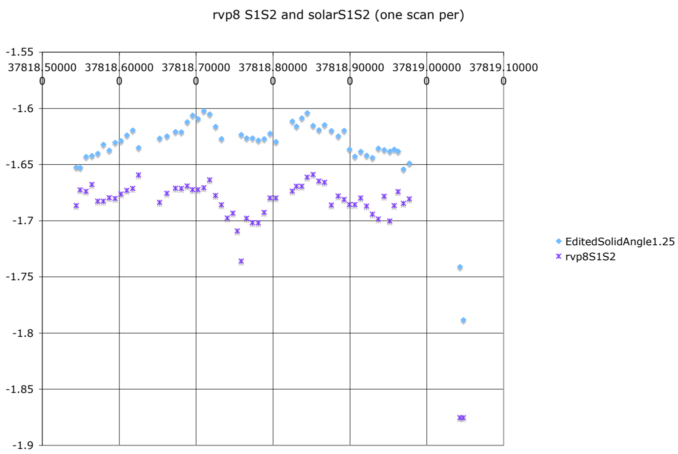

Figure 5: *A comparison of Z_{dr} bias monitoring via test pulse injection (purple markers) and sun scans (blue markers). The horizontal axis is in Unix days and the vertical axis is in dB. Data was gathered on 17 July 2007.*

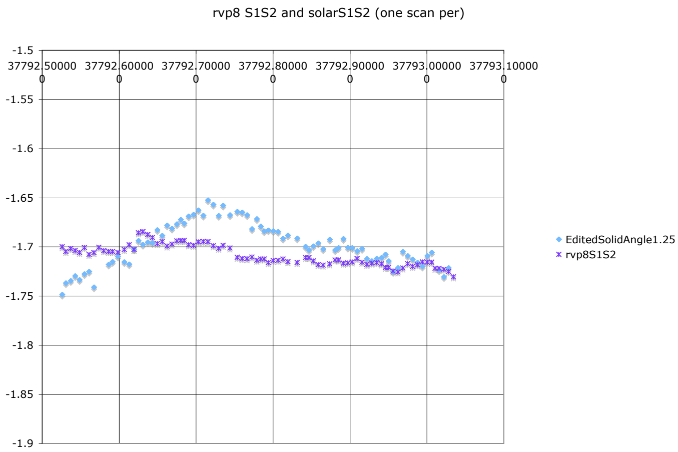

Figure 6: *A comparison of Z_{dr} bias monitoring via test pulse injection (purple markers) and sun scans (blue markers). The horizontal axis is in Unix days and the vertical axis is in dB. Data was gathered on 21 June 2007*