8A.5 CALIBRATION OF Z_{dr} FOR NEXRAD

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1. INTRODUCTION

The United States National Weather Service (NWS) network of NEXRAD radars is scheduled to be upgraded to dual polarization with in the next few years. The NEXRAD radars will simultaneously transmit H (horizontal) and V (vertical) polarization and receive both H and V polarizations. This will allow for the measurement of the dual polarization parameters of Z_{dr} (differential reflectivity) and ϕ_{dp} (copolar differential phase). These new parameters will provide for more accurate rain rate estimates, hail identification and improved radar echo identification in general. Important to this improvement is ascertaining and maintaining radar instrument calibration. In particular, to minimize rainfall estimation error, measurement uncertainty of Z_{dr} should be about 0.1 dB. NCAR (National Center for Atmospheric Research) has been tasked by the NWS (National Weather Service) to determine the uncertainty of various methods to calibrate Z_{dr} using S-Pol, NCAR's S-band polarimetric radar.

One of the most accepted ways to calibrate Z_{dr} is the "vertical pointing" method. Since the orientation distribution of precipitation particles when viewed vertically in the plane of polarization is uniform random, the intrinsic value of Z_{dr} is 0 dB for such scatterers. Data gathered while the radar antenna is pointing vertically in light rain provides an external measure of near-zero Z_{dr} (Bringi and Chandrasekar, 2001). Histograms of Z_{dr} from such precipitation should have intrinsic average values of 0 dB and this is how S-Pol Z_{dr} is calibrated. Unfortunately, the NEXRADs cannot point vertically and therefore can not use the vertical pointing approach for Z_{dr} calibration. A second way to calibrate Z_{dr} for the NEXRADs is with an "engineering" calibration approach based on the following instrument model (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 bases. Transmit powers are also monitored. By combining the passive and active calibration measurements, Z_{dr} can be calibrated. The uncertainty of the engineering approach may be estimated from a combination of prior experience (type B evaluation) and on repeated trials (type A evaluation) (Taylor and Kuyatt, 1994).

A third method for Z_{dr} calibration makes use of the principle of radar reciprocity which states that two crosspolar members of the radar scattering matrix are equal, i.e, $S_{hv} = S_{vh}$ (Saxon, 1955). Practically, this means that the crosspolar powers measured with a fast alternating H-V polarization transmit radar should be equal if the H and V transmit powers are equal. This is termed the "crosspolar power" approach for Z_{dr} calibration. This method is mathematically exact (no assumptions other than reciprocity) and has been demonstrated previously with CSU-CHILL radar data (Hubbert et al., 2003). Operationally, the NEXRADs will transmit H and V polarization simultaneously and thus this 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 when a fast H and V alternating polarization switch is used. However, it is hypothesized that the average crosspolar powers from ground clutter targets from consecutive PPI surveillance scans at H and V polarization should be equal and this measurement can be used to calibrate Z_{dr}. This hypothesis has not been previously demonstrated with experimental data and in this paper we do so with S-Pol data. Results of the three calibration approaches are compared to analyze uncertainty and instrument contribution to the Z_{dr} calibration accuracy. This NCAR Z_{dr} calibration experiment is ongoing and we show preliminary results that indicate the like uncertainty of each method using experimental data from NCAR's S-Pol.

2. ENGINEERING CALIBRATION APPROACH

The engineering calibration method breaks the calibration task into two parts: 1) measurement of the gain of the static portion of the of the signal path via injected signals, passive solar radiation and power meters, and 2) monitoring of the dynamic portion of the received signal path via the injection of test pulses. The static portion of the signal path are the wave guides, antenna and dish. It is hypothesized that these signals can be measured with enough certainty to calibrate Z_{dr} to 0.1 dB. The active or time varying portion of the receiver chain is from the circulators through the I&Q digitizer. The active portion of the receiver chain likely needs to be monitored on a volume scan to volume scan basis using test pulses injected at the end of the radar rays.

A simplified block diagram of a dual polarized radar is given in Fig. 1. Shown are the signal paths for the H and V channels and four test points. By using a hot and cold noise source, a Y-factor method may be employed to determine the differential atten-

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Waveguide Coupler Specifications	
Freq. Band	2.7–3.0 Ghz
Coupling	44.2 $\pm$0.3 dB
Coupling Variation	$\pm$0.2 dB
Coupling Calibration	$\pm$0.2 dB
Directivity	25 dBm
Insertion Loss	0.05 dB maximum
SWR Primary	1.05
SWR Secondary	1.10

Table 1: Specification for WSR-88D waveguide coupler.

uation from test point 2 to test point 3. Using sun microwave radiation, the differential gain from the antenna to point 3 and to the I&Q digitizer (point 4) can be found. The differential transmitted power can be measured at test point 3. In order to to determine the linearity of the receiver chain, calibrated test signals are injected at test point 3 and the resultant power is measured at the I&Q samples (test point 4).

Using these measurements, at least in principle, the differential gain of the entire radar system is known and Z_{dr} can be calibrated. However, in practice it is difficult to determine the measurement error. For example, waveguide couplers represent a crucial component in the absolute measurement of radio frequency (RF) power. Consider the current WSR-88D elevation arm coupler (see rotary joints in Fig. 1) which is specified in Table 1. Though the impedance match specification (SWR) appears within acceptable limits for this application, the coupling factor accuracy specification ($\pm$0.3 dB) is larger than the desired 0.1 dB Z_{dr} uncertainty. The selection of waveguide coupler and the manner n which the coupler assemblies are calibrated may be evaluated by standard methods.

Consider the problem of measuring the power flowing inside a waveguide. To do so requires

1. Waveguide coupler
2. Calibrated bolometer power sensor
3. Precision attenuator, adapters and cables
4. Calibrated power meter instrument
5. Procedures and recording

For each component a connection of some sort needs to be made and for each connection there will be an impedance mismatch that will give rise to unknown reflections (unless this is measured with a high quality network analyzer). Addition uncertainties are associated with the coupler, the bolometer and the power meter instrument. Uncertainty budget analysis for the components used with S-Pol indicates that waveguide absolute power measurements in the field (for example with the HP436A instrument and HP8481A sensor) have a combined uncertainty of about 0.26 dB and the uncertainty of ratio (differential) measurements of about 0.21 dB. If instrumentation corrections are made, the these 2-sigma numbers may be reduced to 0.12 dB and 0.05 dB respectively. The waveguide coupler must be of high quality and have side arm coupling factor of approximately 40 dB and high directivity better than 30 dB. The forward port's coupling factor must be known and maintained to 0.05 dB, and the equivalent mismatch of the side arm port and of the power meter must be known and maintained to within 0.02dB. Whether this is practically possible at a reasonable cost will be determined in the coming months via implementation of the ATE (Automated Test Equipment) described next.

Mechanical processes and procedures such as attaching and re-attaching cables, couplers and meters introduce variability to the engineering approach. To evaluate influence effects, independent, traceable Automatic Test Equipment (ATE) will be built into S-Pol to measure test point signals, inject test signals and monitor environmental variables such as temperature along the signal path. Inside the ATE is a control computer, wideband power meter, signal generator, noise sources, attenuators and an RF switching matrix. Appropriate control connections are established between the ATE and the digital receiver, transmitter, and antenna pedestal. The ATE records the process measurements and the radar scans of the sun. Over a period of months a data base will be created so that a statistical analysis of the calibration measurements will ultimately lead to an estimate of the uncertainty of the engineering Z_{dr} calibration method. Data from the vertical pointing approach will be used with ATE data to evaluate the engineering approach. The engineering method is routinely employed at both CSU-CHILL and S-Pol, however, it typically has been found that a systematic Z_{dr} offset persists which must be corrected using vertical pointing data in light rain.

3. CROSSPOLAR POWER APPROACH

The crosspolar power method has been reported in (Hubbert et al., 2003) where the technique is successfully applied to the CSU-CHILL radar data. The technique uses the property of radar reciprocity (Saxon 1955) which states that the off diagonal terms of the radar scattering matrix, S_{hv}, S_{vh}, are equal. Using this fact, the authors of (Hubbert et al., 2003) derive the calibration equation

$$Z_{dr}^{cal} = Z_{dr}^{m} S^2 \frac{P_{xv}}{P_{xh}} \tag{1}$$

where Z_{dr}^{cal} is calibrated Z_{dr}, Z_{dr}^{m} is measured Z_{dr}, S is the ratio of the V and H power from sun measurements, and P_{xh}, P_{xv} are the average H and V crosspolar powers, respectively. The crosspolar Z_{dr} calibration approach is attractive since waveguide couplers, signal sources or power meters are not required thus eliminating these uncertainty components of the engineering calibration approach.

Recently, the crosspolar power technique was applied to Z_{dr} calibration for S-Pol for data from the field experiment RICO (Rain in Cumulus over the Ocean) taking place in Barbuda, West Indies in the Winter of 2004/2005 . Since the tropical clouds were very shallow, the vertical pointing technique for Z_{dr} calibration was unreliable, i.e., there was not enough precipitation echo far enough away from the antenna to avoid near field effect and to avoid transient effects from the transmit pulse. 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:

$$Z_{dr}^{cal} = Z_{dr}^{m} S_1 S_2 \frac{P_{xv}}{P_{xh}} \tag{2}$$

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 (Hubbert et al., 2003).

Figure 2 shows data from RICO on 22 Jan. 2005. The four panels show Z (reflectivity), velocity, Z_{dr} measured and calibrated Z_{dr}. The resultant Z_{dr} correction was 0.36 dB. There are a few light precipitation cells and some Bragg scattering is also evident (at the 15 km range ring, for example). In the figure, the corrected Z_{dr} appears to have a mean of 0 dB and indeed histogram plots of Z_{dr} were made from very light precipitation regions and Bragg scattering regions and the mode was 0 dB.

4. Z_{dr} CALIBRATION FOR NEXRAD

Since NEXRAD will use simultaneous H and V polarization transmission to achieve dual polarization (Doviak et al., 2000), the Z_{dr} calibration procedure will need to be modified if the crosspolar power technique is to be used. With fast alternating H and V transmission, the resulting H and V crosspolar powers can be obtained essentially simultaneously. This is not the case for simultaneous H and V transmission: the crosspolar powers are not available! Slow mechanical wave guide switches will be needed that will allow only H polarization or V polarization to be transmitted. Reliable, stable ground clutter targets will need to be identified so that the crosspolar power from such targets can still be equated even though the crosspolar power measurements may be separated by tens of seconds.

Additionally, NEXRAD by necessity will need to employ H and V receivers instead of copolar and crosspolar receivers. Since the H and V copolar signals, P_{co}^{H}, P_{co}^{V}, that yield $Z_{dr} = 10 \log 10[P_{co}^{H}/P_{co}^{V}]$ are processed by separate receiver channels, there will likely be significant differential fluctuation of these measured powers (on the order of 0.05 dB is enough to bias Z_{dr} significantly) over time periods of tens of minutes. Thus, for either calibration technique, the receiver chain will need to be monitored. This may be accomplish by several means. One way is to repeatedly make sun scans. However, the sun is not be available at all times: during the night, shadowed by precipitation, or beyond the scanning capabilities of the radar. Another technique would be to again use the crosspolar measurements themselves. This would require that the radar periodically make scans using transmit only H and only V. This obviously takes time and would cause wear on the mechanical switches. The third option, as mentioned above, is to inject test pulses into the receiver (before the low noise amplifiers), observe the I&Q output and in this way monitor any drift of the H and V receivers' gains. For the crosspolar power method, the H and V gain curves of receiver chains are recorded when the initial calibration is accomplished. The difference of the two curves gives the Z_{dr} bias base-line. Any deviation from this base line curve found from subsequent test pulse measurements indicates a drift or bias in Z_{dr} and will need to be corrected.

5. UNCERTAINTY ANALYSIS

Calibration is the process of adjusting an instrument or compiling a deviation chart so that its reading can be correlated to the actual value being measured. Uncertainty of measurement arises from incomplete knowledge, control, understanding, definition, and reading of the parameters by processes influencing the measurement. Influence effects, such as temperature, humidity, frequency, mechanical stresses, path variations, and mismatches affect the result of measurements. Uncertainty basically represents the standard deviation of a set of measurements and is primarily quantified by repetition (sometimes called the frequentist approach) under controlled test conditions, and secondarily by experience (sometimes called the Bayesian approach). Errors can be categorized (modeled), for convenience of treatment, as long-term bias, short-term bias, and random measurement errors. All errors may be considered random variables, so an uncertainty specification is incomplete without a confidence interval (Taylor and Kuyatt, 1994). These considerations have motivated the design of the ATE and analysis procedures.

Figure 3 is provided as a realistic example of a long-term temporal trend of engineering measurements. S-Pol's antenna gain estimates from sun flux used essentially the same procedures over a period of six years. Gain is measured from the reference coupler through the antenna to the far field. It is a factor in the weather radar equation, its error combining with other errors. The evident temporal variation in Fig. 3 includes, at a minimum, changes in true value from antenna reassembly and short-term measurement errors. However, long-term bias effects are undoubtedly at work but hard to quantify at the tenths-of-decibel-level. The important aspect of error decomposition is difficult, especially without intermediate readings and redundant measurements. However, the results show that the overall standard deviation of the set of H-channel system gain estimates is roughly 0.36 dB, and that for the V-channel 0.45 dB. Regressing the V-channel estimates on the H-channel estimates (figure not given), a standard deviation of 0.29 dB is found. These estimates by themselves appear to bound the uncertainty but do not adequately portray the underlying accuracy of the parameter for a specific field experiment.

Use of the ATE for calibration measurements permits more complete decomposition of Z_{dr} uncertainty and will hopefully improve the understanding of measurement process. Whether or not the uncertainty can be reduced to less than 0.1 dB is currently being evaluated using S-Pol as a test bed for NEXRAD.

6. 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.

6.1 *Sun Measurements*

The sun is scanned passively by centering a moving 8° horizontal by 4° vertical box on the sun. The scan rate is 0.5°s° and the elevation steps are 0.2°. After compensating for for the sun's movement, the data can be used to construct pseudo antenna patterns. To get the true antenna pattern one would need to deconvolve the sun illumination pattern. Figures 4, 5 and 6 show the H, V and the H to V ratio antenna patterns. The H and V "pseudo" patterns are very well matched across their 1° beam width but there is some difference outside these limits. To obtain non-biased Z_{dr} measurements of precipitation, the antenna patterns must be well matched. Figure 7 shows the correlation between the measured H and V antenna patterns. Since the sun's radiation is unpolarized (there can be exceptions to this during high solar activity when the radiation can be circularly polarized) the expected correlation between the two patterns is 0. Figure 7 shows that the correlation over the center of the antenna patterns is very low but there are four lobes of higher correlation. These four lobes are caused by the depolarization of the electric field by the four dish support struts.

Figure 8 shows a histogram of a set of 32-point, H-channel, sun-bore-sighted beam powers possessing a sample standard deviation of 1.04 dB. If repeatability of 0.01 dB fractional standard deviation is desired, then about 13,800 samples should be used to compute the overall mean. This amount of data is easily obtained from sun scans over a few minutes

On 8 August 2006, 10 consecutive "box scans" of the sun were made. The highest power points were averaged for each box scan in order to estimate S_1 and S_2 for the crosspolar power calibration technique. The calculated $S_1 S_2$ numbers are (linear scale)

0.7760 0.7789 0.7854 0.7773 0.7843
0.7713 0.7795 0.7745 0.7812 0.7767

The mean is 0.7885 with a standard deviation of 0.0041. The fractional standard deviation is 0.023dB and the 2 sigma uncertainty of the 0.7885 estimate is 0.007 dB. This indicates that the uncertainty of the $S_1 S_2$ product is well within the 0.1 dB uncertainty desired for NEXRAD Z_{dr} measurements. This assumes a standard sun (i.e., no unusual sun activity that may bias the measurements, though very unlikely. If the sun radiation is polarized, it is circular and this would divide evenly between the H and V channels).

6.2 *Vertical Pointing Measurements*

Vertical pointing measurements in rain have intrinsic Z_{dr} of 0 dB. A measured non-zero value is considered the system Z_{dr} bias. Six consecutive volume scans were made while S-Pol was vertically pointing in light rain on 31 August 2006. A Z_{dr} bias was calculated for each 360 degree revolution of the dish over a 1 km range between 4 and 9 km from the radar. This yields 30 Z_{dr} mean bias estimations and each are a result of about 3,400 individual 64 point Z_{dr} estimates. The total mean is 0.712 dB and the fractional standard deviation is 0.019 dB. The two sigma uncertainty of the 0.712 dB estimate is 0.007 dB

6.3 *Crosspolar Power Data*

The crosspolar power technique for Z_{dr} calibration requires the accurate measurement of two crosspolar power ratios. On 31 August 2006 several volume scans of storms cells were made by S-Pol in fast alternating H and V mode. The number of samples per gate is 64 and the scan rate was $12°\mathrm{s}^{-1}$. Data were averaged over 14 separate PPI scans at angles above 2 degrees. Clutter returns are filtered out requiring the absolute radial velocity to exceed $2\,\mathrm{m\,s}^{-1}$. However, clutter returns can also be used since clutter targets should also be reciprocal scatterers and thus can be used for the Z_{dr} calibrations. The power ratios of P_{xh}/P_{xv} are, in dB:

-0.312 -0.335 -0.326 -0.341 -0.347 -0.357 -0.347
-0.263 -0.276 -0.304 -0.337 -0.319 -0.343 -0.319

The mean is -.323 dB and the fractional standard deviation is .026 dB so that the 95% confidence is 0.046 dB for the individual mean estimates. However the, the mean estimate of -0.323 dB is more reliable and the two standard deviation fractional uncertainty is 0.014 dB.

As mentioned before, the NEXRAD dual polarization system will use simultaneous H and V transmission and reception. Thus, near simultaneous samples of H and V crosspolar returns will not be available. Two slow waveguide switches can be used so that transmit H, transmit V or simultaneous H and V transmit modes are possible. One technique for crosspolar power calibration 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 can be paired and used for calibration. On 18 October 2006 this cross polarization approach was tested for the NEXRAD application. Elevation scan data was 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 the fast alternating mode, $P_{xh}/P_{xv} = 0.404$ dB and for the slow switch mode $P_{xh}/P_{xv} = 0.373$ dB. These results suggest that the cross polarization approach are amenable to NEXRAD.

6.4 *Comparison of Vertical Pointing and Crosspolar Power Techniques*

The Z_{dr} calibration factor or bias of the S-Pol system should be the same whether calculated from vertical pointing (VP) data or using the crosspolar power techniques. The Z_{dr} bias calculated above from VP data is 0.708 dB. This bias was also calculated using Eq.(2) from sun measurements and crosspolar power measurements, also gathered on 31 August 2006. $S_1 S_2$ was found to be -1.051dB while the crosspolar power ratio was -0.323 dB. This yields a Z_{dr} bias of -0.323 - -1.051 = 0.728 dB which is in excellent agreement with 0.712 dB.

7. SUMMARY AND CONCLUSIONS

NCAR is conducting an experiment for OS&T of NOAA to evaluate Z_{dr} calibration techniques for the WSR-88Ds using S-Pol, NCAR's S-band polarimetric radar. Three techniques for Z_{dr} calibration were investigated: 1) vertical pointing data in light rain, 2) engineering calibration and 3) the crosspolar power technique. Measurement and analyses were performed in order to quantify the uncertainty of the estimated calibration numbers and the measurement procedures that yield such uncertainty. The uncertainty of measurements can be separated into two categories: 1) systematic and 2) random. Though our work with S-Pol has had a large focus on systematic errors, this paper concentrates on the quantification of the random errors.

Vertical pointing (VP) measurements in light rain are widely regarded as the most accepted way to calibrate Z_{dr}. Measurements with S-Pol thus far show excellent agreement between the Z_{dr} bias found via VP measurements and the crosspolar power techniques. For the experimental data used here, both techniques yielded uncertainties well within the desired limit of 0.1 dB. Additionally, it was shown that the crosspolar power technique can successfully be employed on radar systems that achieve dual polarization measurement via simultaneous transmission of H and V polarizations as NEXRAD will do. In this case, a slow waveguide switch is used to gather alternate PPIs of transmit only H and transmit only V data. Using indexed beams, the crosspolar powers from the alternate PPIs was equated. This was done for ground clutter since the backscatter cross sections of many clutter targets should remain constant over periods of several minutes. Thus, these results showed that the crosspolar technique could be used with NEXRAD type radars.

Further evaluation of the engineering calibration technique awaits the completion of the Automated Test Equipment (ATE) system. The success of the engineering calibration technique will depend in part on precise measurement of the specifications for the waveguide couplers. The impedance mis-matches between the various connections will also need to be measured very accurately if Z_{dr} is to be calibrated to within 0.1 dB uncertainty.

Acknowledgment

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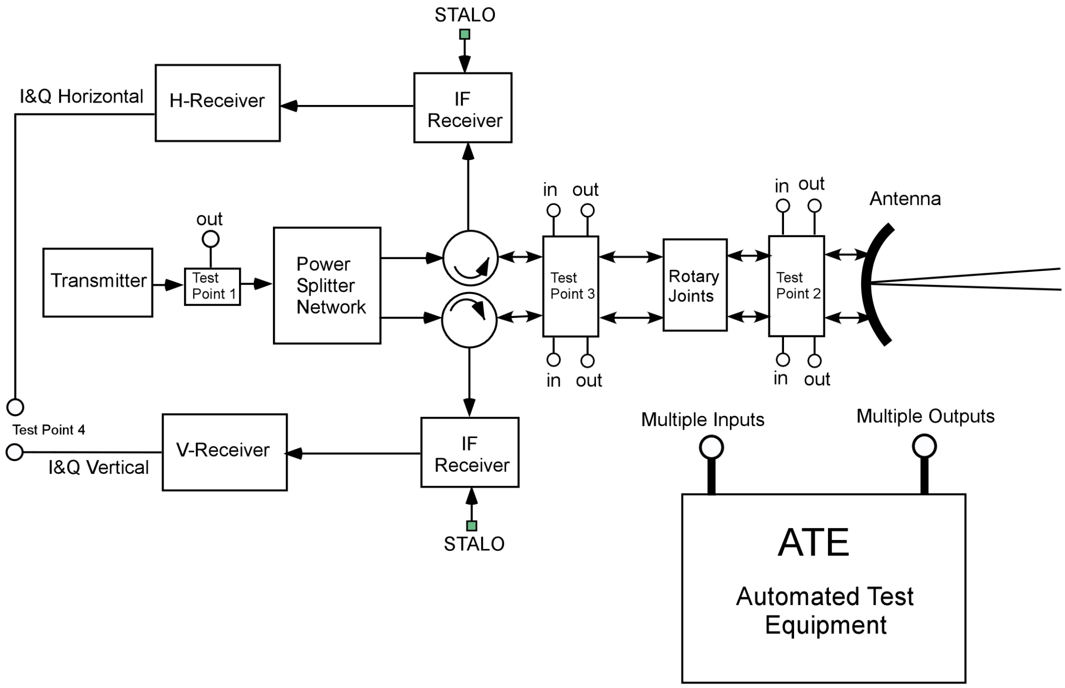

Figure 1: A block diagram of a radar system.

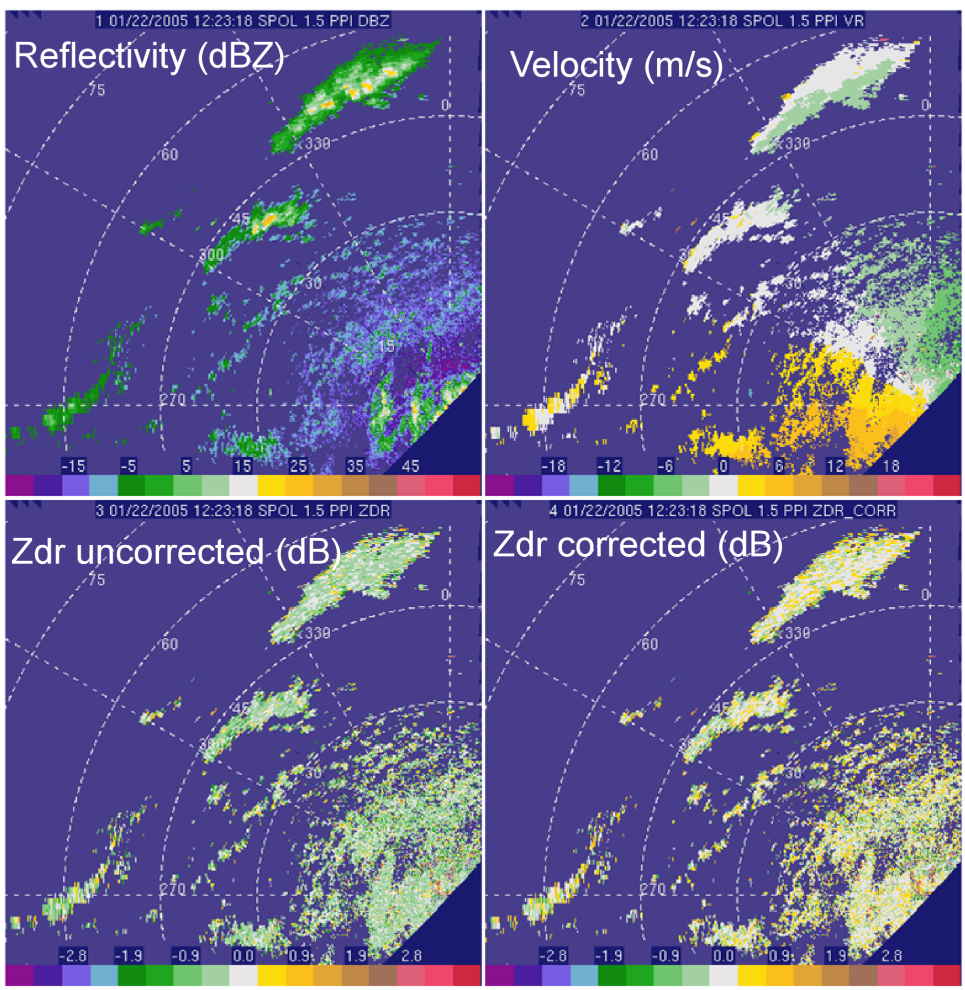

Figure 2: PPI data from S-Pol from the RICO Field Program.

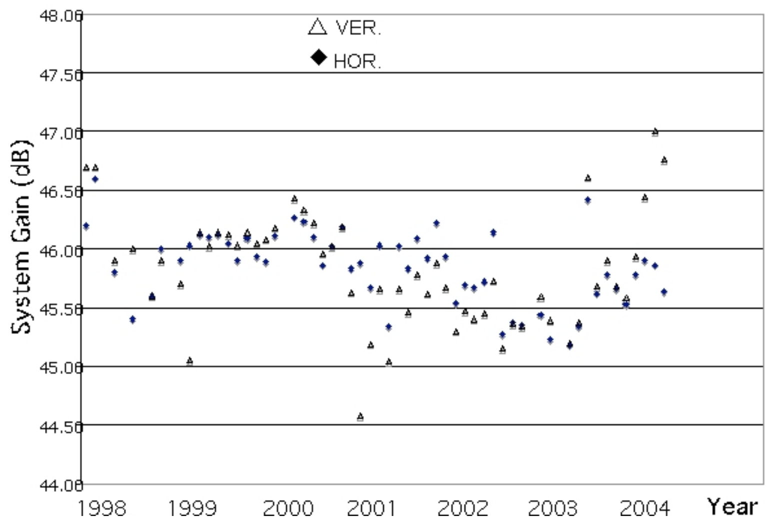

Figure 3: S-Pol copolar antenna gain estimates from sun flux over 6 years.

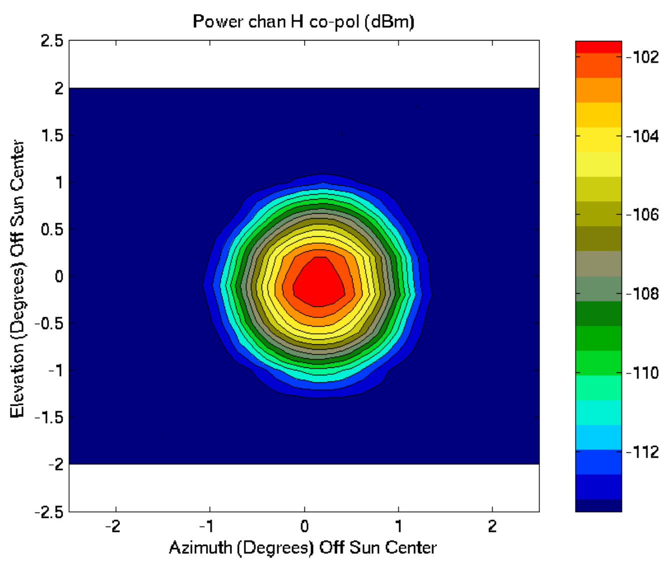

Figure 4: Pseudo H antenna pattern from sun measurements

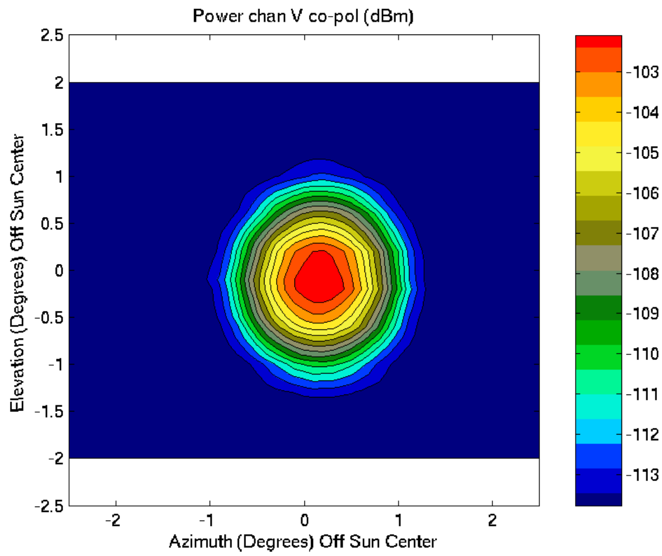

Figure 5: Pseudo V antenna pattern from sun measurements

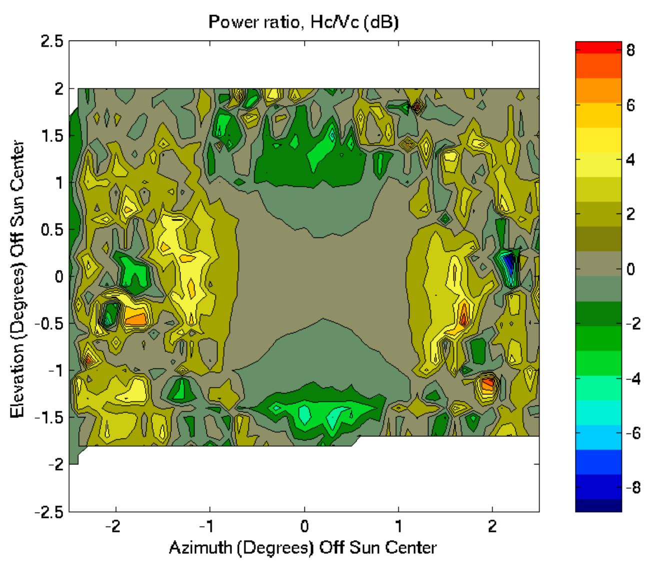

Figure 6: The ratio of H and V antenna patterns from Figs. 4 and 5.

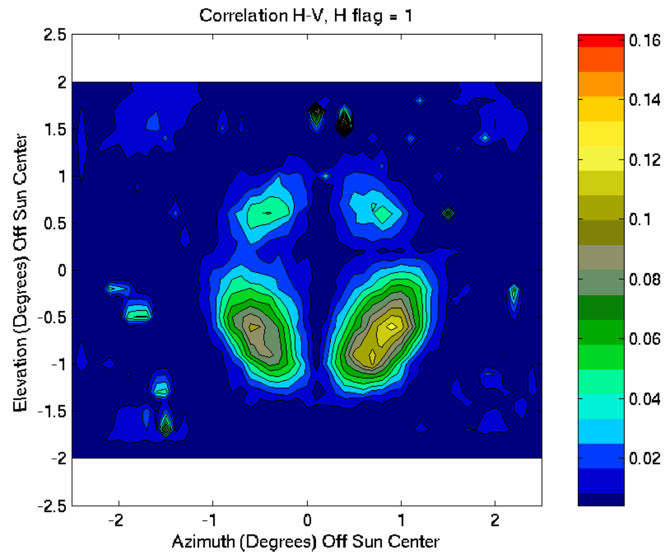

Figure 7: Correlation between the H and V antenna patterns of Figs. 4 and 5.

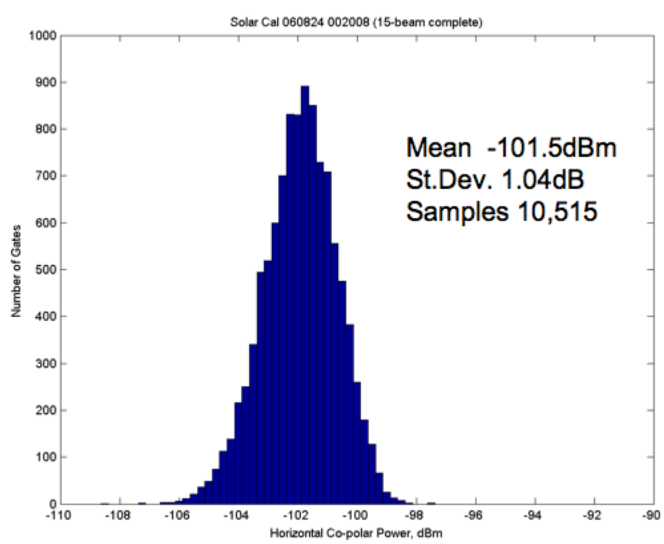

Figure 8: Histogram of 32 point integrated sun power measurements.