

Characteristics and Correction of NPOL During Periods of Wet Attenuation

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Abstract. NASA's polarimetric radar (NPOL), first deployed in 2001, utilizes a unique and ultra-modern flat panel antenna that was designed to increase portability and decrease wind-loading. However, through observation it has been noted that NPOL's transmitted and subsequently received RF signal is severely attenuated at times when the antenna becomes wet. The performance of NPOL during periods of wet attenuation after an evaluation of its calibration when dry is presented here. Correction techniques and results, including the use of polarimetric returns, are also discussed in an attempt to lessen the effects of the attenuation.

1. Introduction

The NASA polarimetric radar (NPOL) is a unique weather radar system that first became operational in 2001. Developed by a research team from NASA's Wallops Flight Facility, the radar has participated in three field campaigns to date and is scheduled again for deployment in the summers of 2005 and 2006.

NPOL utilizes an ultra-modern flat panel antenna that is fully portable and self-contained. A mesh-like antenna cuts down on wind loading and makes NPOL quickly deployable in any weather situation; including category 1 hurricanes.

Designed by the California-based Malibu Research, NPOL's Flat Parabolic Surface (FLAPS) antenna, although not physically parabolic, achieves the same function as typical parabolic antennas (Figure 1). Hundreds of specifically cut dipoles are imbedded in the antenna that act to create the same RF field as with a parabolic antenna. The radar system can operate continuously, and because of its dual polarized design can

measure rainfall amounts and more specifically the characteristics of the raindrops such as shape and size, as well as several other radar characteristics including Doppler velocity, differential reflectivity (ZDR) and specific differential phase (KDP), all of which lead to more accurate rainfall estimations.

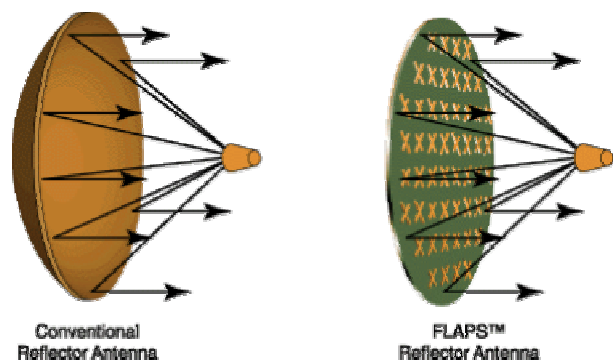


Figure 1. FLAPS schematic (taken from Malibu Research Home Page).

To support NPOL's transportability and ruggedness, the instrument lacks a radome; the thin fiberglass dome that surrounds the radar and protects it from the elements.

Because of this, NPOL's antenna is often forced to operate in the rain. Through observation, it has been noted that when subjected to rain and a subsequent wet antenna, NPOL does not perform as well as is anticipated; the transmitted power is evidently not received at the expected intensities, severely inhibiting the performance of NPOL. This power loss is easily seen in the reflectivity field of a radar. The image on the left of Figure 2 is a radar plan position indicator (PPI) showing the reflectivity field as observed by NPOL when the antenna is dry, and the image on the right is of a PPI just 15 minutes later when the antenna is wet. Placed side by side, it is easy to see the extent of the power loss when the antenna is wet.

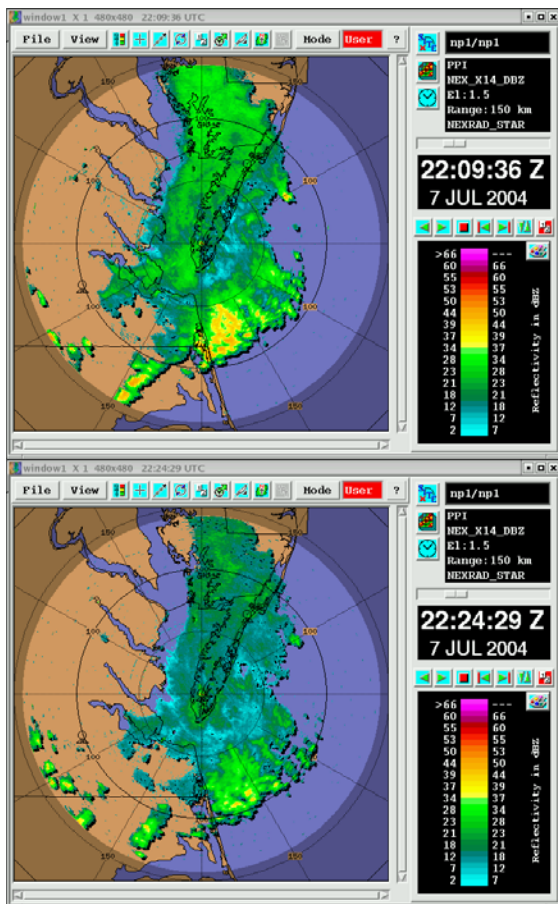


Figure 2. Reflectivity PPIs of a dry NPOL (left), and a wet NPOL (right); an example of wet antenna attenuation.

Such loss of signal is referred to as attenuation, and is the result of the radar's electromagnetic radiation passing through any medium. The amount of attenuation depends on the kind of material present and its density (Rinehart, 1997). Several common sources of attenuation of a radar signal include atmospheric attenuation caused by composition of the atmosphere, clouds, rain, snow and even hail. Rinehart in his 1997 publication "Radar for Meteorologists" provides a further explanation of causes and amounts of attenuation. Similarly, loss of signal due to a wet radome is small but possible with systems that employ a radome, but not to the degree that is observed by NPOL when its antenna is fully saturated.

The goal of this study is to thoroughly characterize NPOL's antenna during periods of saturation and present possible solutions to the issue. Fortunately, NPOL is surrounded by several other weather radars that are available for comparison. Using these radars, an evaluation of NPOL's performance, while both dry and wet, will be presented and followed by methods employed to correct the problem and their initial results.

2. Characterization of NPOL's performance

a. Background

Rain gauge networks have been one of the most accepted standards of rainfall measurements made by weather radars (Sachidananda and Zrnice, 1987). However, there was not an adequate rain gauge network in place to sufficiently compare NPOL measurements for the duration of the sample collection. As mentioned, there exists several operational radars within a close enough proximity of NPOL to adequately make comparisons. Two NASA operated radars, the Tropical Ocean-Global Atmosphere (TOGA) and the Space Range Radar (SPANDAR) stationed out of Wallops Island, VA, and a National Weather Service

radar out of Wakefield, VA (KAKQ) complimented each other to compose an extensive dataset in which to compare NPOL. Figure 3 provides a map of the coverage area by NPOL and its neighboring radars.

The comparison procedure began by first separating NPOL scans with a wet antenna from those with a dry antenna. Matching scans from KAKQ, SPAN and TOGA were subsequently collected. Once a set of matching times from all available radars was acquired, comparisons of radar reflectivity factor values (or simply reflectivity) were made. This was performed by first converting all radar data to a common Cartesian grid from the normal polar grid, using a program created by Paul A. Kucera from the University of North Dakota. The new grid retrieves values from a constant height of 2 km over an area covered by the each radar's 150 km range. Figure 3 shows an example grid of the radar reflectivity observed by NPOL.

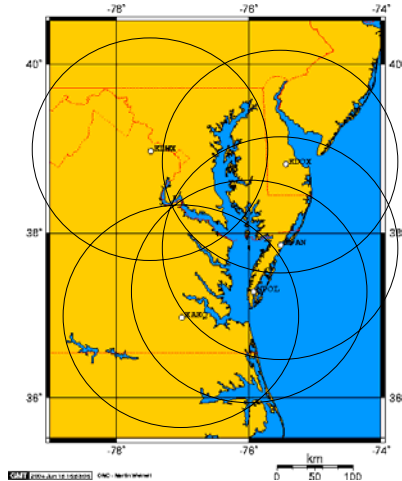


Figure 3. Area coverage of NPOL and surrounding radars. Rings indicate range values of 150 km.

Once 2km height grids are created, reflectivity values of NPOL can be compared to reflectivity values of KAKQ, SPANDAR, and TOGA for matching latitude and longitude locations, ensuring that the same volume of space is being sampled by each

radar. Several sets of comparisons were made through the course of this study and are presented in this paper.

b. NPOL dry comparisons

For years, SPANDAR has been a reliable source of well-calibrated radar data. Because of this, the most confident comparison results should come between NPOL and SPANDAR. However, because SPANDAR operations are relatively few and the time between scans is so long (on average one scan every 18 minutes), the number of comparisons between NPOL and SPANDAR is much fewer than for KAKQ which is continuously running, and TOGA which runs nearly simultaneously with NPOL. With that the case, matching scans of NPOL's dry antenna and KAKQ provided the largest dataset for comparisons. To ensure that KAKQ was first well-calibrated, a comparison with SPANDAR was performed.

1. Checking the Calibration of KAKQ

Reflectivity data in the overlap region of scans of matching times (less than 2 minutes apart) of KAKQ was compared to those of SPANDAR. The overlap region was chosen for comparison so that both radars are viewing regions of rain that are approximately the same distance away from each respective radar. Shrinking the comparison region to a smaller size that is equidistant from both radars might be a more ideal comparison, but the number of rain events that passed through this region is too small to give a representative sample. This smaller, equidistant region is employed in a different comparison described later in this paper.

At each matching latitude and longitude, reflectivity values for KAKQ and SPANDAR were extracted and compared to yield both an average bias, and average reflectivity. Average bias was computed using the following equation,

$$Bias_{avg} = \frac{\sum_{i=1}^n [Z_{KAKQ}(i) - Z_{SPANDAR}(i)]}{n}, \quad (1)$$

where n is the number of samples, Z_{KAKQ} is the radar reflectivity factor (Z) expressed in dBZ, observed by KAKQ and similarly $Z_{SPANDAR}$ is the radar reflectivity factor (dBZ) observed by SPANDAR. Average reflectivity is simply the mean of each reflectivity value in linear space (z) observed by either KAKQ or SPANDAR, and then converted back to a logarithmic value (dBZ). Mathematically, this process can be expressed as

$$Z_{avg} = 10 \log \left[\frac{\sum_{i=1}^n 10^{\left(\frac{Z(i)}{10}\right)}}{n} \right], \quad (2)$$

where Z_{avg} is the average reflectivity (in dBZ) of either the KAKQ or SPANDAR overlap region. Furthermore, average bias was often broken down into intervals according to the reflectivity of the validation radar; in this case SPANDAR. The bias values of Table 1 show that there is no dependence of Z_{KAKQ} on $Z_{SPANDAR}$, indicating both radars are fairly well calibrated over a wide range of reflectivities.

Table 1. KAKQ bias for 5 dB reflectivity intervals of SPANDAR.

SPAN (dBZ)	Bias (dB)
20-25	2.9
25-30	3.3
30-35	-0.4
35-40	-2.5
40-45	-1

Table 1 supports the data plotted in Figure 4 which plots SPANDAR's Z_{avg} vs. KAKQ's Z_{avg} for each matching radar scan. The average reflectivity observed in the overlap region by KAKQ is 29.4 dBZ, and 26.0 dBZ as observed by SPANDAR, indicating that on average KAKQ is overestimating SPANDAR reflectivity by 3.4 dB. 2. *Comparison of NPOL's dry antenna vs. KAKQ*

A similar analysis as described above was performed for matching radar scans of NPOL's dry antenna to KAKQ, showing how well calibrated the radar is during most operations. Enough matching scans and rainfall events were available with KAKQ for extraction of reflectivity over a region equidistant from both radars. This ensures that one radar will not be observing reflectivities at a farther range; reducing the possibility for error. Table 2, which represents the bias at 5 dB intervals, shows a dependence of bias on the intensity of the reflectivity being measured. That is, NPOL's bias increases

Table 2. Dry NPOL bias for 5 dB reflectivity intervals of KAKQ.

KAKQ (dBZ)	Bias (dB)
20-25	-2.7
25-30	-3.3
30-35	-4.3
35-40	-4.5
40-45	-6.3
45-50	-6.7
> 50	-7.8

for more intense rain events. This result is troublesome in that no reliable explanation for this phenomenon is available at this time. Figure 5a, the top-left plot of Figure 5 shows this dependence graphically. Scatter plots of average reflectivities, calculated for each radar scan, as well as the overall average reflectivities compose the remaining three plots of Figure 5. A plot is shown for all reflectivity values of a scan (Figure 5b, top-right), stratiform reflectivities (Figure 5c, bottom-left) and convective reflectivities (Figure 5d, bottom-right). A dependence of bias on reflectivity intensity is observed in the scatter plots as well; indicating that for light rainfall NPOL's measurements compare nicely to KAKQ's with an overall average reflectivity bias of only -0.1 dB. With regard to heavier rainfall, NPOL does not compare as well to KAKQ, showing a bias in the

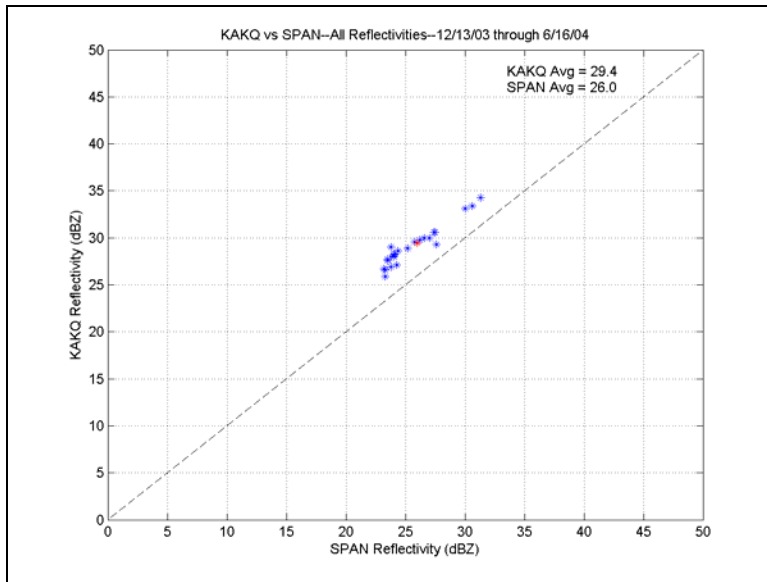


Figure 4. Scatter plot of KAKQ reflectivity values vs. SPANDAR reflectivity values for all reflectivities.

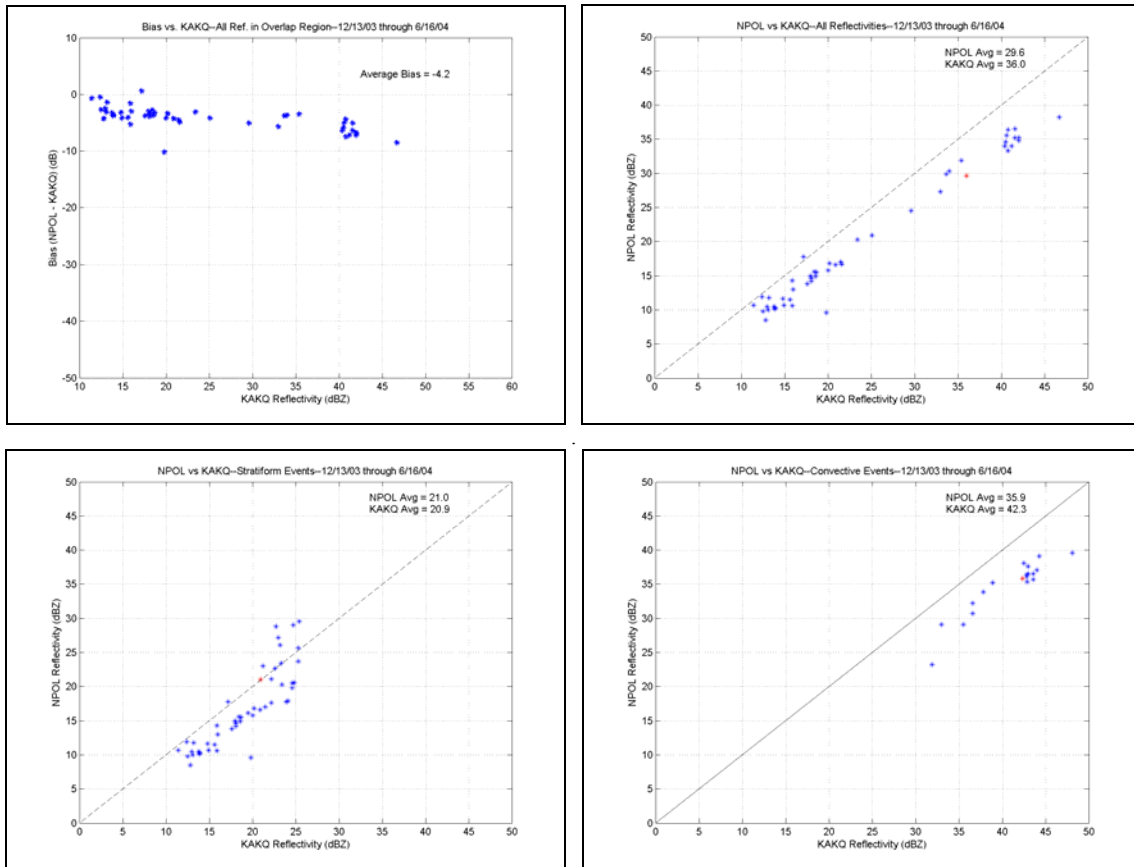


Figure 5. Difference plot of NPOL bias vs. KAKQ reflectivity (upper-left), and scatter plots of NPOL vs. KAKQ over range of all reflectivities (upper-right), stratiform reflectivities (lower-left), and convective reflectivities (lower-right).

overall average reflectivity of -6.4 dB. As for all reflectivities, this comparison yields an overall average reflectivity bias of again -6.4 dB. This analysis indicates that NPOL underestimates reflectivity intensities even when its antenna is dry.

c. NPOL wet comparisons

With the evaluation of NPOL’s performance while dry finished, its performance with a wet antenna can now be analyzed. Two methods were employed for this evaluation. The first of which compared reflectivity intensities in the overlap regions between each pair of radars, and the second compared intensities in the common overlap region shared by all four radars.

1. Comparison of overlap region for each pair of radars

In the same way that comparisons were made between a dry NPOL and KAKQ as discussed above, three more comparisons were made with KAKQ, SPANDAR and TOGA, but this time with NPOL radar scans indicating a wet antenna. Average biases for each 5 dB interval of validation radar (KAKQ, SPANDAR and TOGA) intensities are shown in Table 3, and graphically in Figure 6.

The trend noticed in the dry comparison of NPOL with KAKQ can be observed again in the comparisons with all three radars. However, the intensity is much greater. NPOL’s wet antenna causes biases to be severely attenuated, often times as much as 23 dB when observing reflectivities greater than 50 dBZ. Again, no explanation for this occurrence is known at this time.

2. Comparison of shared overlap region for all four radars

Possessing a large enough dataset, matching times, locations and regions for all four radars were collected. The sample area in this case is approximately the same

distance from each radar, ensuring that inaccuracies due to range dependence are minimal.

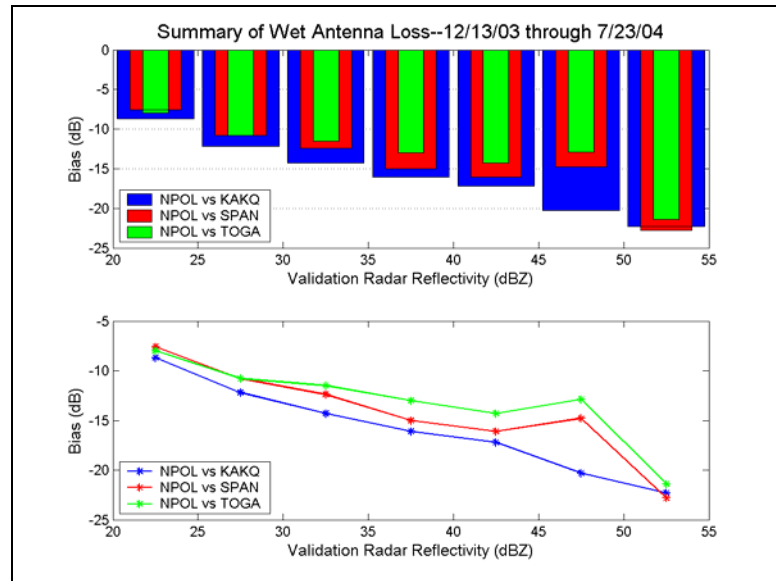


Figure 6. Plots of wet NPOL bias vs. KAKQ, SPANDAR and TOGA reflectivities.

While the average biases are not exactly the same because of the smaller sample area and number of matched scans, Figure 7a again shows a dependence on reflectivity intensity on the amount of attenuation observed by NPOL’s wet antenna. The average overall bias is still the largest when compared to KAKQ (-11.8 dB), and very large compared to SPANDAR (-9.9 dB) and TOGA (-8.7 dB). The scatter plots shown in Figure 7(b,c,d) graph reflectivity averages observed over the entire range of intensities, similar to Figure 5b. For each set of comparisons, total bias was again found. Compared to the validation radars, NPOL’s bias with KAKQ is -12.1 dB, while -10 dB with SPANDAR, and -7.8 dB with TOGA over the range of all intensities. For stratiform comparisons, NPOL’s bias with KAKQ is -8.3 dB, while -9.3 with SPANDAR, and -7.7 dB with TOGA. And for convective comparisons, NPOL’s bias with KAKQ is -11.5, while -10.1 dB with SPANDAR, and -8.1 dB with TOGA.

Table 3. Wet NPOL bias for 5 dB reflectivity intervals of KAKQ, SPANDAR and TOGA

Ref. (dBZ)	NPOL Bias (dB)		
	vs. KAKQ	vs. SPAND	vs. TOGA
20-25	-8.7	-7.6	-8
25-30	-12.2	-10.8	-10.8
30-35	-14.3	-12.4	-11.5
35-40	-16.1	-15	-13
40-45	-17.2	-16.1	-14.3
45-50	-20.3	-14.8	-12.9
> 50	-22.3	-22.8	-21.4

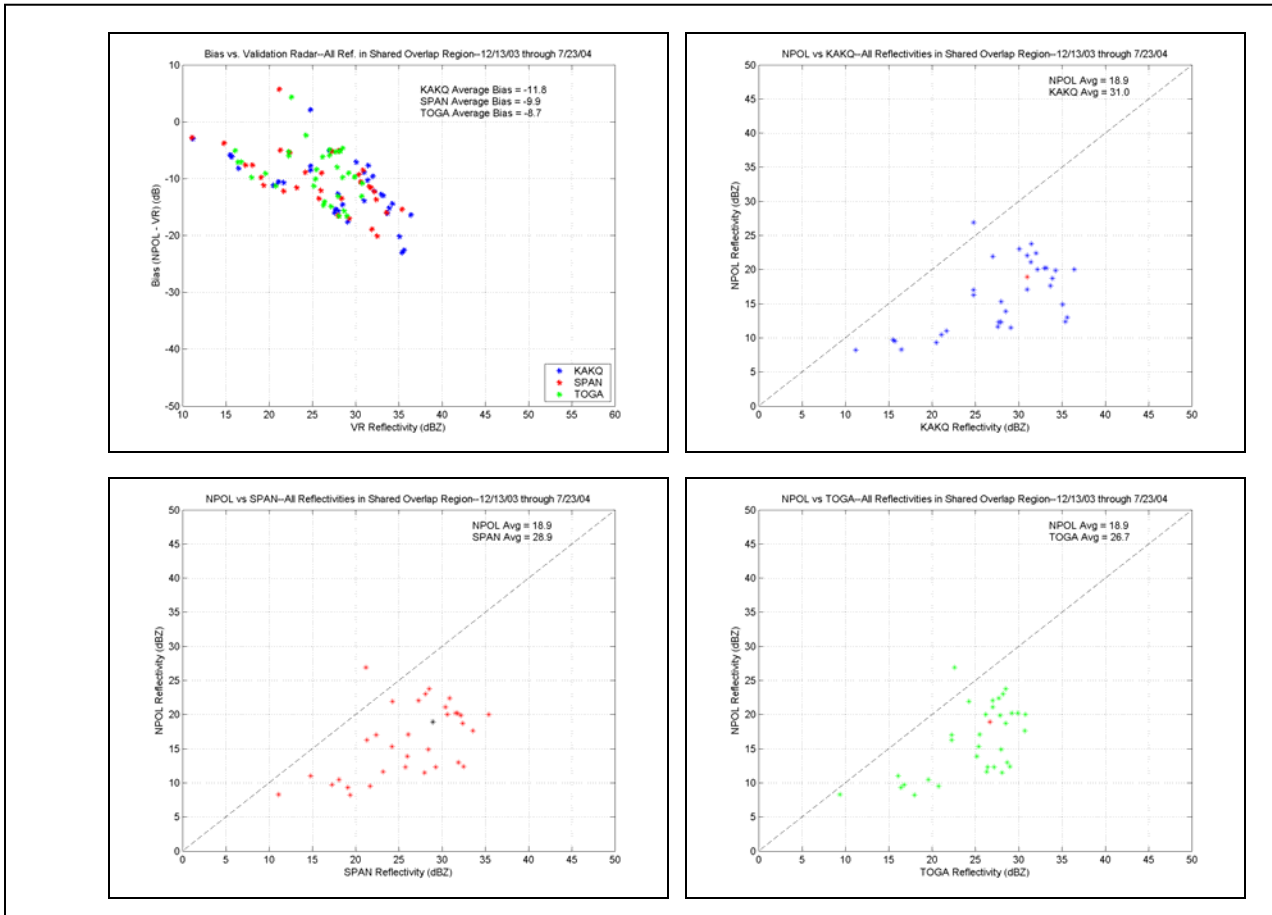


Figure 7. Difference plot of NPOL bias vs. KAKQ, SPANDAR and TOGA reflectivity (upper-left), and scatter plots over range of all reflectivities for NPOL vs. KAKQ (upper-right), NPOL vs. SPANDAR (lower-left), and NPOL vs. TOGA (lower-right).

3. Correction attempts

Correcting for NPOL's wet antenna presents a difficult task. Simply adding 10 or 12 dB to the reflectivity data will not due because it has been shown that the attenuation is not linear. Also, the power that is returned to the antenna is often attenuated so badly at times that the signal disappears; and knowing when to replace data where no signal is even recorded is impossible. Correction attempts using polarimetric data seem promising, but will not alleviate the problem completely. Regardless, attempts have been made to reduce the severity of NPOL's wet antenna issue and are discussed here.

a. Increasing NPOL's pulse width

One attempt at correcting NPOL's wet antenna issue was made by the TRMM Radar Group of Wallops Flight Facility. Pulse width, the amount of time corresponding to the duration of the radar transmitted pulse (Rinehart, 1997), is usually set to $0.8 \mu\text{s}$ for normal radar operations. Holding all other radar variables constant and increasing the pulse width should result in an increase in the returned power observed by NPOL as seen in the radar equation for distributed targets,

$$p_r = \frac{\pi^3 p_t g^2 \theta \phi h |k|^2 l z}{1024 \ln(2) \lambda^2 r^2}, \quad (3)$$

where h is pulse width, p_r is the power received and p_t is the power transmitted (Rinehart, 1997). Essentially all that is happening is that the reflectivities are being increased uniformly over the whole range of values. An analysis similar to the ones mentioned before shows the effectiveness of this solution.

An analysis of data occurring in the shared overlap region has been performed for all four radars at times when NPOL was operating at an increased pulse width of $2 \mu\text{s}$. As seen before, there is again a dependence of bias on reflectivity intensity, shown in Table

4. However, the overall average reflectivity bias did reduce significantly, but is still present. Compared to the $0.8 \mu\text{s}$ pulse width, NPOL's bias was effectively cut in half while using the longer pulse width for "all" and stratiform intensities. However it was not as effective for convective intensities.

b. Increasing NPOL's beamwidth

Another attempt at correcting NPOL's wet antenna issue involved changing what was believed to be its beamwidth. Prior to the change, NPOL calculated its reflectivities based on a beamwidth value of 1.4° in the horizontal and 1.3° in the vertical. Beamwidth is defined as the angular width of an antenna's main focus. It is measured as the angular width where the power density is one-half that on the axis of the beam (Rinehart, 1997). However, from several measurements of NPOL's beamwidth while both wet and dry, it was discovered that the 1.4° horizontal beamwidth (as well as the 1.3° vertical beamwidth, but the horizontal beamwidth is used for most calculations) was incorrect. Numerous attempts at gathering this beamwidth, including point target returns and using the sun as a target, indicated that dry NPOL was operating at a value closer to 1.6° or 1.7° , and 1.8° or 1.9° when wet. The likely cause for this is rainwater pooling up on the antenna and essentially acting as a prism, scattering both transmitted and received energy in several directions; decreasing the amount of energy returned and measured by NPOL.

Additional information that supports the claim that NPOL's beamwidth is incorrect can be found through mathematical equations. It has been shown that antenna gain (the measure of the effectiveness of an antenna) and beamwidth are related (Nelson, 1999),

$$G = \eta \left(\frac{\pi k}{\alpha} \right)^2, \quad (4)$$

where G is the antenna gain, η is the net antenna efficiency, α is beamwidth and k is a factor that depends on the shape of the reflector and the method of illumination. Inserting typical values for η and k of 0.55 and 70° (if α is in degrees) and rearranging for beamwidth, (4) becomes

$$\alpha = \sqrt{\frac{27,000}{G}}. \quad (5)$$

Using NPOL's previously measured gain of 39.5 dB (converted to linear space), (5) yields a beamwidth of 1.74° .

By increasing the beamwidth value used for radar calculations, the minimum detectable signal, dBZ_0 , is lowered as seen in the following set of equations,

$$dBZ_0 = 10 \log [Cr_0^2 I_0], \quad (6)$$

where C is a term referred to as the radar constant,

$$C = \frac{2.69 \times 10^{16} \lambda^2}{p_t u \theta \phi G^2} L_t, \quad (7)$$

and λ is the radar wavelength, ϕ is the vertical beamwidth, θ is the horizontal beamwidth and L_t is the transmit loss. NPOL's operating value of I_0 , a term referring to the minimum detectable signal in power measurements (in mW) is usually determined by a separate calibration procedure. Increasing both the vertical and horizontal beamwidth in (6) and (7) results in a decrease in dBZ_0 by approximately 4 dB. That is, NPOL will be able to receive and process the weaker signals that are often perceived due to NPOL's wet antenna.

At the time this paper was written, NPOL had only operated for one day at the increased beamwidth value of 1.6 dB. While the antenna did not get wet, the analysis results for a comparison with KAKQ are

presented here. The average reflectivity bias over the range of all reflectivity intensities was found to be -6.8 dB, -1.2 dB for stratiform reflectivities, and -7.1 dB convective reflectivities. Compared to results from the dry analysis performed in the entire NPOL/KAKQ overlap region, these new average reflectivities show little effect on bias. However, it must be noted that this analysis was performed for only one day of operations and thus the sample size may not be big enough to yet make generalizations. Further analysis needs to be performed in the future to adequately make a conclusion of how effective this solution is.

c. Correcting for attenuation using polarimetric measurements

Ryzhkov and Zrnice (1996) have pointed out that specific differential phase (K_{DP}) has several advantages to reflectivity factor (Z) for rainfall measurement, mostly because of the fact that Z is obtained from returned power, it is prone to calibration errors, attenuation by rain and radome and suffers from beam blockage. K_{DP} is immune to these factors. Meischner (2004) provides a well-rounded description of this parameter, which in brief describes K_{DP} to be the rate of change of differential phase (the difference of phase between the vertical and horizontal polarized returns of a polarized radar signal) with range.

As mentioned above, it has been shown that a relationship exists between rain rate, R and K_{DP} (Sachidanada and Zrnice, 1987),

$$R(K_{DP}) = 40.6 K_{DP}^{0.866}, \quad (9)$$

Further relationships relating rain rate to other polarimetric variables, most notably differential reflectivity (Z_{DR}) have also been presented (Bringi and Chandrasekar, 2001). However, Z_{DR} is determined from the returns of both horizontally and vertically measured reflectivity; the two radar parameters that are

so badly attenuated due to NPOL's wet antenna.

It has also been noted that, although a good estimator of R , inaccuracies of rainfall estimates take place at rain rates greater than 50 mm h^{-1} (Ryzhkov and Zrnich, 1996) or 70 mm h^{-1} (Chandrasaker et al., 1990) when K_{DP} is used. Because of this, several algorithms comprised of combinations of Z , and K_{DP} at varying thresholds were composed to determine R . Once R is known, a non-attenuated Z can be backed out of the equation using the Marshall-Palmer relationship for rain rate

$$z = 200R^{1.6}, \quad (10)$$

where z is the radar reflectivity factor in linear space ($\text{mm}^6\text{mm}^{-3}$) and R is in mm h^{-1} .

Being the only polarimetric radar available, radar scan comparisons at the same time were not possible. Alternatively, scans just before (after) NPOL's antenna was wet were compared to the next available scan just after (before) NPOL's antenna became dry. Time between scans was on the order of 5-10 minutes. Single rain cells were extracted rather than comparing whole regions, eliminating any contamination from non-precipitation echoes.

Three separate algorithms were employed to correct the reflectivities measured when NPOL was wet. All of the routines used data in the lowest 3 elevation angles, eliminated reflectivity values less than 20 dBZ, those with a negative K_{DP} value, and those with a copular correlation coefficient value less than 0.95, all in order to reduce noise and assure that the reflectivity values were of a meteorological origin.

The first algorithm examined each reflectivity value that passed the criteria mentioned above. If the reflectivity passed through the filter, its corresponding K_{DP} value was used in equation (9) and (10) to obtain a corrected Z value in its stead, as long as that

K_{DP} value was greater than $0.4^\circ \text{ km}^{-1}$, as performed in Ryzhkov and Zrnich (1995). Results from this analysis on a case-by-case basis are shown in Table 5, under the heading "Wet Alg 1" and "Dry Alg 1," referring to average reflectivity values for either a wet or dry antenna. Upon inspection of the results from Table 5, it can be seen that the bias that was present due to NPOL's wet antenna has nearly disappeared when the data is run through the algorithm. At first glance, both averages for the wet and dry algorithm output appear to overestimate reflectivity when compared to the average reflectivity value of the dry scans before the algorithm. However, the "Dry No Alg" data is not necessarily the "truth," as it has been shown that there is a -6.4 dB bias with KAKQ convective reflectivities when dry. Correcting for this dry bias by adding 6.4 dB to the 36.6 dBZ average of the "Dry No Alg" data produces a result of 43.0 dBZ; making the averages of this first algorithm much more dependable.

The changes between the 1st and 2nd algorithm run was that the $0.4^\circ \text{ km}^{-1}$ K_{DP} filter was replaced by a 0° km^{-1} filter, and that all reflectivities less than 30 dBZ were kept. If greater than 30 dBZ with a corresponding K_{DP} value greater than a 0° km^{-1} , it was corrected using equations (9) and (10). If greater than 30 dBZ and less than 0° km^{-1} , the value was thrown out. This resulted in the higher averages seen in table 5.

The third algorithm run was the same as the second, but instead of ignoring all negative K_{DP} values, it replaced them with the average of the positive K_{DP} values as presented by Ryzhkov and Zrnich (1996). Results from this algorithm produced nearly the same values as the first algorithm.

Table 4. 2 μ s results of NPOL bias according to validation radar intensity

Ref. Intensity Class	NPOL Bias (dB)		
	vs. KAKQ	vs. SPAN	vs. TOGA
All	-7.6	-5.0	-3.9
Stratiform	-5.6	-4.5	-3.1
Convective	-9.7	-7.5	-6.9

Table 5. Summary of reflectivity correction using K_{DP}

Event #	Average Reflectivities (dBZ)							
	Wet No Alg	Dry No Alg	Wet Alg 1	Dry Alg 1	Wet Alg 2	Dry Alg 2	Wet Alg 3	Dry Alg 3
1	32.5	36.8	41.9	42.7	45.1	44.8	41.9	42.8
2	33.5	36.1	41.6	42.4	44.5	44.9	41.6	42.5
3	34.1	39.7	43.4	44.2	46	46.1	43.6	44.5
4	32.7	36.5	42.6	42	45.2	43.9	42.7	42.1
5	32.6	39.5	44.2	43.9	46.9	46	44.3	44.2
6	31.9	37	43.3	42.3	45.8	43.9	43.4	42.5
7	31.2	33.9	42.2	42.5	47	46.3	42.3	42.6
8	33.2	33.5	46.6	42.4	49.4	46.5	46.7	42.6
9	25.9	33.7	35	40.1	44.3	43	35.1	40.2
10	25.8	33.1	34.9	39.5	43.6	42.5	35	39.6
11	29.7	34.6	39.6	41.2	45.4	45.2	39.6	41.4
12	30.8	34.7	38.9	41.6	44.6	45.3	38.8	41.7
13	24.4	29.7	29.2	37.2	44.6	43.2	29.2	37.1
14	35.7	40.8	42.2	44.5	46.2	46.5	41.7	44.8
Avg. Refl.	32.0	36.6	42.0	42.3	45.9	45.1	42.0	42.4

4. Conclusions

Several analyses were presented in this paper that showed the performance of NPOL with both a wet and dry antenna. With a dry antenna NPOL moderately underestimates reflectivities; showing a bias of -6.4 dB for all reflectivities when compared to the local NWS radar, KAKQ. This bias is not constant, but rather shows a dependence on the intensity of the precipitation being measured. Bias for stratiform reflectivities is small at -0.1 dB, but large for convective reflectivities at -6.4 dB. However, a separate analysis was performed to show that KAKQ operates at 3.4 dB higher on average than SPANDAR.

With a wet antenna, NPOL severely underestimates reflectivities showing a bias of -12.1 dB for all reflectivities when compared to KAKQ, -10 dB when compared to SPANDAR, and -7.8 dB when compared to TOGA. An even stronger dependence on reflectivity intensity was observed when the antenna was wet. At this time, no explanation for this bias dependence is available. Further analyses should be performed to alleviate this problem, possibly through the use of rain gauge data.

Three correction techniques were also presented and appear promising. Increasing NPOL's operational pulse width from $0.8 \mu\text{s}$ to $2 \mu\text{s}$ decreased biases by around 5 dB when the antenna was wet. However, this solution is not ideal, as the longer pulse increases not only reflectivities when wet, but when the antenna is dry also; creating the need for two separate operational modes.

Increasing NPOL's operational beamwidth should have a large effect on the data, as it was found that NPOL had been using a smaller beamwidth in calculations than what it was producing physically, but only a small number of scans were available for comparison which showed little to no improvement. A larger dataset is needed to determine if the increase in beamwidth causes any improvement.

Polarimetric corrections appear exceptionally promising. Three different algorithms that corrected reflectivity using K_{DP} data were employed and showed excellent results, returning reflectivity values to levels on par with KAKQ returns. However, only reflectivity data that is received (and not attenuated so much that it disappears) can be corrected; correcting for this power loss should be addressed with future work.

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