P6R.6 REFLECTIVITY DEPENDENCE OF REFLECTIVITY GRADIENTS OBSERVED BY RADAR PROFILERS

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1.0 INTRODUCTION

The relationship between the radar reflectivity of rainfall observed aloft and the precipitation that reaches the earth's surface has been studied since the early days of radar. From a human point of view, of course, it is the ability of the radars to improve our observational and forecast capabilities, with implications at all scales, from local to climate. But the relationship may also be used the other way around, and as a necessary step preliminary to the applications for human good, observations are often studied for what they can tell us about our radars. Indeed, in the early days efforts to reconcile observed the reflectivity factor z with simultaneous surface observations of drop size distributions (DSDs) were used as a check of radar theory, and a most notable accomplishment of this work was a significant improvement of the radar equation by Probert-Jones (1962). In this same vane, Atlas et al. (1997) regard work reported by Joss and Waldvogel (1970) comparing rain rates observed with their rather newly invented disdrometer with Z-R rain rates deduced using a vertically pointing radar, as evidence that radars are "performing according to theory".

This study, some 35 years later, is in a sense, is a follow on to this earlier work, and represents part of an ongoing effort to asses how precisely a vertically pointing radar may be calibrated by comparison with a collocated Joss-Waldvogel disdrometer. The recent interest in such work has been peaked by the recent NASA/NASADA Topical Rainfall Measuring Mission (Simpson et al., 1996), and several of the data sets analyzed here were obtained in support of the ground validation portion of that mission (Gage et al., 2000).

Of course, this method of calibration has been attempted many times before, most often with scanning radar looking nearly horizontally. The novelty of this study stems from the optimization of the experimental setup due to the vertical pointing, the rapid cadence of observations, the careful matching of the sampling times of the two instruments, and the extensive time and geographical coverage of the comparison campaigns. In the end, we find that the main limit to the precision of the calibration is due to uncertainty about changes with altitude that occur in the drop size distribution --- and thus in the reflectivity Z --- as the raindrops fall through the last few hundred meters to the surface.

Because of different clutter characteristics at each site, the lowest useable profiler heights for the first three campaigns analyzed ranged from 300 to 500 m AGL. The results of this study show that such high reference heights undoubtedly led to a bias in our calibrations that in some cases could be of the order of 1 dBZ. The results appear better in the fourth campaign. As mentioned before, at Wallops Island the profiler range resolution, dynamic range, and recovery characteristics were improved, and a reference altitude of 200 m AGL was possible. These results appear to be much less affected by the vertical gradient of reflectivity, and it seems likely the calibration is within a half dBZ or so.

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2.0 CAMPAIGNS

The observations in these case studies come from four profiler/disdrometer campaigns. Three of the campaigns occurred in support of the TRMM Ground Validation effort: TEFLUN B, 1998, in Florida; LBA, 1999 in Brazil; and post TRMM KWAJEX results from 2001. These TRMM sites were more or less tropical, with LBA being continental, TEFLUN B coastal, and KWAJEX maritime. The fourth campaign, here denoted Wallops 2004, took place next to a disdrometer comparison test bed at NASA's Wallops Island facility in Virginia and is temperate and coastal. The locations of these campaigns are shown on the global map in Figure 1.

3.0 EXPERIMENT CONFIGURATION

The profiler-disdrometer setup during each campaign was nearly identical. A 2835 and/or 915 MHz precipitation profiler was collocated (within 20 m or so) of a Joss-Waldvogel impact disdrometer. As an example, Figure 2 shows the setup for the LBA campaign at Ji-Parana Municipal Airport in Brazil. For all three TRMM campaigns, the same disdrometer and profilers were moved from site to site. At the Wallops site, however, a different disdrometer was used, no 915 MHz system was installed, and the 2835 MHz profiler was significantly upgraded with a higher power transmitter and replacement of the analog receiver with a new digital receiver. Also at this time the controlling software was changed from POP4 to LAPXM.

The profilers transmitted and received through a vertically pointing 4 foot diameter dish antenna (nominal 6 degree beamwidth) for TRMM and an 8 foot diameter dish at Wallops (nominal 3 degree beamwidth) so that, in the ideal case (i.e., in the absence of strong horizontal wind), the disdrometer sampled precipitation that had fallen through the profiler sample volume. The control computer logged data from both the disdrometer and the profiler(s) during the TRMM campaign, ensuring the sample times were synchronized on the minute. At Wallops the logging of the disdrometers was separate from the profiler, and the synchronization relied on accurate determination of time through the use of GPS systems.

The disdrometer observations used here are the reflectivities Z_{JWD} calculated from drop size distributions accumulated over each minute. The TRMM profiler data used here are the reflectivities, Z_{2835} and/or Z_{915}, observed at the lowest useable reference height using a 105 m pulse. Since this pulse alternated every 30 s with a 250 m or 60 m pulse, depending on the site, the 30 second mean z's are followed by a 30 s gap. At Wallops a faster profiler cadence was used, so that 2835 MHz 7.5 s mean reflectivities were available every 15 seconds for either the 31 m or 62 m pulse length. For this analysis, the 7.5 s linear reflectivities z [mm^6/m^3] were averaged again to produce one-minute mean values that were then transformed to $Z = 10\log_{10}(z)$ [dBZ] to match the one-minute disdrometer data.

4.0 CALIBRATION

Figure 3 shows an example of a comparison during stratiform conditions taken at Kwajelein September 2-3, 1999, with a 915 MHz profiler. The band of high reflectivity near 5 km altitude is the melting layer. The DSD data observed by the disdrometer has been transformed to Z in dBZ for the comparison.

Gage et al. (2004) have shown, from examination of time series comparing one disdrometer with another and one profiler with another, that the observational error associated with minute by minute observed dBZ values (i.e., observations of $10\log_{10}z$) is very Gaussian like, and characterized by a standard deviation of several dBZ, generally a little less in the case of the profiler. An example comparison of a disdrometer with another disdrometer, and a profiler with another profiler, is shown in Figure 4 left and Figure 4 right, respectively.

Consequently, to the extent that they are sampling the same representative precipitation, the observed time-series mean Z values between these two independent, collocated, and synchronized instruments may be brought into ever more precise agreement by extending the length of the time series observed.

This technique is especially powerful because there is no need to work with just a single event, but an extended time series consisting of the concatenation of many events may be used to improve the precision. This has been done for Figure 5, where profiler/disdrometer comparisons covering 40 days during the LBA1999 campaign are shown. Figure 5, top panel, shows the s-band reflectivity observations Z_{2835} plotted against the Joss-Waldvogel (JWD) disdrometer observations Z_{JWD}. The bottom panel shows the difference $Z_{2835} - Z_{JWD}$ plotted against Z_{JWD}. If the instruments were in perfect agreement the points would all lie about the horizontal zero line in the bottom panel, except for the Gaussian noise fluctuations. But inspection shows that this is not quite the case. Looking at the yellow dots, which represent the median difference observed in 1-dBZ bins along the Z_{JWD} axis ---we found the median to be significantly more robust than the mean--- we see there is a slight slope in the sense that Z_{JWD} appears to be increasing relative to the profiler as Z_{JWD} increases.

5.0 COMPARISON OF Z DIFFERENCE TRENDS BY CAMPAIGN

This trend was observed in all the campaigns. This is shown in the left hand panel of Figure 6 where we show the trend lines for median difference points from 5 dBZ bins of Z_{JWD}, instead of for one dBZ bins represented by the yellow circles in Figure 5. Note that we have calibrated these lines over the band between Z_{JWD} = 27.5 to 32.5 dBZ, so that all of these lines agree by definition over that range. This focuses attention on the slopes. Significantly, although LBA, KWA, and TEFLUN B all have about the same slope, it is obvious that WAL is flatter. Although at first we thought this might be due to the fact that a different disdrometer was used at Wallops, the right hand panel, however, suggests a different explanation.

6.0 EFFECT OF ALTITUDE

In the left hand panel of Figure 6 the data were all taken at different heights above the surface because the lowest useable height depended on the site. Note that the reference height used is given in meters after the pulse lengths in the legend. The reference height for Kwajelein was particularly high (518 m AGL) due to sea clutter. The reference height at the Wallops site is particularly low (209 m AGL) due not only to a lack of clutter but to the upgraded electronics. Thus, the lowest useable range gate at Wallops to be 100 m closer to the surface than at LBA and over 300 m closer than at Kwajelein. Since KWA is the weak link, we reset the reference height for all sites to its nominal 500 m AGL lowest useable height. The results are shown in the right panel of Figure 6. The slopes now appear similar for all sites, suggesting that the main effect causing the slope is a significant change in the DSD as the rain falls the last few hundred meters to the surface.

The four panels of Figure 7 present vertical profiles of median Z_P --- p stands for 2835 or 915 --- where the profiler data has been stratified on 5 dBZ wide bins of Z_{JWD}. Each panel is for a different campaign, and the horizontal red line near the lowest heights indicates the profiler calibration height and the Z_{JWD} calibration range. Points on these profiles were suppressed if there were fewer than 20 points at any given height over which to calculate the median Z_P. For ZJWD greater than 40 dBZ or so the reflectivity significantly decreases with height for all sites. This is not surprising, as most events in this reflectivity range are convective. These profiles also tend to be less smooth, as there are fewer and fewer observations as Z increases (not shown). The profiles between 20 and 35 dBZ tend to be smooth, as there is a lot of data here. At some sites the fall off of reflectivity with altitude still seems significant, while at some sites, such as Kwajalein, the vertical reflectivity gradient appears nominal for the 30 dBZ bin.

Figure 8 examines the vertical reflectivity gradient on an expanded scale. Here the binned median profiler Z_P at each height has been differenced from the median disdrometer Z_{JWD} for its respective bin. Thus, if there were no vertical gradient of reflectivity, all profiles would be a vertical line above 0 dBZ on the x, or $Z_P - Z_{JWD}$, axis. In this figure it is clearer that the vertical gradient of reflectivity is significant at all sites. It is also apparent that the ability at Wallops to observe closer to the surface has improved the accuracy of the calibration. But it is also clear that even here what happens as the rain falls the next 200 m could be significant.

7.0 DISCUSSION

In the analysis of observations taken in four different campaigns at different times and geographical locations, we observed small Z dependent and height dependent biases between precipitation profiler radars and Joss-Waldvogel disdrometers. This bias doesn't appear to be instrumental, but is most likely due to height dependent changes in the DSD as rain falls the last few hundred meters to the surface. It is likely that three precipitation processes are causing the changes: evaporation, drop break up, and coalescence by faster moving big drops sweeping up smaller drops. It is tempting to conclude that coalescence must be the dominant process, since Z grows as the drops fall. However, this study is statistical, and some of the character of the profiles must reflect the lumping together of various types of rain (e.g., convective, stratiform, transitional, and beginning and ending parts of events that cannot be expected to be in equilibrium).

We find that the dBZ range over which calibration is made is significant, due to dependence of the vertical reflectivity gradient on Z. In the extreme, we find that when the lowest useable heights for calibration are several hundred meters or more above the disdrometer, a radar calibrated solely under extremely high reflectivity conditions would thereafter produce dBZ values up to 3 dBZ higher than those from a radar calibrated under extremely low reflectivities. This extreme bias appears to be reduced to about 1 dBZ if heights only two hundred meters or so above the disdrometer are useable.

Focusing on the 20-30 dBZ band, and imagining the simplest extrapolation to the surface, it would appear from Figure 8 that the calibration of TEFLUN B, LBA, and KWA could easily be in error by a dBZ or so. The Wallops data looks better, and the results may approach a precision of 0.5 dBZ. It is tempting to perform such extrapolations, but it would be better to back them up with actual observations or understanding of reflectivity changes in the lower altitudes. There is an extensive literature on the change of DSDs as rain falls, especially within clouds, and numerical models of these processes exist. It remains to see if this effect is adequately explained, and if these models can be used to improve a calibration. Barring this, the next best thing is to restrict the data to robustly stratiform, and such a study is in progress.

8.0 REFERENCES

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10.0 FIGURES

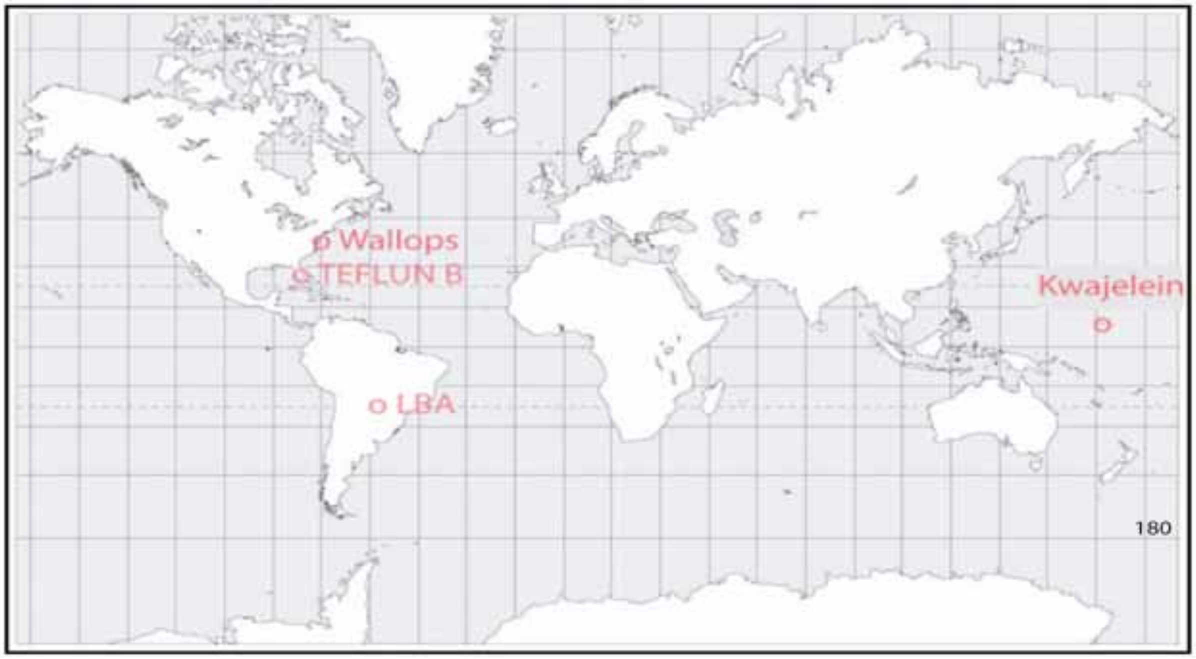

Figure 1: Geographic world map of the profiler/disdrometer sites used in this study. TEFLUN B, LBA, and Kwajelein were sites used in the TRMM Ground Validation campaigns.

Figure 2: From left to right are the radar control container, the 915 MHz profiler antenna shroud and transmitter, the smaller 2835 MHz antenna shroud and transmitter, and the Joss-Waldvogel disdrometer in the right foreground, sitting on a tripod 1 m off the ground.

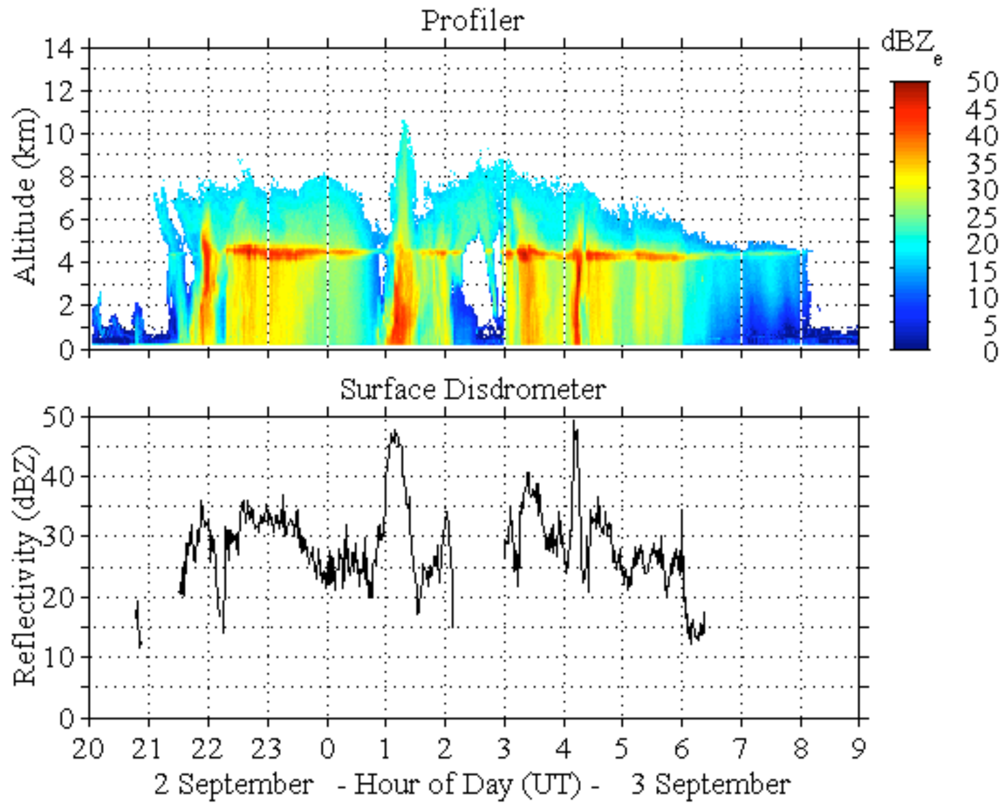

Figure 3: Example of the 915 MHz profiler time height display of Z at Legan Island in the Kwajelein Islands. The data are for September 2-3, 1999. A time series of the minute-by-minute Z values observed by a collocated Joss-Waldvogel disdrometer are shown in the bottom panel.

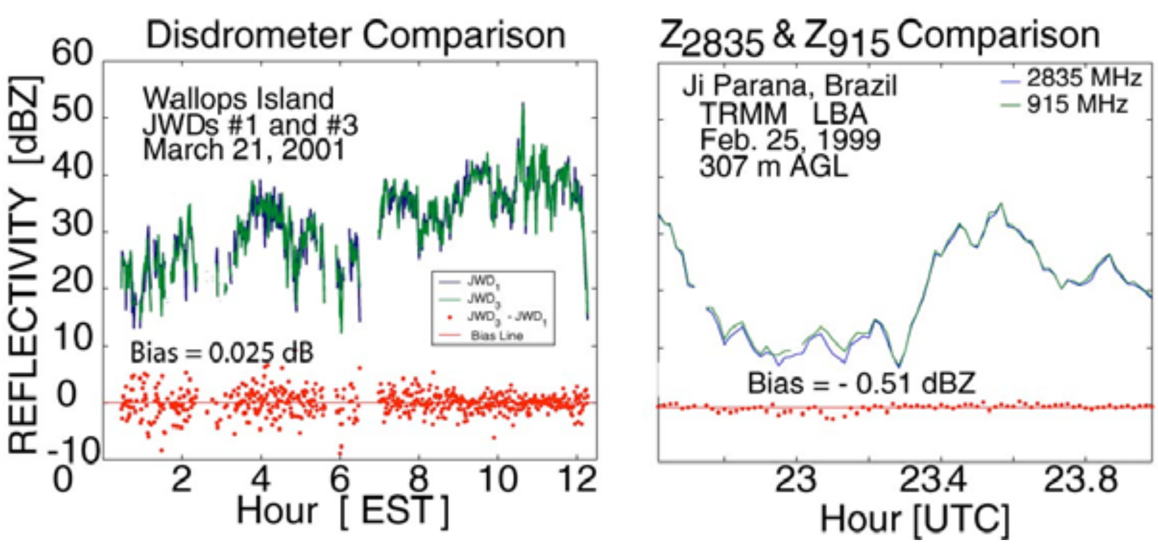

Figure 4: The **left panel** shows overlaid time series of the simultaneous observations from two collocated disdrometers. The red dots show the minute-by-minute differences between them. Although the minute-by-minute differences are large (standard deviation = ~3 dBZ) the 12 hour means differ by only 0.25 dBZ. The **right panel** shows a similar display for two collocated radar profilers, but at a different time and place. Here the 1 hour means differ by only 0.51 dBZ.

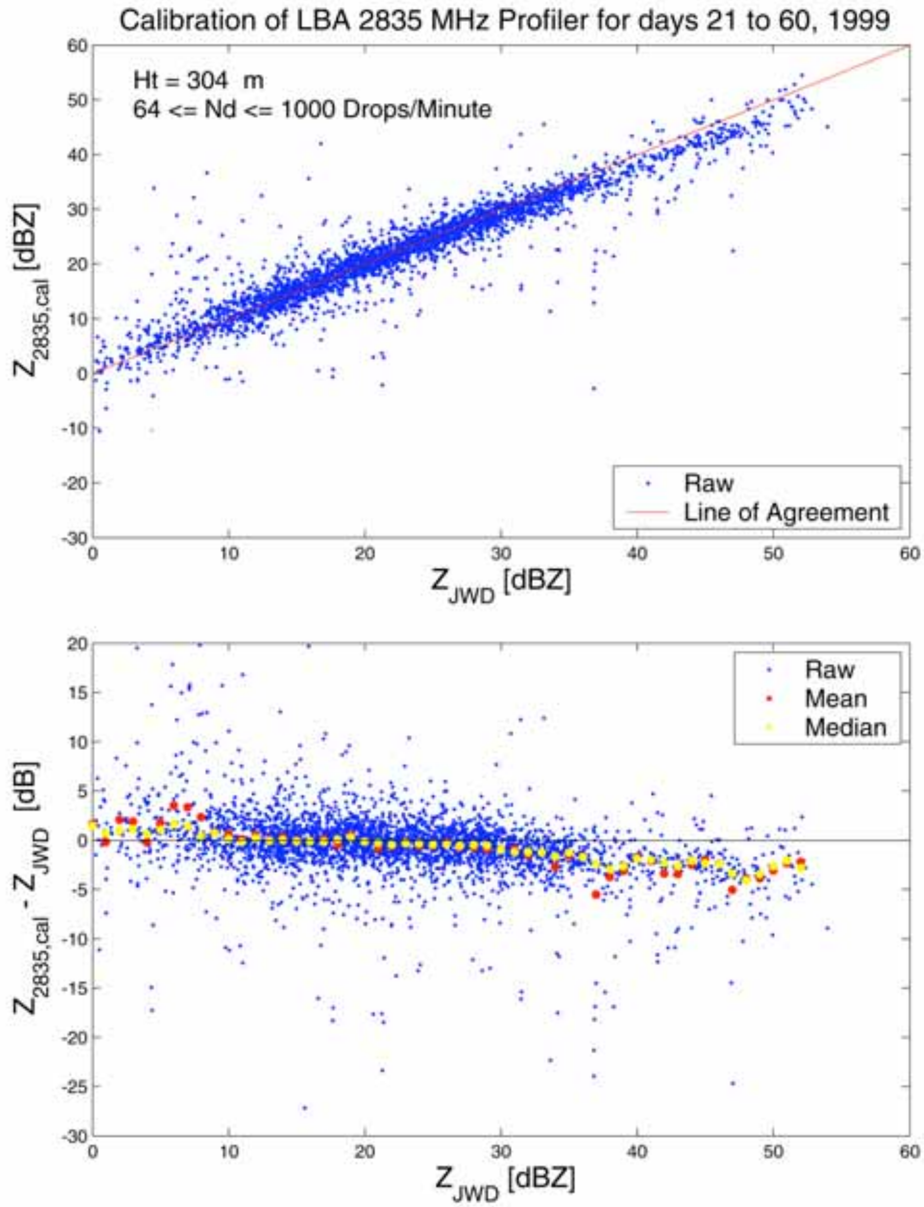

Figure 5: The top panel shows a scatter plot of all the profiler/disdrometer reflectivity values for the 1999 LBA TRMM Ground Validation Campaign. This data utilizes the profiler range gate centered 304 m above the disdrometer. The red line is the line of agreement between the two instruments. It can be seen that they agree well up to about 30 dBZ on the Z_{JWD}, or disdrometer, reflectivity axis. This is easier to see in the bottom panel where the differences between the two instruments are plotted along the y-axis. The yellow and red circles in this plot represent the median and mean difference found in bins centered on 1 dBZ steps along the disdrometer axis. As explained in this paper, the unexpected reflectivity dependent trend of the differences is due to the vertical gradient of reflectivity. We note in passing that the medians proved to be significantly more stable in this analysis, and hence have been used instead of the mean throughout.

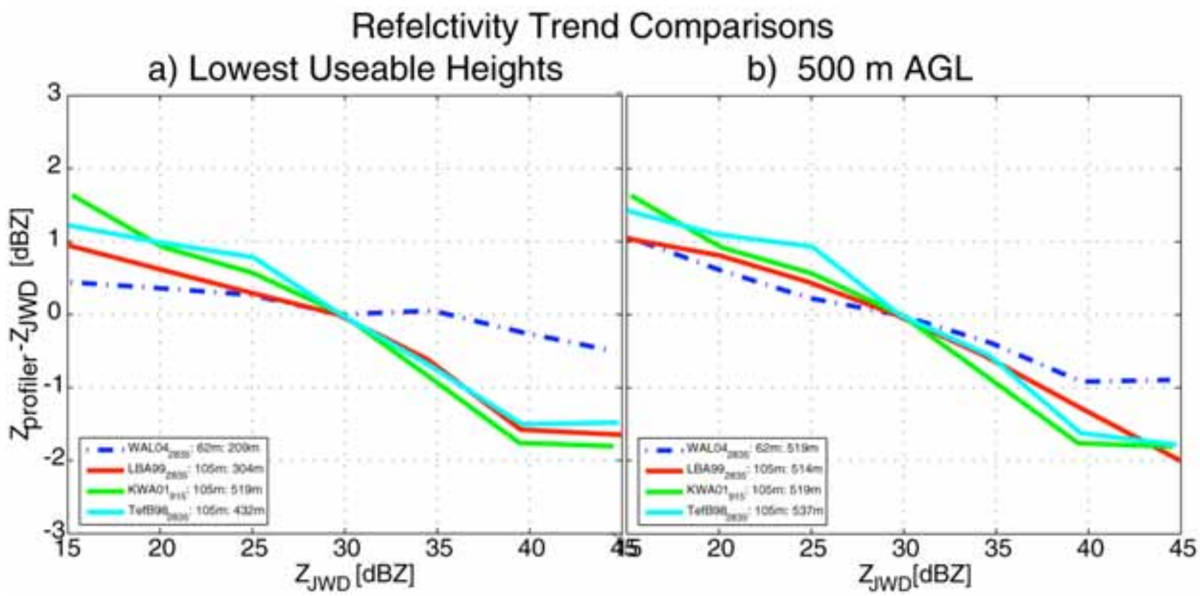

Figure 6: Left Panel) The reflectivity differences calculated for 5 dBZ bins of Z_{JWD} are plotted versus Z_{JWD} for four campaigns. Three of the campaigns (Red=LBA, Green=KWA, Cyan=TEFLUN B) show a similar slope, but Wallops (blue dashed line) shows a much shallower slope. The calibration height for each campaign was the lowest useable height at that station: 208 m for Wallops, 304 m for LBA, 519 m for KWA, and 432 m for TEFLUN B. **Right Panel)** This panel is similar to that on the left except that here we used the closest range gate to 500m for all the stations as a 'calibration' height. This height was used to match the Kwajelein data, where sea clutter made 500 m the lowest useable height. The slopes of the difference lines are now very similar for all sites. This suggests that the trend is due to changes in the rain drop size distribution as the rain falls through the last few hundred meters to the surface.

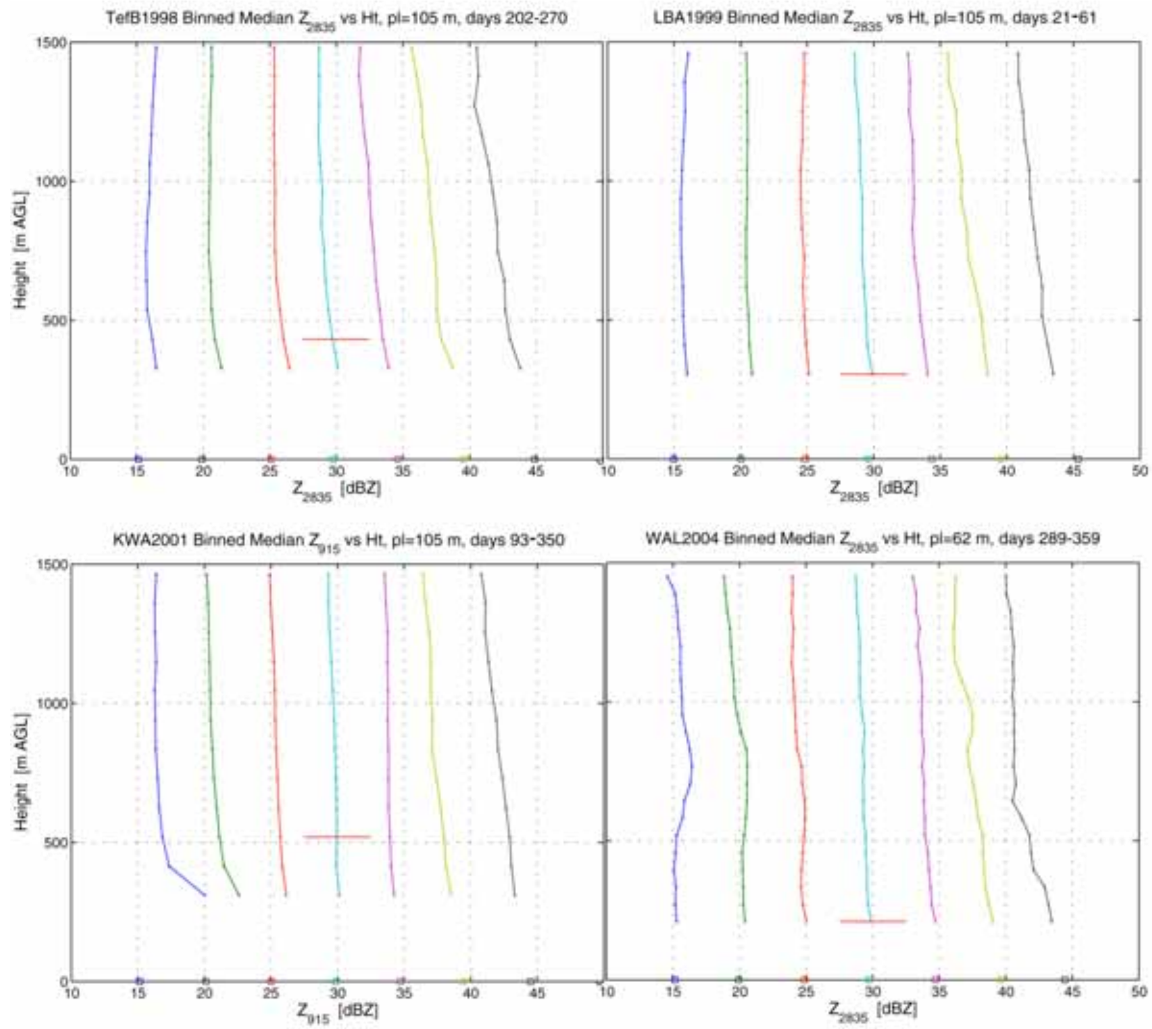

Figure 7: The median profiles of reflectivity for four campaigns, stratified by 5 dBZ bins of Z_{JWD}. If there were no vertical reflectivity gradient, each profile would line up above its same colored square on the Z_P axis, since this square represents the median value of Z_{JWD} observed in that bin. The horizontal red lines near the bottom of the profiles and centered on Z_P = 30 dBZ indicate the calibration height and the Z_{JWD} bin of the calibration. The top left panel is for TEFLUN B, the top right LBA, bottom left KWA, and bottom right WAL. Note the significantly lower calibration height possible at WAL.

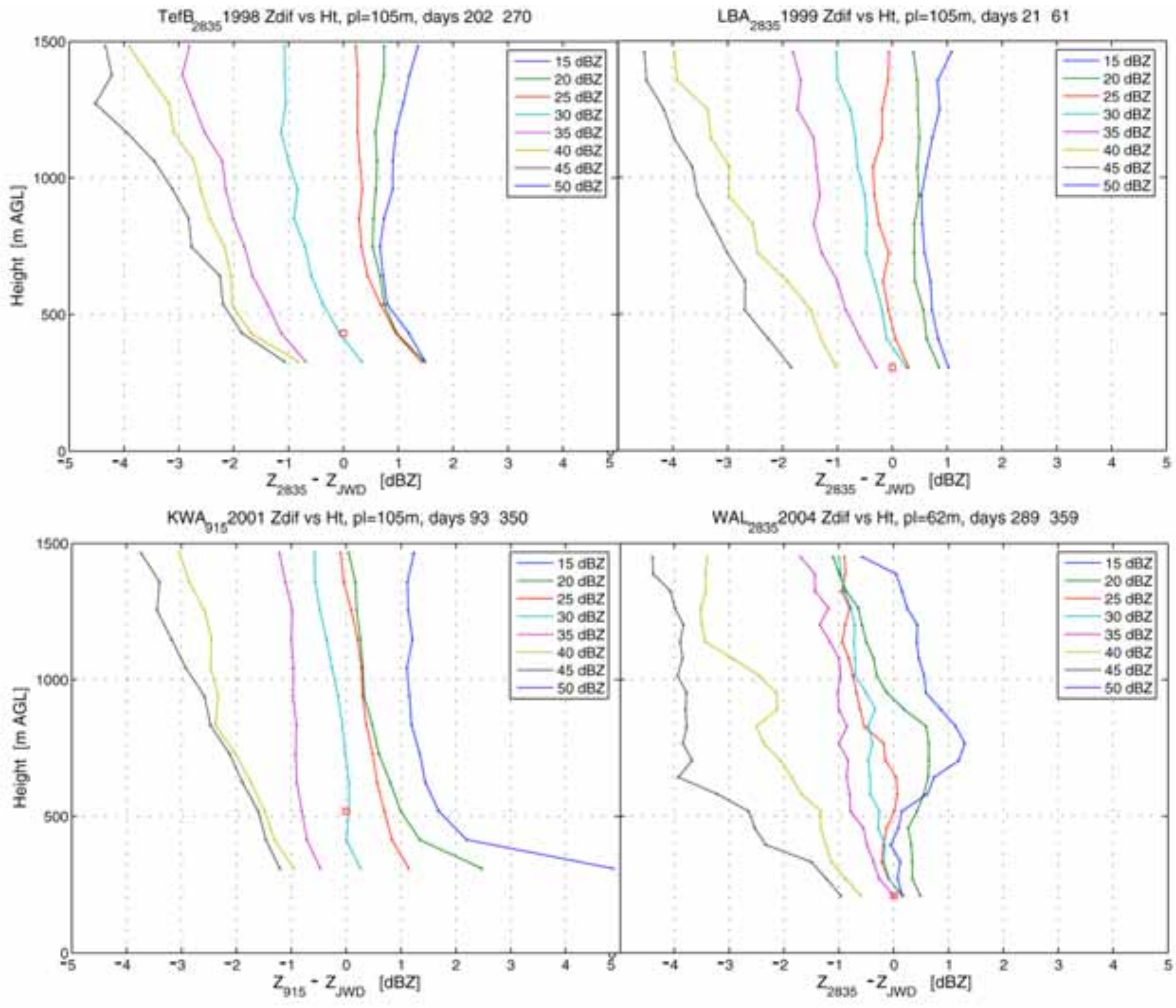

Figure 8: Vertical binned profiles of $Z_P - Z_{JWD}$. The profiles represent the bin median of Z_{JWD} subtracted from the corresponding profiles of median Z_P shown in Figure 7. If there were no vertical gradient of reflectivity, these differences should all line up above the zero value on the x-axis. The curves associated with the low reflectivity bins are on the right. For example, the right most blue curve belongs to the $12.5 <= Z_{JWD} < 17.5$ dBZ bin. At the one-dBZ level, it is clear that figures that the vertical gradient of reflectivity is significant for calibrations. The campaigns are paneled as in Figure 7.