# Monitoring Radar Calibration using Ground Clutter

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## 1. Introduction

To obtain high quality data from clouds and precipitation, weather radars have to be precisely calibrated. The WSR-88D's (Weather Surveillance Radar) system specifications establish uncertainty of ±1 dB for the equivalent reflectivity factor (Z, reflectivity in short hereafter) and ±0.1 dB for differential reflectivity ($Z_{DR}$). The uncertainties in radar variables depend on the quality of radar hardware and the statistical properties of returned radar signals. Calibration of Z and $Z_{DR}$ refer to hardware accuracies. In the WSR-88D, dedicated hardware and corresponding software have been designed to calibrate Z and $Z_{DR}$. The characteristics of antenna, transmitted pulse, and receivers are measured during the calibration procedures. The measurement electric chains, involved in the calibrations, should be calibrated as well (Melnikov and Zrnic 2015). To minimize impacts of environmental temperature and humidity, the calibration hardware have been placed into a climate controlled box. The manufacturer of the first low noise amplifier (LNA) of the WSR-88D guaranties its stability in an interval of ±0.5 dB, The WSR-88D Z calibration process maintains Z measurements within 1 dB that satisfies the specifications, but there is other hardware that introduces its own uncertainty. The guarantied accuracy of Z measurements is not sufficient for $Z_{DR}$ calibration, where two LNAs are involved and much finer accuracy is required. Because of variety of the factors, there is no consensus on sufficiency of built-in radar equipment to achieve indicated accuracies.

Various procedures have been developed to verify radar calibration. All such procedures are based on remote sensing of scatterers that possess certain characteristics. To calibrate Z and $Z_{DR}$, signal reflected from a metal sphere has been utilized (e.g., Bringi and Chandrasekar 2001, section 6.3.1; Atlas 2002, Williams et al. 2013). The main problem with this approach is its arrangement complexity that makes routine measurements impractical. Moreover, such measurements give the system gain at one point of the antenna pattern (usually the center of pattern which in itself is hard to hit) whereas weather scatterers are distributed and therefore the shape of antenna pattern needs to be known. Antenna pattern depends on temperature that could affect radar measurements (Hubbert 2017).

A procedure for relative Z calibration for adjacent WSR-88D radars has been developed by Zhang et al. 2011. This procedure is applied when adjacent radars observe the same parts of precipitation where measured reflectivity values should be equal. However, bringing reflectivity to the same level does not guarantee the correct absolute Z calibration, which remains one of the major problems in radar meteorology.

Another method to calibrate Z, involves comparisons of measurements of the rain rates with radar and ground rain gages (e.g., Bringi and Chandra 2001, Frech et al. 2017). Vertical sensing of precipitation with weather radar and micro-rain radar along with rain gage measurements are used on the German radar network (Frech et al. 2017).

Vertical sensing of precipitation is used on some radars to calibrate $Z_{DR}$. Raindrops appear round in the mean at zenith radar sensing if there is no strong wind shear, which can incline/cant the drops relative to radar beam (Gorgucci et al. 1999). This method is used on the German, French, and Finnish weather radar networks (Frech 2017, Sugier and Tabary 2006, Vaisala 2014) but cannot be used on the WSR-88Ds because the maximum antenna elevation is $60^o$.

To verify $Z_{DR}$ calibration, three methods are used operationally on the WSR-88D network (Cunnigham et al. 2013, Ice et al. 2014, Richardson et al. 2017). The first is based on measurements of $Z_{DR}$ in light rain and within the reflectivity interval 10-30 dBZ. It assumes that the climatological $Z_{DR}$ values can be used to verify long time calibration. However actual values in a given case can deviate from the climatological mean. Reflectivity is very sensitive to big drops so a small number of such droplets can bias $Z_{DR}$ high.

The second method to verify $Z_{DR}$ calibration utilizes measurements from snow/crystal cloud areas. It assumes that snow aggregates exist just above the melting layer thus their $Z_{DR}$ values are about 0.2 dB. The problem with this approach is that characteristics of snow particles above the melting layer are not precisely known hence applicability of this approach to a given case is uncertain. Cloud layers with $Z_{DR}$ values much larger than 0.2 dB and located just above the melting layer have been observed with the WSR-88Ds.

The third method is based on observations of reflection from refractive index fluctuations in clear air. The top of convective boundary layer contains continuum of turbulent eddies including sizes of about 5 cm (half of the radar wavelength) that cause Bragg scatter at S frequency band (Doviak and Zrnic 2006, chapter 11). Due to small eddies' sizes and their chaotic spatial orientations in turbulent air, the average $Z_{DR}$ is 0 dB (Melnikov et al. 2011). Bragg scatter is easy to observe in cold seasons; in warm months Bragg scatter is often masked by contributions from insects. Nevertheless, operational radar observations show sufficient detectability of Bragg scatter year round on almost all radar sites (Cunningham et al. 2013, Hoban et al. 2013, Ice et al. 2014, Richardson et al. 2017).

The first two methods utilize precipitation that makes $Z_{DR}$ calibration "after the fact", i.e., to verify $Z_{DR}$ calibration, sufficient amount of data should be collected. The third method (i.e., Bragg scatter) is used in clear air and should be conducted right before a precipitation event, which is not always possible.

The three methods require appropriate weather conditions which are not observed continuously. Ground clutter is continuously present in radar returns at low antenna elevations. In the previous report by Melnikov and Zrnic (2015) it was shown that ground clutter returns in a spectral interval ±0.5 m $s^{-1}$ exhibits SNR stability of ±1 dB and $Z_{DR}$ stability of about ±0.1 dB that can be used for monitoring Z and $Z_{DR}$ calibrations in fair weather and in situations where rain is outside a range of 30 km from radar. Ground clutter returns have been used by Louf et al. (2017) to monitor reflectivity calibration.

The goals of this report are

- to increase the number of observations and confirm the findings of 2015 report (sections 3 and 4),
- to analyze changes in SNR and $Z_{DR}$ values from ground clutter and relate these to variations in radar hardware (sections 3 and 4),
- to further analyze relations between the reduction in SNR from ground clutter due to a wet radome and the intensity of rain on a radar site (section 5).
- to summarize recommendations for implementation of the Z and $Z_{DR}$ monitoring into operations (section 6).

## 2. Signal processing

Distributions of the intensity of ground clutter are shown in Fig. 1. The data were collected with the WSR-88D KOUN located at Norman, OK. The level 1 data for about one day from the radar channel with horizontal polarization were used. The green curve is the distribution of all SNR within 30 km from the radar and denoted 'Unfilt'. The red curve denoted 'Filt" is the distribution of SNR from the ground in the Doppler velocity interval ±0.5 m $s^{-1}$. These data were obtained by converting level 1 signals into frequency domain, selecting spectral lines from the interval ±0.5 m $s^{-1}$, converting this spectrum back into time domain, and applying the standard procedures for obtaining all radar variables. The blue line corresponds to the DC component in the signal, i.e., the spectral line at 0 m $s^{-1}$. Ground clutter with SNR weaker than 40 dB is more variable in time; it is due to reflection from swinging vegetation (leaves, grass, small tree/bush branches) and automobiles. Thus, signals with SNR < 40 dB were thrown away from the analysis.

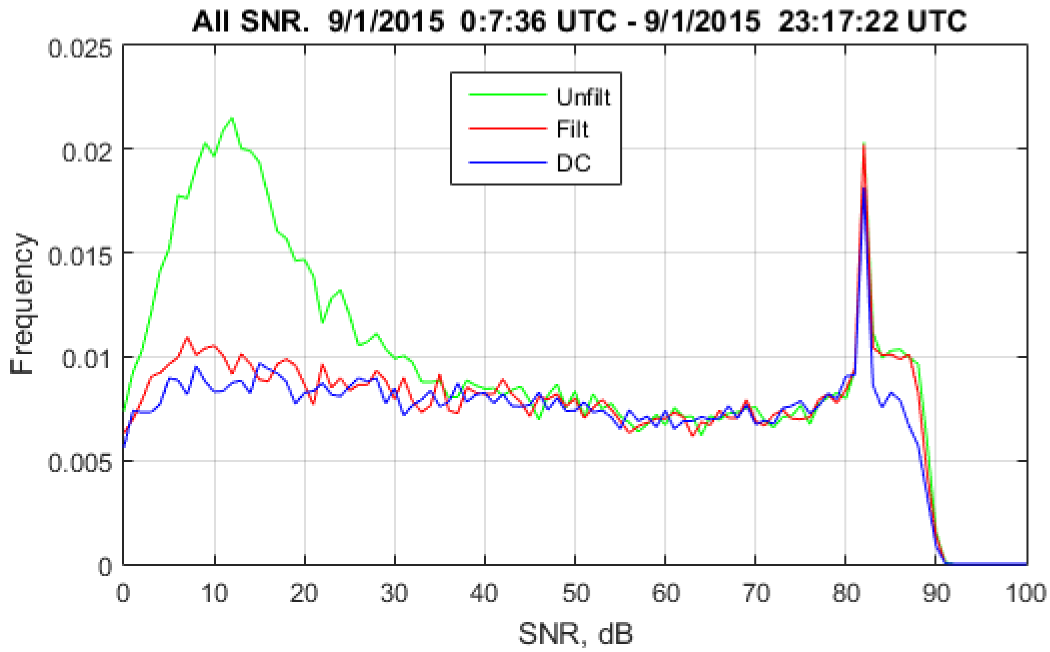


*Fig. 1. Distributions of SNR of signals from the ground in the horizontal channel (green line), signal with the narrow spectra (red line) and DC signal (blue line). WSR-88D KOUN, June 20, 2015.*

$Z_{DR}$ values from ground clutter lie in an interval of ±20 dB. System $Z_{DR}$ outside interval ±5 dB points to serious miscalibration and needs a technical fix. So very high absolute $Z_{DR}$ values are thrown away from the analysis and $Z_{DR}$ values from ground clutter in the interval of ±5 dB are analyzed. System $Z_{DR}$ changes (since the last calibration) outside interval ±1 dB will raise an alarm to alert the need for a technical fix. An example of a distribution of $Z_{DR}$ values from the ground for about 1 hour is shown in Fig. 2 with the blue line. This distribution then filtered out with the Golay (the red line) or median (the black line) filters and $Z_{DR}$ at the maximum of the Golay distribution is taken as a $Z_{DR}$ value for this 1-hour time interval. There are 24 $Z_{DR}$ values for a day a time series of which are analyzed.

The Golay FIR filter, called Savitzky-Golay in the Matlab documentations, has been applied to $Z_{DR}$ data in a form sgolayfilt($x$, $k$, $f$), where $x$ is the number of data in the interval ±5 dB, $k$ is the polynomial order of the approximating curve, and $f$ is the frame size. The values of the latter parameters were $k = 3$ and $f = 19$.

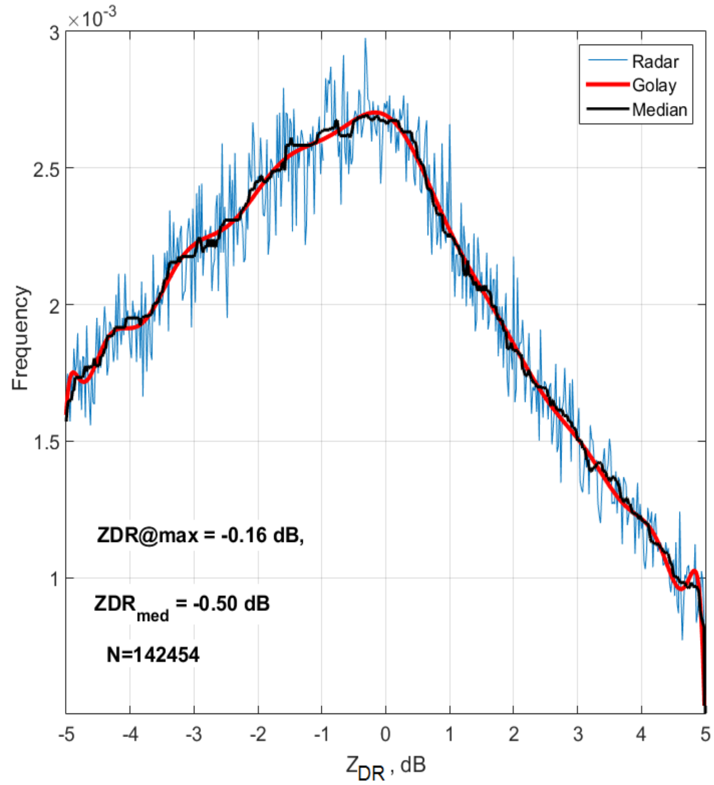


*Fig. 2. Distribution of $Z_{DR}$ in an interval -5 to 5 dB collected from 9:06 to 9:58 UTC on March 17, 2017. WSR-88D KOUN. The blue curve represents the radar data, the red and black curves are radar data filtered with the Golay and median filters respectively. The total number of radar measurements (N) is 142,454. ZDRmed is median $Z_{DR}$ in the interval and ZDR@max is $Z_{DR}$ at the maximum of distribution obtained with the Golay filter.*

## 3. Reflectivity monitoring

Time-series data of the mean SNR from ground clutter for March – August 2017 are shown in Figs. 3 and 4. The red curve is the SNR. The blue line corresponds to the pulse width used to collect the data: the lower (upper) line shows interval with the short (long) 1.54 us (4.5 us) pulse. The black line shows the rain rate obtained from the NRMN Mesonet weather station situated

200 m to the west of KOUN. The Mesonet stations measure the rain accumulation every 5 min, so the rain rate in mm/hour was obtained by multiplying the 5 min accumulated water amount by 12. This is the average rain rate over 5 min, the actual rate, which creates a water film on the radome, can be stronger or weaker at any given time during this time interval. The second issue is the duration of the VCP, which is typically longer than 5 min. The gaps in the curves occur at times when the radar was running not standard VCPs (vertical cross sections, experimental VCPs) or was unavailable.

Overall stability of SNR from the ground is good in fair weather if the radar is functioning well. Fluctuations of SNR in such periods are within ±1 dB with a standard deviation of about 0.25 dB. This supports the conclusion that SNR can be used for monitoring reflectivity calibration. If it is raining on the radar site, SNR drops due to attenuation through the wet radome and rain along the beam from the antenna to the ground. This is further discussed in section 5. In Figs. 3 and 4, one can see some discontinuities in the SNR curves which are marked with green numbers. An analysis of these features is presented next.

Feature 1: There is an increase in SNR on March 2, 2017 by about 1.5 dB. Analysis shows that the transmitter and receivers were operating properly and are most likely not responsible for the increase. The lowest antenna elevations at this period were $0.439^{o}$ , which is slightly less than $0.483^{o}$ at previous times. This antenna pointing variance is within normal expectations +/- 1 BAM, but the lower pointing angle causes the beam to illuminate more the ground scatterers and that would increase the SNR. Similar antenna pointing issue was observed on 28 October 2015 (Fig. 5). At the beginning of the day (UTC), there was a 3.5-dB increase in SNR. A check of the transmitter and receivers indicated that they were operating properly. The lowest antenna elevations were from $0.3516^{o}$ to $0.3955^{o}$ until about 12 UTC and then went to the normal position of $0.4395^{o}$.

Features 2 and 3: SNR went up due to switching over to the long pulse mode. This effect is similar to that for weather, where switching to the long pulse leads to an increase in received power by 9 dB. The ground is not fully volumetric radar target therefore the increase is about 4 - 4.5 dB. This effect was discussed in the previous report (Melnikov and Zrnic 2015).

Feature 4: The drop in SNR is due to rain at the radar site. Wet radome attenuates the transmitted and received radar waves. This impact is further discussed in section 5.

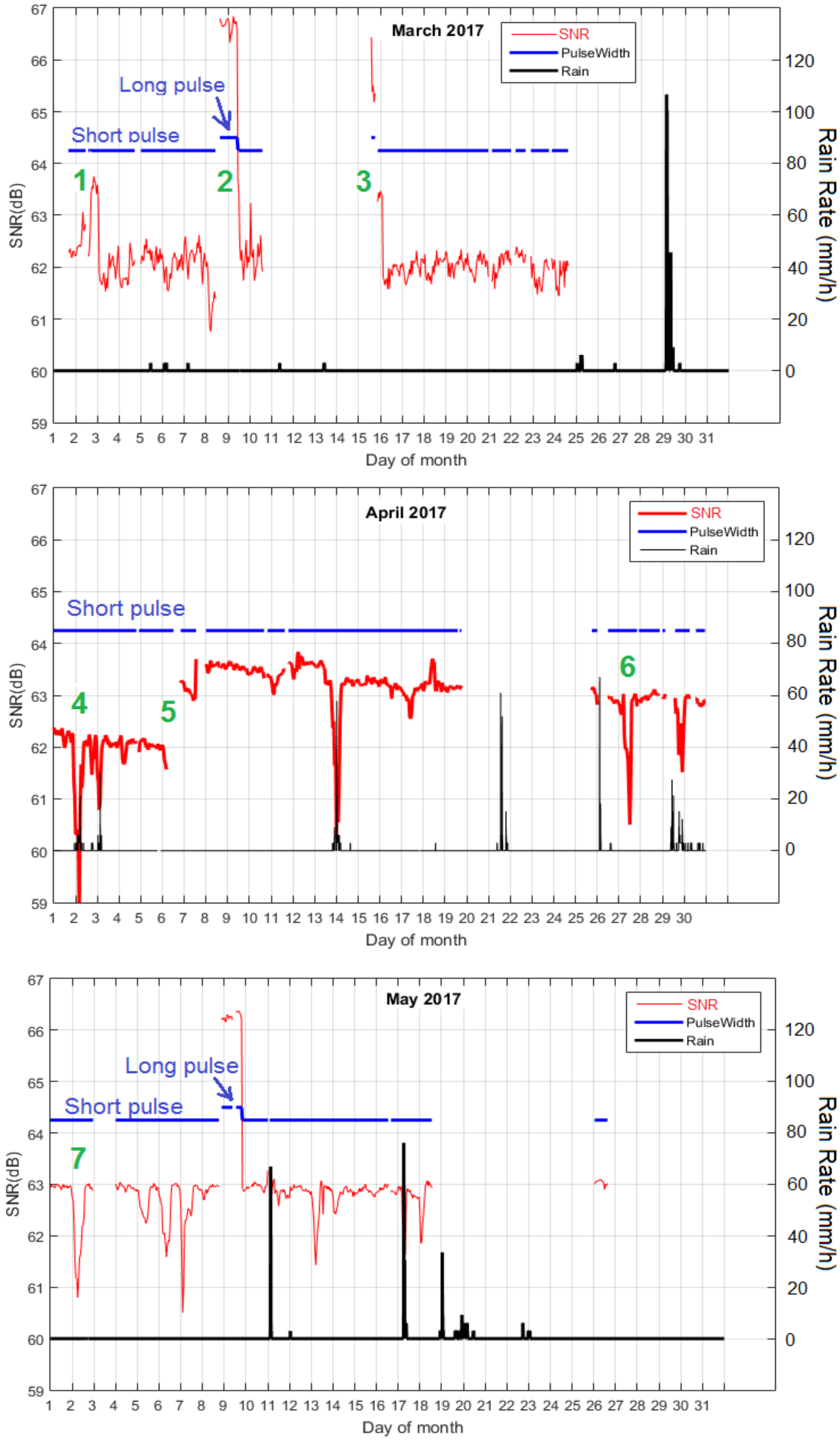


*Fig. 3. The mean SNR from ground clutter in March – May 2017.*

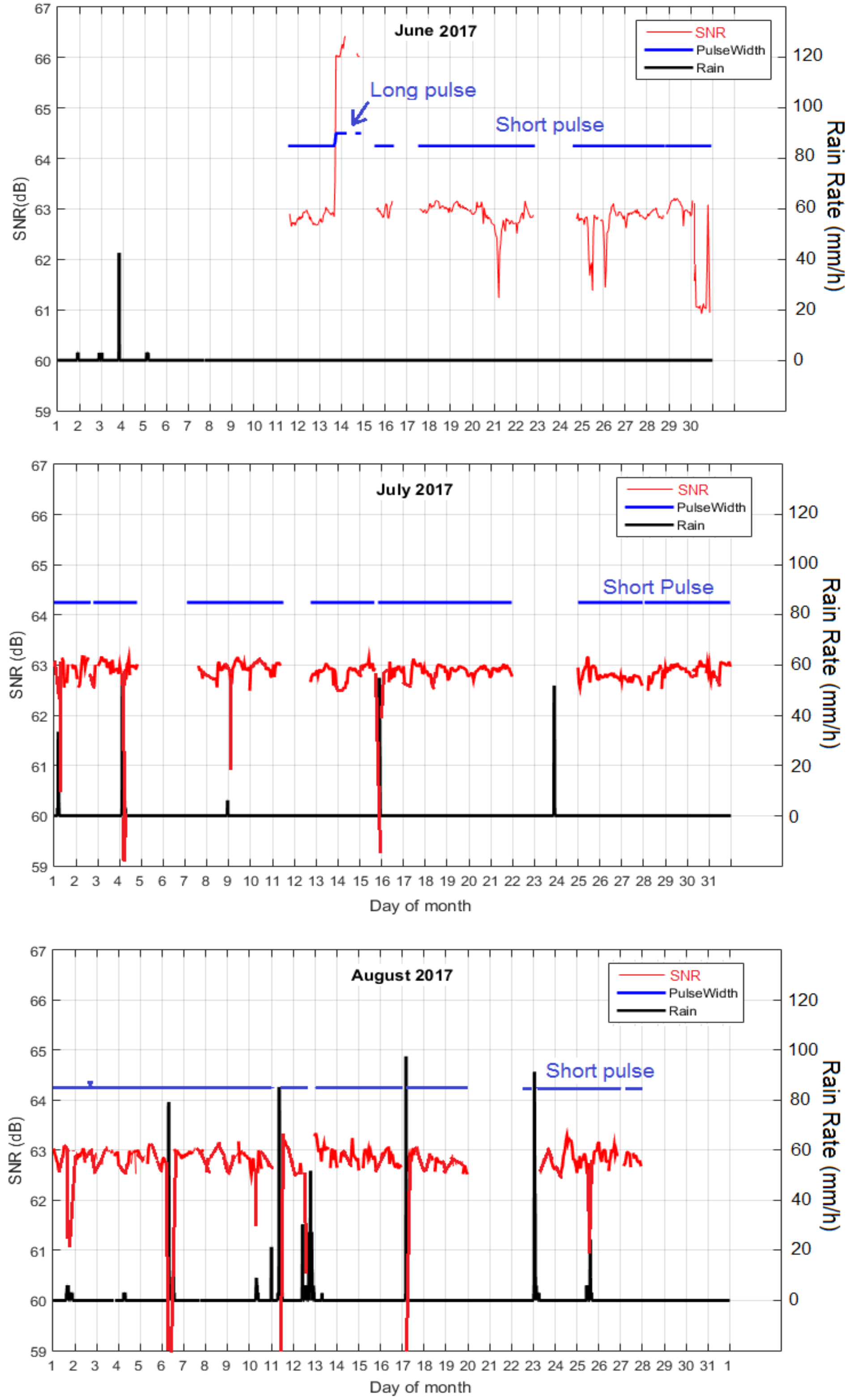


*Fig. 4. Same as in Fig. 3 but for June- August 2017*.

Feature 5: One can see an increase of about 1.6 dB during 6-8 of April. The KOUN's transmitter was tuned up at that time, i.e., the transmitted pulse is actually matched. In the fleet, when the matched filter loss increases at a site, it is an indication of a transmitter issue and the site is instructed to correct it.

Features 6 and 7: The drops in SNR have not been studied and explained yet due to lack of time/funding.

SNR stability in June-August 2017 (Fig. 4) was good with some drops due to rain on the radar site.

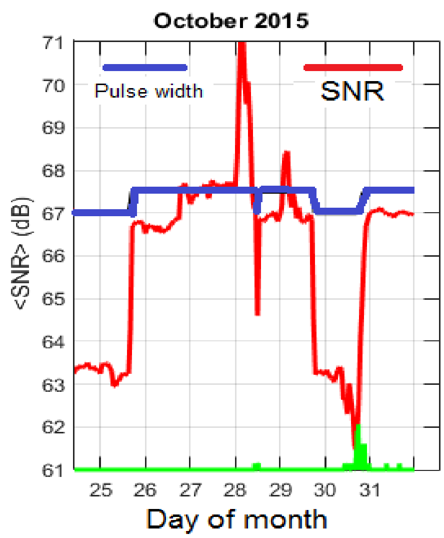


*Fig. 5. Mean SNR from ground clutter on 24-31 October 2015. WSR-88D KOUN. The rain rate is in green.*

KOUN is Research & Development radar and is used to test experimental VCPs. Some of such VCPs were used in this project to test ground clutter algorithms. An example of running VCP-51 and -52 is shown in Fig. 6. VCP-51 is an experimental pattern for testing the staggered PRT sequence. VCP-52 is a batch pattern ran at low elevation angles. On 19 May 2017, these VCPs were alternating. SNR from ground clutter for batch VCP-52 is shown in Fig. 6. The decrease in SNR at about 15 UTC is due to rain at the radar site. The big drop around 20 UTC was caused by malfunction of the radar transmitter. KOUN's RF Generator's STALO signal dropped abruptly and the RF Drive pulse dropped as well causing very low Transmitter pulse power. STALO remained low from 20:18Z through 21:41Z. There were many alarms indicating malfunction of the RF Generator. Very low STALO also reduced H and V receiver sensitivity. The receivers still worked, but lost 0.6 dB in sensitivity (Fig.6c).


*Fig.6. (a): SNR from ground clutter collected with KOUN 19 May 2017 using VCP-52. (b) ROCSTAR data on the transmitter power. (c) Same as in (b) but for noise levels in the horizontal (blue) and vertical (brown) channels.*

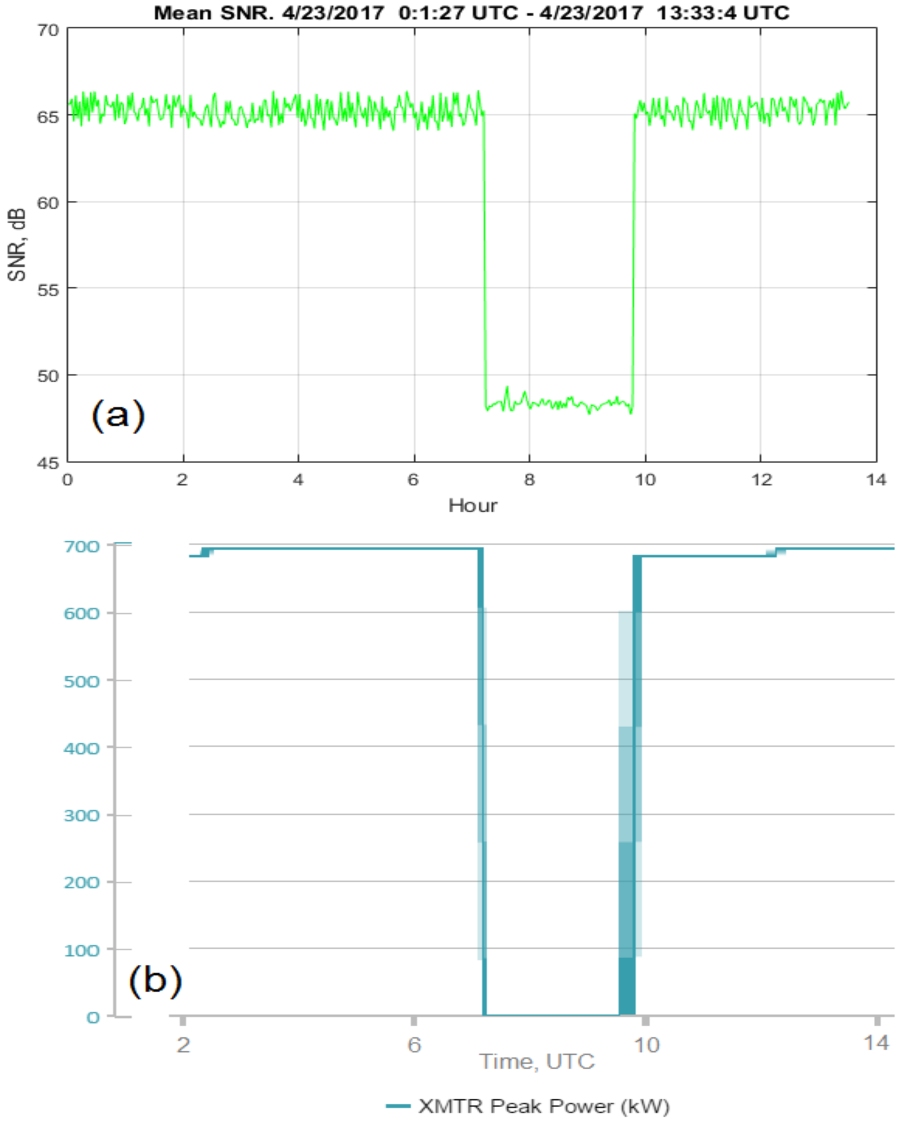


*Fig. 7. (a): The mean SNR from ground clutter on 23 April 2017. (b): The transmit peak power (kW) obtained from the ROCSTAR. WSR-88D KOUN.*

A similar transmitter malfunction was observed on 23 April 2017 (Fig. 7). At about 0630 UTC, SNR of ground clutter lost about 12 dB (Fig. 7a). At that time, KOUN had multiple missing STALO alarms, STALO signal was on and off and the transmitter was on and off as well. This malfunction led to the drop in the mean reflected power. Fig. 7b shows signal from the power sensor. If the power drops by more than 10 dB, the sensor reports no power as in Fig. 7b.

We conclude that SNR from the ground can be used to monitor the stability of reflectivity measurements; the receivers and transmitter are monitored. If the radar is functioning properly, the variations in SNR are well within ±1 dB with the standard deviations of about 0.25 dB. Some hardware malfunctions indicated by SNR from the ground can be obtained from an analysis of the radar performance log (malfunctions of STALO and antenna pointing). The increase in radar sensitivity after the system tuning cannot be deduced from the log, but can be obtained from SNR from the ground. Thus real time display of the ground clutter SNR could alert operators of potential radar problems.

## 4. Monitoring the system $Z_{DR}$ bias

Time series of $Z_{DR}$ from ground clutter, obtained by using an algorithm described in section 2, are plotted in Figs. 8 and 9. Switching from the short pulse to long pulse leads to an increase in $Z_{DR}$ by about 0.10 - 0.15 dB, see March 8-9$^{th}$ and May 9$^{th}$.

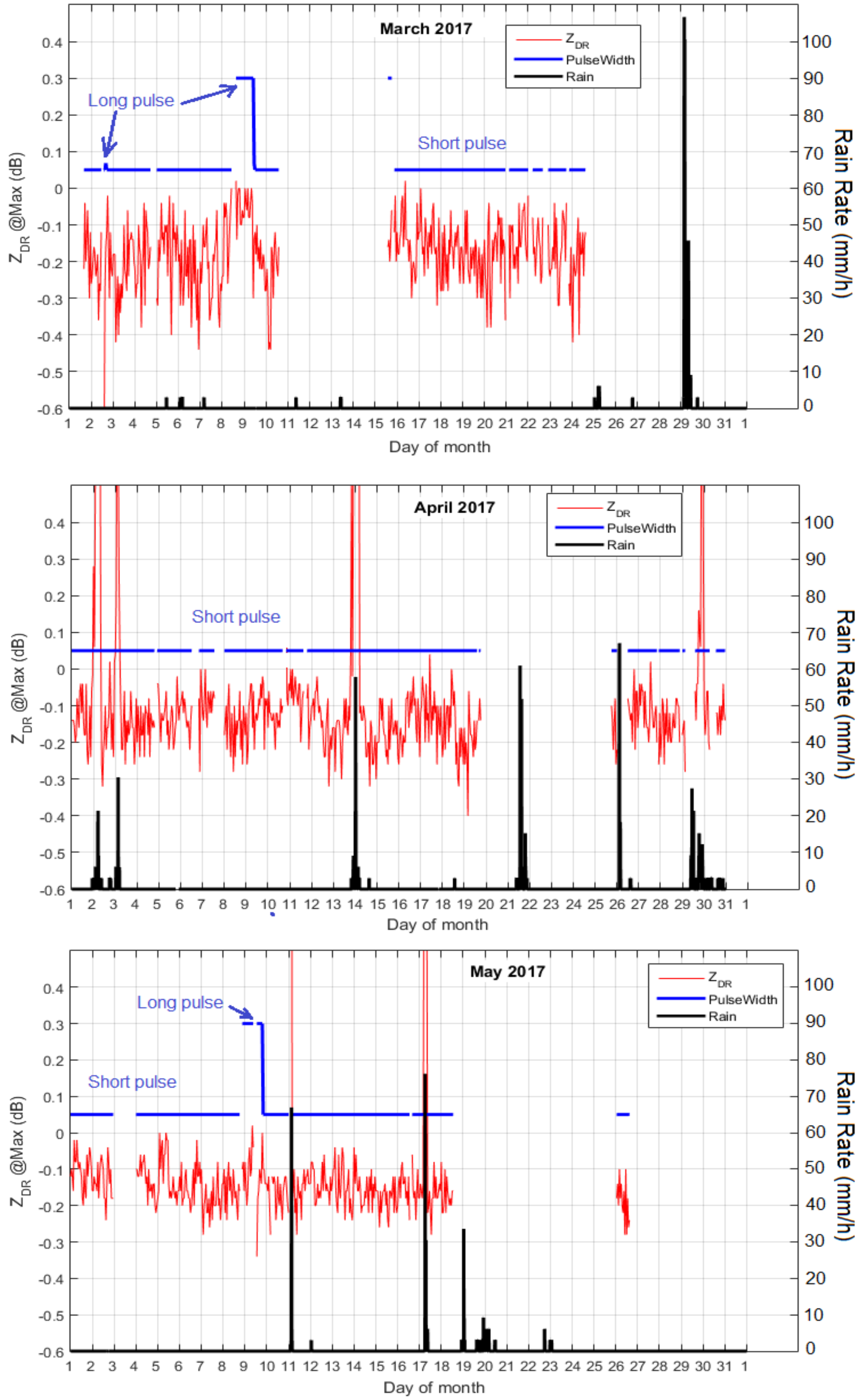


*Fig. 8. Time series of $Z_{DR}$ values at the maximum of there distribution for March – May 2017.*

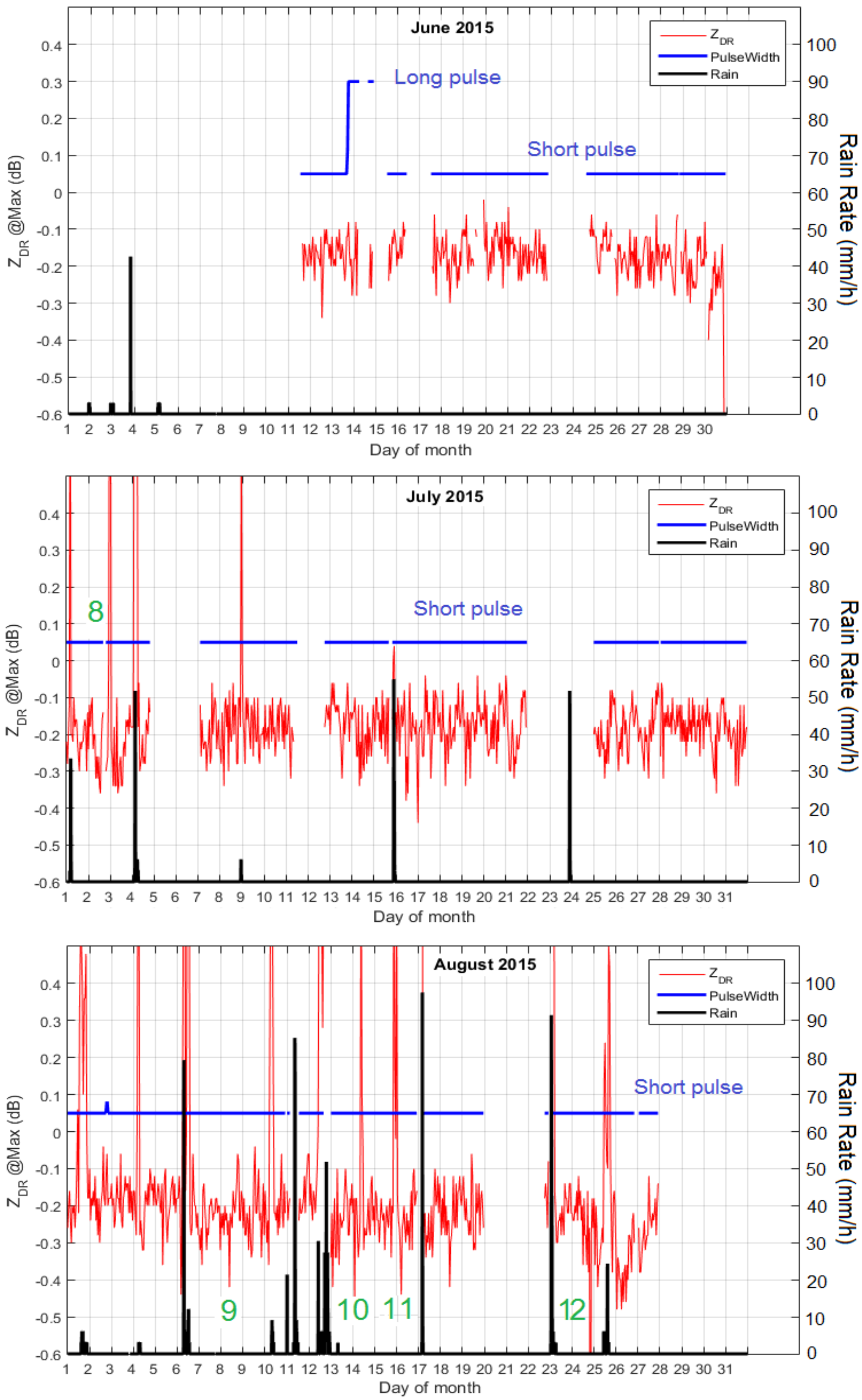


*Fig. 9. Same as in Fig. 5 but for July – September 2017.*

Fluctuations in $Z_{DR}$ values from the ground typically are within ±0.1 dB in fair weather if no switching between short and long pulses occurs. Changes in the total power do not impact $Z_{DR}$. $Z_{DR}$ values experience strong positive jumps in rain on the radar site. This is most likely due to vertical water streams on the radome in rain, which affect (attenuate and diffract) vertically polarized wave stronger than the horizontally polarized one. Some positive $Z_{DR}$ bumps remain unexplained, for instance, features 8, 10, and 11 in July and August 2017 (Fig. 9). In August 2017 some $Z_{DR}$ drops of about 0.2 dB were observed (features 9, 10, 11, 12), which remain unexplained also.

## 5. Decreases in SNR from the ground due to wet radome

A rain water film on a radar radome attenuates the transmitted and received waves. This leads to a decrease in reflectivity measured by radar. A correction for attenuation by wet radome is a problem in the quantitative precipitation measurements. It could be addressed by two approaches.

The first approach could be based on the measurements of noise power obtained at high antenna elevations, where thermal noise from precipitation is negligible. This approach assumes that the thickness of a water film is the same at high and low elevations. The thermal noise measurements at low elevations contain contributions from the water film on the radome and from precipitation along the radar radial. The difference in noise powers (power at low elevation minus power at high elevation) can in principle be related to attenuation. This approach could suffer from non-uniform water film on a radome. Very fine noise measurements are also needed.

The second approach could be based on measurements of ground clutter. Our measurements of SNR from ground clutter (Melnikov and Zrnic 2015) show that the SNR does not depend on wetness of the ground. So the drop in SNR during rain can be attributed to attenuation by the wet radome. This approach has also few weaknesses. Firstly, the water film on a radome is most likely not uniform but SNR from the ground is measured using signals from the whole $360^{o}$ sweep. If SNR is measured from a smaller sector, the power fluctuation would be larger and obtaining the mean SNR would be less reliable. Secondly, a Mesonet disdrometer measures the rain accumulation over 5 minutes. So the rain rate is the mean value over 5 min period. It is known that rain can be very variable during such a time period. Thirdly, the duration of the radar VCP is typically more than 5 min. The rain rates are measured by radar at low elevations, which are scanned every 5-6 min and not synchronized with the Mesonet measurements. Fig. 10 presents a scatterplot of the mean SNR drops (the blue circles) as a function of rain rate obtained from the NRMN Mesonet station located about 200 m to the West from KOUN. The red line presents a mean dependency. One can see that scatter of measured SNR is rather large. This could be due because of the issues mentioned above. There is a need to refine this relation by getting data on the rain rate more frequently (every 30 sec?) and link these data to the SNR drops more closely in time.

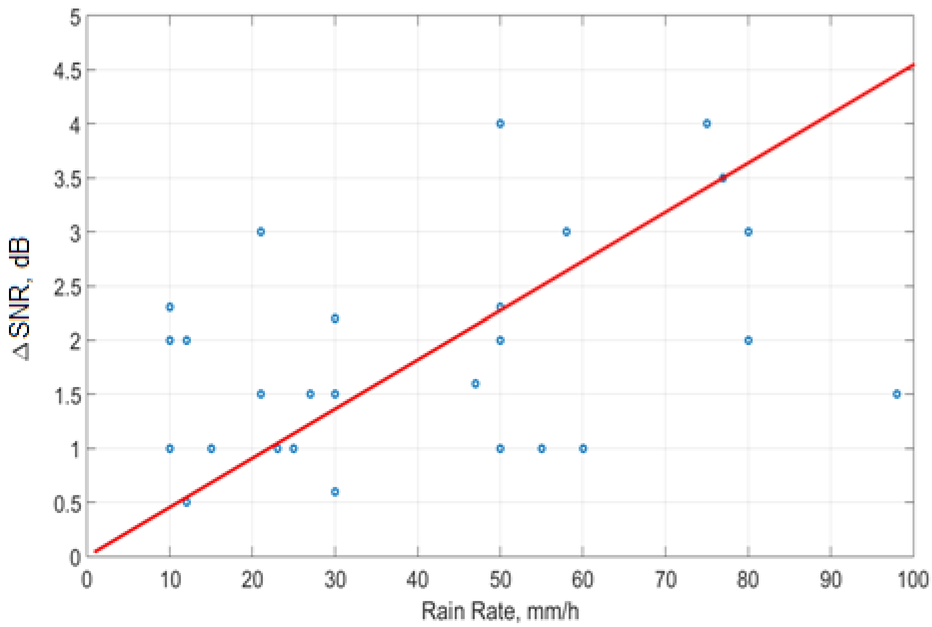


*Fig. 10. Drops in SNR from ground clutter (the blue circles, ΔSNR) in rain on the radar site as a function of the rain rate obtained from the NRMN Mesonet station. The red line is the mean approximation.*

## 6. Conclusions and recommendations

Radar signals from the ground have been processed to establish its stability for monitoring reflectivity and differential reflectivity. The processing consists of the Fourier transformations, selecting spectral lines from the interval ±0.5 m $s^{-1}$, and computing SNR and $Z_{DR}$. SNR from the ground can be used to monitor the stability of reflectivity measurements. If the radar is operating properly, the variations in SNR are well within ±1 dB with the standard deviations about 0.25 dB. Some hardware malfunctions indicated by SNR from the ground can be obtained from the radar performance log (e.g., the malfunctions of STALO and antenna pointing). The alternations in radar sensitivity after the system tuning cannot be deduced from the log, but can be obtained from ground clutter SNR.

Fluctuations in $Z_{DR}$ values from the ground typically are within ±0.1 dB in fair weather if no switching between short and long pulses occurs. Changes in the total power typically do not impact $Z_{DR}$. In rain on the radome, $Z_{DR}$ values experience strong positive jumps, which are most likely due to vertically oriented water streams on the radome. Such streams attenuate and refract vertically polarized wave stronger than the horizontally polarized one. Some positive $Z_{DR}$ bumps remain unexplained because of lack of time and funding.

To check the hardware calibration of $Z_{DR}$, the rain, snow, and Bragg scatter methods are used operationally. These methods require certain weather conditions and therefore cannot be used continuously. The ground clutter approach monitors the transmitter and receivers and can be used continuously.

There is correlation between the drops in SNR from the ground and the rain rate on a radar site when radar radome is wet. This can be potentially used to correct precipitation reflectivities when a radar radome is wet. The preliminary analysis (section 5) exhibits a rather wide scatter between the observed drops in SNR and the rain rate estimated from rain accumulations measured by a Mesonet station. To refine such dependence, more accurate rain measurements and synchronous radar observations are needed.

Returns from the ground cannot provide absolute calibrations of Z and $Z_{DR}$. Absolute calibration of Z remains one of the unsolved problems of radar meteorology. The literature contains an approach for absolute calibration of Z based on so called self-consistency, which uses a relation between Z, $Z_{DR}$, and $K_{DP}$ (the specific differential phase) in rain. If two of the three variables are known with sufficient accuracy, the third can be obtained from the consistency relation for rain drops. According to the literature, this relation weakly depends on the size distribution of rain drops. About 70% of the WSR-88Ds have the system ZDR bias within ±0.2 dB (R. Lee, communication at the DQ meeting in September 2017). In moderate rain, $K_{DP}$ can be measured with a sufficient accuracy. If $Z_{DR}$ accuracy of ±0.2 dB is sufficient to calibrate Z with accuracy better than ±1 dB using the consistency relation, this approach can be used operationally as a routine on the RPG. This requires further study.

### Recommendations

- $Z$ and $Z_{DR}$ monitoring by using ground clutter is recommended to be implemented operationally. This approach has many potential benefits in the diagnostic of radar hardware and correcting measured reflectivity for wet radome.
- More study is needed to connect some features of SNR and $Z_{DR}$ from the ground with changes in radar hardware.
- More study is needed to use SNR from the ground to correct the drops in weather reflectivity in situations with wet radome.
- $Z_{DR}$ from the ground could be used to study possible dependence of system $Z_{DR}$ on ambient temperature.
- A possibility to absolute calibrate reflectivity by using the consistency relations should be studied.

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### References

Atlas, D., 2002: Radar Calibration: Some Simple Approaches. *Bull. Amer. Meteor. Soc.*, **83**, 1313–1316.

Bringi, V. N., and V. Chandrasekar, 2001: *Polarimetric Doppler Weather Radar. Principles and Applications.* Cambridge University Press. 636 pp.

Cunningham, J.G., W. D. Zittel, R. Lee, and R. L. Ice, 2013: Methods for identifying systematic differential reflectivity (ZDR) biases on the operational WSR-88D network. 36th Conf. Radar Meteor. AMS, Breckenridge, CO. Available online at: https://ams.confex.com/ams/36Radar/webprogram/Paper228792.html

Doviak, R.J., and D. S. Zrnic, 2006: *Doppler radar and weather observations*, 2nd ed., Academic Press, 2006. 562 pp.

Frech, M., M. Hagen, and T. Mammen, 2017: Monitoring the Absolute Calibration of a Polarimetric Weather Radar. *J. Atmos. Oceanic Technol.*, **34**, 599-615.

Gorgucci, E., G. Scarchilli, and V. Chandrasekar, 1999: A procedure to calibrate multiparameter weather radar data using the properties of the rain medium. *IEEE Trans. Geosci. Remote Sens*., **17**, 269–276.

Hoban, N.P., J. G. Cunningham, and D. Zittel, 2014: Estimating Systematic WSR-88D Differential Reflectivity (ZDR) Biases Using Bragg Scattering. *30th Conf. Environmental Information Processing Technologies.* AMS, Atlanta. Available online at: https://ams.confex.com/ams/94Annual/webprogram/Paper237404.html

Hubbert, J., M. Dixon, S. Ellis, and G. Meymaris, 2009: Weather radar ground clutter. Part I: Identification, modeling, and simulation. *J. Atmos. Oceanic Technol*., 26, 1165–1180.

Hubbert J.C., 2017: Differential Reflectivity Calibration and Antenna Temperature *J. Atmos. Oceanic Technol*., **34**, 1885-1906.

Ice, R.L., A. K. Heck, J. G. Cunningham and W. D. Zittel, 2014: Challenges of polarimetric weather radar calibration. ERAD 2014 - The Eighth European Conf. Radar Meteorol. Hydrology, Germany. Available online at: http://www.pa.op.dlr.de/erad2014/programme/ExtendedAbstracts/117_Ice.pdf

Louf, V., A. Protat, C. Jakob, S. Rauiyar, R., Warren, 2017: The relative calibration adjustment technique for calibrating australian operational radars in near real-time. 38th AMS Weather Radar Conference, Chicago. Available online at: https://ams.confex.com/ams/38RADAR/meetingapp.cgi/Paper/320618

Melnikov, V., and D. Zrnic, 2015: Feasibility of monitoring ZDR calibration using ground clutter. NSSL interim report, 34 pp. Available online at: http://www.nssl.noaa.gov/publications/wsr88d_reports/NPI_2015_report.pdf

Richardson, L. M., J.G. Cunningham, W.D. Zittel, R.L. Lee, R.L. Ice, V.M. Melnikov, N.P. Hoban, and J.G. Gebauer, 2017: Bragg scatter detection by the WSR-88D. Part I: Algorithm development. *J. Atmos. Oceanic Technol.,* **34,** 465-478.

Sugier, J., and P. Tabary, 2006: Evaluation of dual polarization technology at C-band for operational weather radars as part of the EUMETNET OPERA program. 4th European Conf. Radar Meteorol. Hydrolog., Barcelona, Spain. http://www.crahi.upc.edu/ERAD2006/proceedingsMask/00010.pdf

Vaisala Co., 2014: Meteorological Solutions Worldwide. http://www.vaisala.com/en/meteorology/products/weatherradars/Pages/default.aspx

Williams, E., K. Hood, D. Smalley, M. Donovan, V. Melnikov, D. Forsyth, D. Zrnic, D. Burgess, M. Douglas, J. Sandifer, D. Saxion, O. Boydstun, A. Heck, and T. Webster, 2013: End-to-end calibration of Nexrad differential reflectivity with metal spheres. 36th Conf. Radar Meteor. AMS, Breckenridge, CO. Available online at: https://ams.confex.com/ams/36Radar/webprogram/Paper228796.html

Zhang, J., K. Howard, C. Langston, S. Vasiloff, B. Kaney, A. Arthur, S. Van Cooten, K. Kelleher, D. Kitzmiller, F. Ding, D-J. Seo, E. Wells, C. Dempsey, 2011: National Mosaic and Multi-Sensor QPE (NMQ) System: Description, Results, and Future Plans. *Bull. Amer. Meteor. Soc.*, 92, 1321-1338.