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ANALYSIS OF 94 GHZ CLOUD RADAR CALIBRATION BASED ON DISDROMETER MEASUREMENTS

Felix Yanovsky[1,2], Christine Unal[1], Aleksander Pitertsev[2], Herman Russchenberg[1]

Delft University of Technology, the Netherlands[1]
National Aviation University, Kyiv, Ukraine[2]

ABSTRACT

This paper describes the results of the research fulfilled in TU-Delft by joint Ukrainian and Dutch team. It analyzes multi-instrument rain observations, using the instrument set, which includes W-band cloud radar, laser optical disdrometers, weather station, and microwave radiometer. New friendly interface software is developed, presented, and used as a tool for comparison and fusion of diverse sensors datasets. The results obtained demonstrate the synergy of multi-instrument measurements and corresponds to the overarching trends of big data analysis. The intricacies of combining data from various sources to enhance calibration and improve the accuracy of atmospheric studies is discussed. In particular, analysis of 94 GHz cloud radar calibration based on disdrometer measurements with application of additional multi-instrument measurements is performed.

Index Terms—remote sensing, signal processing, data processing, calibration, data fusion

1. INTRODUCTION

The precision and accuracy of meteorological instruments are paramount to reach reliable and maximally useful results in weather, climate and other applications related to atmospheric observations. However, the accuracy of any instrument is always limited, and this is especially obvious when researchers are dealing with indirect measurements as it is in the remote sensing of the atmosphere. Multi-instrument measurements can play a crucial role in enhancing the accuracy and comprehensiveness of such observations. The measurements fulfilled with a set of different instruments give a chance to get more accurate information even when each instrument separately is not accurate enough. For this special signal and data processing is used leading to final more reliable result based on data fusion. Moreover, multi-instrument measurements open great possibilities for instrument calibration, that is, help to improve the accuracy of an instrument that can then be also used separately for more accurate quantitative remote sensing after the calibration.

Meteorological radar is a typical remote sensing instrument. A lot of methods have been developed for radar absolute calibration over different parameters, first, over radar reflectivity Z [1-5], and they mostly describe calibration of S-, C- and X-band radars. Nowadays, cloud radars operating at 94 GHz (W-band) are important in providing high-resolution data crucial for understanding cloud dynamics and other atmospheric phenomena. However, the challenge of calibrating these sophisticated instruments still is a significant hurdle in ensuring data reliability. Traditional methods cannot be directly applied for calibration of W-band radar due to several reasons. The most important is the inapplicability of Rayleigh approximation for radar cross section (RCS) of a droplet because its size becomes of the same order as the wavelength, and RCS is subjected to Mie theory [6].

Several articles are devoted to calibrating millimeter weather radar [7-9]. Detailed study to W-band radar is done in [10], where two basic approaches are adapted particularly for W-band meteorological radar, namely: the self-consistency method and the disdrometer-based method. The first one is reasonable to be applied when no additional instruments are available, but the second one corresponds to our concept of multi-instrument measurements and is applied in this research. Implementing this method for calibration using a large amount of data involves a lot of complex calculations. Therefore, in our previous work [11], the first version of user-friendly software was developed as a tool for automatically selecting the relevant data files recorded from various measuring devices, and the basic mathematical transformations are implemented for the correct comparison of these data, in particular, the disdrometer data (distribution of droplets by size and speeds) and W-band radar (reflectivity and Doppler spectrum).

In this paper, we present a new modified version of this software, and most importantly, the results of a study carried out with its help based on multi-instrumental measurements carried out for three years in the Netherlands. These data were used to verify the calibration of the 94 GHz cloud radar. Our analysis encompasses a series of multi-instrument experiments and field studies in rains of different intensity, where we meticulously compared the 94 GHz cloud radar readings with corresponding disdrometer and weather station measurements under various atmospheric conditions. This comparative approach not only validates the effectiveness of disdrometer-based calibration but also sheds light on the limitation of devices and intricacies of cloud/rain microphysics as captured by W-band radars.

2. SENSORS AND DATA

The following measuring devices served as the sources of the data: 1) cloud radar operating in W-band; 2) optical laser disdrometer; 3) weather station. Hence, such experimental set included both remote sensing and in situ measuring instruments.

Radar. The RPG-FMCW-94-DP dual-polarization cloud radar [12] operates at a 94 GHz carrier (central) frequency. It provides high spatial resolution and good sensitivity to all types of hydrometeors, including cloud droplets. Performance characteristics of the radar can be found at [13]. The radar's Doppler capabilities enable the measurement of radial velocities, providing information on wind speed and direction within the observed atmospheric column. The FMCW technique allows for high range resolution. The narrow beam width of the 94 GHz radar reduces beam spreading. Further, a rain/snow/fog mitigation system based on a powerful dew blower and a heater allows avoiding liquid drops and ice on the hydrophobic antenna radomes. This is important for mitigating large attenuation due to the presence of liquid water on the antennas.

Disdrometer. Laser disdrometer system is the OTT Parsivel². It is a laser precipitation disdrometer [14], [15] designed for accurate and reliable measurement of various precipitation types and intensities. Using laser technology, the sensor captures detailed information on particle size, velocity, and type in the place where it is installed. In fact, the Parsivel² measures particle size distribution in the range of 0.3 to 25 mm and particle velocities from 0.2 to 20 m/s, providing detailed information on raindrop, snowflake, and hailstone characteristics. The OTT Parsivel² uses a high-resolution laser optical system to accurately measure precipitation parameters, providing reliable data even in low-intensity or mixed precipitation events. The sensor processes the raw data in real-time, calculating parameters such as precipitation intensity.

Weather station. The automatic Vaisala weather station, which is located on a pole in the radar system, is equipped with sensors to measure atmospheric pressure, air temperature, relative humidity, rainfall rate, wind speed, and wind direction. At least a part of this information is necessary for correct radar and disdrometer data comparison and fusion.

The radar and disdrometer data have been recorded using the netCDF file format. Disdrometer data are stored in monthly files with 1 min time resolution, while radar data are presented in hourly files for every 3.07 s. The data selection procedure is developed to provide comparing radar and disdrometer data at the same day and time automatically.

Among many other information, in radar data files we have the measured radar reflectivity Z_{rad}, which is proportional to the received power and presented in dBZ. A laser disdrometer directly determines drop size distribution (DSD) and drop velocity distribution, providing simultaneous measurement of 32 classes for drop sizes and velocities. Estimated radar reflectivity is also provided by disdrometer from the measured DSD in supposition of Rayleigh model, which is not applicable in W-band. So, the main problem is calculating radar reflectivity from disdrometer data, based on Mie scattering. There are many other issues, which should be taken into account and fixed by data processing.

The location of the disdrometer and the reflective volume of rain (radar bin) do not coincide. We are forced to ignore the mismatch in the horizontal position of the instruments, which is 150 m, assuming that the rain is uniform within these limits. However, the disdrometer is located on the ground, while, at vertical sounding, the height of the radar bin under observation corresponds to the range, which is chosen as close as possible but in the transmit and receive antenna overlapping zone (more than 200 m). This is a source of uncertainty, since falling raindrops, which serve as radar scatterers, will reach the sensitive area of the disdrometer only after some time delay. In addition to time coordination, it may be necessary to take into account the possible change of droplet sizes due to evaporation during the time they fall down from the radar bin height to the disdrometer.

3. ANALYSIS TOOL

The software tool for joint data processing from different measur instruments features a graphical interface, written in the MATLAB programming environment. The software combines a multitude of individual utilities and functions aimed at both preliminary and main data processing. Since the disdrometer data file contains information on measurements for an entire month, and the radar file only for one hour, to compare the readings, it is necessary to know on which day and hour it is advisable to perform this comparison. Furthermore, the instruments do not always operate in a 24/7 mode, and sometimes they can be disconnected for maintenance. Therefore, the software interface includes the option to select a folder with radar data for an entire month, which, in turn, contains folders with data for specific days, each with 24-hour measurement recordings.

After selecting a month folder, the software plots a graph of recorded rain rates for each day and hour, allowing to understand, which radar file and corresponding disdrometer observation period can be choosen for comparison.

For confidence in the accuracy of the disdrometer readings, disdrometers are placed in pairs at the same location, perpendicular to each other. The preliminary data processing allows selecting readings from both disdrometers and calculate the mutual correlation function based on the registered spectra of diameters and velocities of raindrops. If the correlation between the data of two disdrometers is above a certain established limit, then with a high probability such data can be trusted. Next, raw data from the disdrometer and the radar are read from the selected data files.

The disdrometer data is presented in the form of a 3-dimensional array, with axes for diameter, velocity, and time, in each cell of which the recorded number of droplets is noted. The radar reflectivity of each droplet is calculated using the Mie theory formulas with the help of the pytmatrix software package [16]. Subsequently, both the total reflectivity and the reflectivity spectrum for each droplet velocity are calculated. These data are compared with radar data, where both total and spectral reflectivity are already recorded in the data file after some preliminary processing of the raw radar reflected signal. Additionally, the software interface provides the ability to compensate on graphs for the time shift of the registered values, which is observed due to the difference in rain heights at which measurements were made. For a height of about 240 meters, this time shift, which is calculated by the maximum of the mutual correlation function of the reflectivity values of the radar and disdrometer, usually amounts to 60-80 seconds.

The software interface contains several tabs that allow for the comparison of such disdrometer and radar indicators as graphs of radar reflectivity, rain intensity, Doppler velocity, as well as the spectrum width and the average value of Doppler velocity, distributions of droplets by size, and others. Separate features are provided to either consider or disregard in reflectivity calculations the attenuation of the radar signal in droplets and gases, as well as the effect of reducing droplet diameter due to evaporation when falling from a certain height.

Additionally, the developed software tool allows viewing on a separate tab data from the weather station, such as graphs of humidity, temperature, and air pressure, which can also be considered in the calculations.

4. METHODOLOGY

The analysis tool is used in this paper for the first analysis of the calibration of a 94 GHz cloud radar. In [17], it is shown using simulations that the reflectivity factor of raindrops at a range of 250 m is on average 19 dBZ. This averaged value results of the combined effects of extinction and Mie scattering and is valid in the rain rate range, 3 to 10 mm h^{-1}.

Consequently, the methodology consists of selecting the reflectivity factor corresponding to the height of about 250 m in the case of vertical profiles of rain. Next, the rain rate data provided by the weather station are chosen in the range 3 to 10 mm h^{-1}, providing the final time intervals selection for the cloud radar data. With this rain rate range, the cloud radar data does not suffer severe attenuation yet.

Concerning the disdrometer, which acts as ground truth, this regime of rain rates prevents the underestimation of the computed reflectivity factor because of the presence of many small raindrops, which cannot be measured by the disdrometer. Further, when the cloud radar reflectivity factor shows an averaged value near 19 dBZ, while the averaged computed disdrometer reflectivity factor exhibits a significant deviation from this nominal value of 19 dBZ, we may re-examine the disdrometer data and their processing, in particular DSD, to compute the reflectivity factor at 94 GHz considering all losses and mismatches that were discussed above. The results will be presented as scatterplots between cloud radar and disdrometer reflectivity factor, with the accompanying statistics.

5. RESULTS

We analyzed the time profiles of rain reflectivity and Doppler spectrum data using one-hour samples. As an example, spectrograms of 12:00 to 13:00 on November 2, 2021, measured by a 94 GHz radar and by disdrometer are presented in Fig. 1 and Fig. 2 correspondingly.

Figure 3 presents scatter plots of disdrometer – cloud radar data, in particular, reflectivity, mean Doppler velocity, and Doppler spectrum width. These results are shown for illustration. The period of analysis is one hour, height of radar resolution volume location is about 250 m, and the rain rate is in the interval 3 to 10 mm/h. Moreover, this figure presents the friendly interface and its wide possibility to analyze big data accumulated during a long period. These results can be used for data comparison, data fusion, and cloud radar calibration.

The observations during period of 2021-2023 is covered by this research. Such comparative approach is used not only to validate the effectiveness of disdrometer-based calibration but also shed light on the limitation of the devices and intricacies of cloud/rain microphysics captured by W-band radars. As an example, Fig. 4 shows the comparative series of reflectivity measured by radar and processed from disdrometer DSD data. Radar data normally are a little bit bigger because disdrometer is not sensitive to droplets less than 0.2 mm while W-band radar fills them rather well and even still in Rayleigh zone.

6. CONCLUSION

The method of multi-instrument W-band radar calibration using disdrometers, radiometer and compact meteorological stations has been analyzed in detail. The issues and their solutions have been discussed.

The convenient friendly software has been developed for comparative analysis of the huge data base of GRS Dep, which contains W-band radar and laser disdrometer data during continuous measurements of rain characteristics.

Specialized MATLAB software tool for processing, comparison, and fusion sophisticated multi-instrument data has been developed, tested and used as the tool for correct comparison of radar reflectivity factors, Doppler spectra, mean and root-mean-square velocities. Applying the developed software tool, statistical analysis is doing now using the big data available.

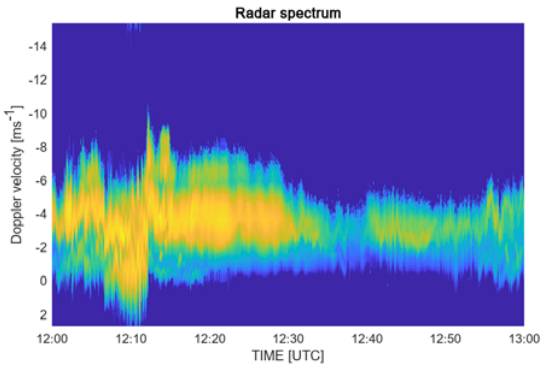

Fig. 1. Doppler spectrum measured by W-band radar.

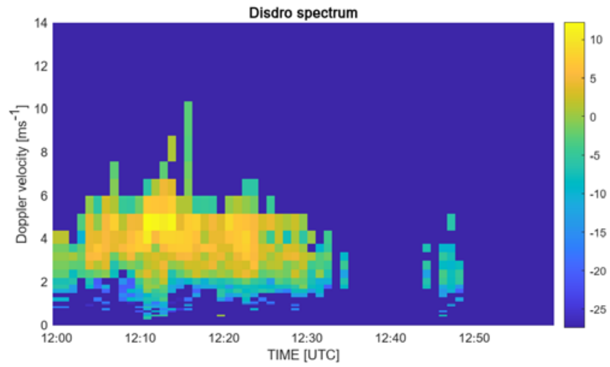

Fig.2. Doppler spectrum measured by disdrometer.

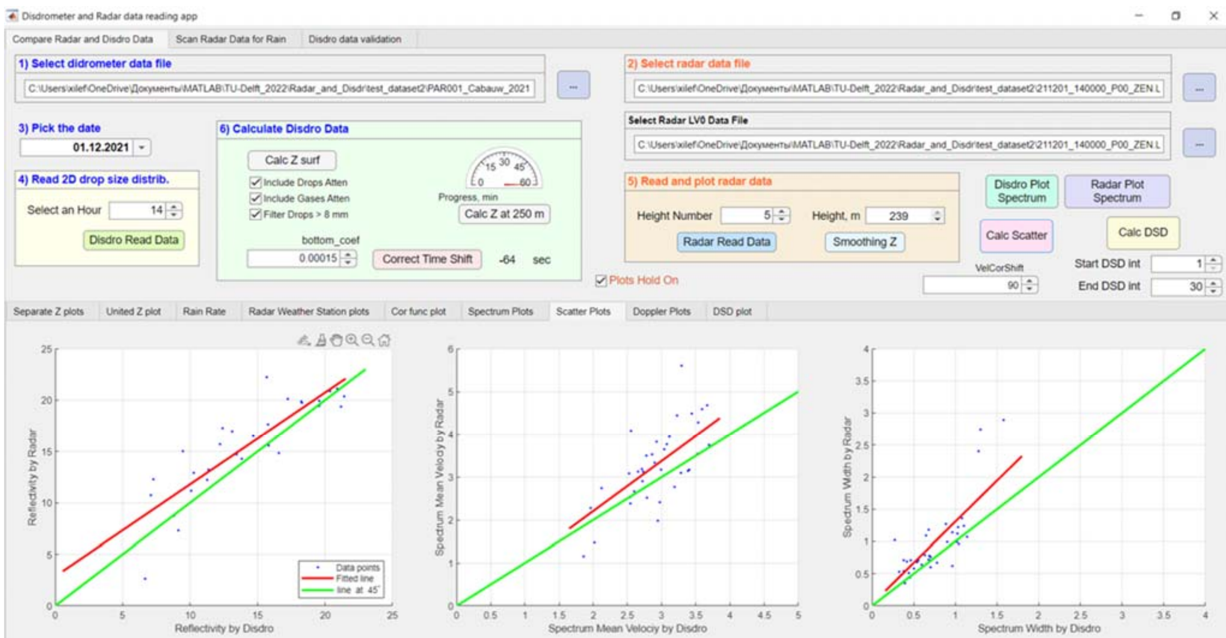

Fig.3. Scatter diagrams of measurands 'disdrometer – cloud radar', in particular: reflectivity, mean velocity of droplets, and RMS droplet velocity.

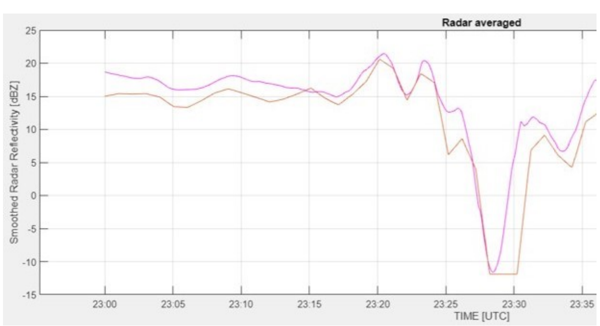

Fig.4. W-band radar (upper curve) and disdrometer reflectivity curves.

Multi-instrument rain observations using W-band cloud radar, laser optical disdrometer, radiometer, and weather station have been analyzed.

The developed software provides the possibility to calculate also polarimetric parameters from disdrometer DSD for comparison with multiparametric radar measurements. This should be done in the future research including the case of slant radar sounding and radiometric data.

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REFERENCES

[1] J. Yin, P. Hoogeboom, C. Unal, H. Russchenberg, F. Van Der Zwan, and E. Oudejans, "UAV-aided weather radar calibration," *IEEE Trans. GRS*, 57(12), 2019, pp. 10362-10375.

[2] S. A. Baun, A. C. Bagtzoglou et al, "Progress Towards Developing a Radar Calibration Method for Improved Rainfall Estimation," *Ninth ASCE Biennial Conference on Engineering, Construction, and Operations in Challenging Environments*, March 2004, pp. 290-298.

[3] C. Merker, G. Peters, M. Clemens, K. Lengfeld, and F. Ament, "A novel approach for absolute radar calibration: formulation and theoretical validation," *Atmos. Meas. Tech.*, 8, 2015, pp. 2521–2530.

[4] E. Gorgucci, G. Scarchilli, and V. Chandrasekar, "A Procedure to Calibrate Multiparameter Weather Radar Using Properties of the Rain Medium," *IEEE Trans. GRS*, vol. 37, No. 1, Jan. 1999, pp. 269-277.

[5] G. Scarchilli, E. Gorgucci, V. Chandrasekar, and A. Dobaie, "Selfconsistency of polarization diversity measurement of rainfall," *IEEE Trans. GRS*, vol. 34, Jan. 1996, pp. 22–26.

[6] Bohren, C. F.; Huffmann, D. R. *Absorption and scattering of light by small particles*. New York: Wiley-Interscience, 2010, ISBN 978-3-527-40664-7

[7] Felipe Toledo et al., "Absolute calibration method for frequency-modulated continuous wave (FMCW) cloud radars based on corner reflectors," *Atmospheric Measurement Tech*, vol. 13, issue 12, 2020, pp. 6853-6875.

[8] Ulrike Romatschke et al., "The NCAR Airborne 94-GHz Cloud Radar: Calibration and Data Processing," *Data* 2021, 6(6), 66; https://doi.org/10.3390/data6060066

[9] Lihua Li, Paul E. Racette, Gerald M. Heymsfield, and Lin Tian, Calibration of a 94 Ghz Airborne Cloud Radar Using Measurements from the Ocean Surface, *Goddard Earth Sciences and Technology Center*, https://ams.confex.com/ams/pdfpapers/64142.pdf.

[10] A. Myagkov, S. Kneifel, and T. Rose, "Evaluation of the reflectivity calibration of W-band radars based on observations in rain," *Atmospheric Measurement Tech*, vol. 13, issue 11, 2020, pp. 5799–5825.

[11] F. Yanovsky, A. Pitertsev, C. Unal, and H. Russchenberg, "Data fusion and processing tool for comparing rain reflectivity estimations using 94 GHz radar and laser disdrometer," *International Conference on Microwaves, Communications, Antennas, Biomedical Engineering & Electronic Systems*, COMCAS 2023, Tel Aviv, Israel, 6-8 Nov. 2023, 6 pp. (in press, postponed to 9-11 July, 2024).

[12] N. Küchler, S. Kneifel, U. Löhnert, P. Kollias, H. Czekala,and T. Rose, "A W-Band Radar–Radiometer System for Accurate and Continuous Monitoring of Clouds and Precipitation," *J. Atmospheric and Oceanic Tech,* vol. 34, pp. 2375–2392, 2017.

[13] https://www.radiometer-physics.de/products/microwave-remote-sensing-instruments/94-ghz-fmcw-doppler-cloud-radar/#tabs-container-5

[14] A. Tokay, D. B. Wolff, and W. A. Petersen, "Evaluation of the new version of the laser-optical disdrometer, OTT parsivel^2," *J. Atmos. and Oceanic Tech,* vol. 31, no. 6, pp. 1276–1288, 2014.

[15] OTT Parsivel² - Laser Weather Sensor, ott.com/products/ meteorological-sensors-26/ott-parsivel2-laser-weather-sensor-2392/productAction/outputAsPdf/

[16] JLeinonen/PyTMatrix. A Python code for computing the scattering properties of homogeneous nonspherical scatterers with the T-Matrix method. https://github.com/jleinonen/pytmatrix

[17] R. J. Hogan, D. Bouniol, D. N. Ladd, E. J. O'Connor, and A. J. Illingworth, "Absolute Calibration of 94/95-GHz Radars Using Rain," *J. Atmos. and Oceanic Tech,* vol. 20, pp. 572–580, 2003.