Multi-Sensor Data Fusion Based on Millimeter Radar and Laser Disdrometer

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***Abstract*—This paper is devoted to discussing peculiarities of multi-instrument measurements of rain using millimeter band radar and laser optical disdrometers as basic sensors with application of weather station and radiometer as sources of additional information. After brief discussion of meteorological radar application for quantitative information obtaining, the paper considers the problems and their possible solutions in respect to data fusion and comparison the results of measurements with sensors of different physical nature. 94 GHz radar, laser optical disdrometers, weather station and potentially the radiometer are considered as information sources. Experimental part of the research is based on measurements of rain provided during several years at the experimental range located in Cabauw, the Netherlands. Specialized MATLAB software with friendly interface is developed for this sophisticated processing and used for fusion and comparison of 94 GHz radar data with non-radar synchronous data**

Keywords—weather radar, data fusion, multi-sensor measurements, remote sensing, W-band radar

I. INTRODUCTION

The accuracy of any instrument is of paramount importance to obtain reliable and most useful results. This concerns also weather, climate and other observations provided with meteorological radar. However, the accuracy of any instrument is always limited, and this is especially obvious when researchers are dealing with indirect measurements, as is the case with atmospheric remote sensing. Multi-instrument measurements can play a critical role in improving the accuracy and completeness of these observations. Measurements made by a set of different instruments make it possible to obtain more accurate information, even if each instrument individually is not accurate enough. For this purpose, special signal and data processing should be used, giving a final more reliable result based on data fusion. In addition, measurements with several instruments open up great opportunities for instrument calibration, i.e. help improve the accuracy of the instrument, which can then be used separately for more accurate quantitative remote sensing after calibration.

Many methods have been developed for absolute calibration of radars according to various parameters, firstly, according to the radar reflectance *Z*. These methods are described in many publications, for example [1-5]. They typically describe the calibration of S-, C-, and X-band radars.

Currently, cloud radars operating at 94 GHz (W-band) play an important role in providing high-resolution data needed to understand cloud dynamics, precipitation processes and atmospheric phenomena. However, the challenge of accurately calibrating these complex instruments is a significant barrier to ensuring data reliability. Traditional methods cannot be directly applied to calibrate millimeter wave radar for several reasons. The most important among them is the inapplicability of the Rayleigh approximation for the radar cross section (RCS) of a drop, since its size becomes in the same order as the wavelength, and the RCS obeys Mie theory [6].

There are several articles devoted to the calibration of weather radar operating in the millimeter wave range [7-9]. A detailed study on W-band radar calibration is carried out in [10], where two main approaches are adapted, namely the self-consistency method and the disdrometer-based method. The first is appropriate to use when there are no additional instruments other than a calibrated radar, but the second is consistent with our concept of multi-instrument measurements and is applicable in this study.

Implementing this method for calibration using large amounts of data involves many complex calculations. Therefore, in our previous work [11], the first version of user-friendly software was developed as a tool for automatically selecting relevant data files recorded from various measuring devices, and basic mathematical transformations were implemented to correctly compare these data, in particular, data from the disdrometer (droplet size and velocity distribution) and W-band radar (reflectivity and Doppler spectrum). It is important to take into account that both instruments provide indirect measurement only, and you never can be sure, which of them can be taken as an etalon.

In this paper we present a new modified version of the processing software and, most importantly, the results of data fusion based on multi-instrument measurements that mutually supplements each other increasing accuracy and the reliability of the information obtained.

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II. Sensors and Data Characterization

A. Radar

The RPG-FMCW-94-DP cloud radar of Radiometer Physics, Rohde & Schwarz Company [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. With dual-polarization (DP) capabilities, the system can provide additional information about hydrometeor shape and orientation, averaged over the resolution volume. 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, enabling the radar to detect fine-scale vertical structures in clouds and precipitation. The narrow beam width of the 94 GHz radar reduces beam spreading and ground clutter, resulting in more accurate measurements of low-level atmospheric features. Although signal attenuation is more significant at 94 GHz, the radar's high sensitivity and polarimetric measurements help compensate for these effects in the case of light to moderate precipitation. 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.

B. Optical 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 sensor can automatically classify precipitation into different types, such as drizzle, rain, snow, mixed precipitation, and hail, based on the measured particle size and velocity data.

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.

C. Weather station

The automatic Vaisala weather station, which is located on a pole in the radar system, is equipped with sensors to measure meteorological parameters, more exactly, 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

D. Radiometer

The ground-based radiometer is the RPG-HATPRO-G5, which is a sophisticated passive microwave system designed for obtaining vertical profiles of atmospheric temperature and humidity, with its technology enabling a wide range of meteorological observations and applications. This system is characterized by its use of microwave and infrared technologies to derive detailed atmospheric data, including temperature profiles, humidity levels, and cloud liquid water content. The RPG-HATPRO-G5 [16] operates across two frequency bands: 22-31 GHz (seven channels) for humidity profiling and 51-58 GHz (seven channels) for temperature profiling. It uses a combination of microwave radiometry and infrared measurements to detect and measure atmospheric conditions. The system is designed to operate in various environmental conditions and can be used as a standalone system for automated weather-station applications.

In contrast to other systems that utilize a sequential channel scanning e.g. with a synthesizer (the classical spectrum analyzer concept) the RPG-HATPRO is capable of performing fast LWP (Liquid Water Path) sampling with 1 second time resolution and outstanding noise performance of < 2 g/m^2 RMS while simultaneously measuring full troposphere (up to 10 km altitude) profiles of temperature and humidity. Accuracy and vertical resolution for temperature profiling in the full troposphere (up to 10000 m, vertical resolution 150 m) and boundary layer (less than 1000 m, vertical resolution 50 m). For smaller heights better resolution is expected.

E. Data to be analyzed

The multi-instrument data processing being considered below is related to measurements of rain events done in the Delft University of Technology during long time. In this study, the data obtained in 2021-2023 were used for processing.

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; 4) radiometer. Hence, such experimental set included both remote sensing using different physical principles and in situ measuring instruments.

III. Processing Algorithms and the Software for Analisis

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, that is, in logarithmic scale. A laser precipitation 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, that is, this estimation is not correct. That is why one of the data processing problems is calculating radar reflectivity from disdrometer data, based on Mie scattering. However, 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, normally more than 200 m. This is a source of uncertainty, since falling raindrops, which serve as radar signal 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 droplets sizes due to evaporation during the time they fall down from the radar bin height to the disdrometer.

The developed earlier software [11] was significantly modernized. The software tool for joint data processing from different measurement instruments has a graphical interface, written in the MATLAB programming environment. This tool 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 of the instruments, it is necessary to know on which day and hour it is advisable to perform this comparison. Furthermore, as the analysis of the recorded data shows, the instruments do not always operate in a 24/7 mode, and sometimes they can be disconnected for several days 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 the monthly folder, the program plots a graph of the recorded rain intensities for each available day and hour, allowing to understand which radar file and which observation period of the disdrometer is appropriate to choose for comparison.

For additional confidence in the accuracy of the disdrometer readings, disdrometers are placed in pairs at the same location, perpendicular to each other. The next step in preliminary data processing allows selecting readings from two disdrometers for the same moment of interest, and to calculate the function of mutual correlation of these instruments based on the registered spectra of diameters and velocities of raindrops. If the correlation between the two disdrometers is above a certain established limit, then with a high degree of probability, such data can be trusted, and then the comparison of the readings of one of the disdrometers and the radar is carried out.

Next, raw data from the disdrometer and the radar with some preliminary processing 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 [17]. 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. Moreover, during the time of falling from the height of the considered radar resolving volume down to the disdrometer, the drop undergoes evaporation. Therefore, the droplets that form the radar signal may be slightly larger than those measured by the disdrometer. The effect of evaporation is also taken into account using information on temperature, pressure and humidity got from a weather station and radiometer.

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.

IV. Methodology

The analysis tool is used in this paper for the first analysis of the calibration of a 94 GHz cloud radar. In [1], 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.

V. 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.

One can see a certain similarity to these spectra, although the radar data is updated every 3 seconds, and the disdrometer data every 1 minute. In addition, the disdrometer, unlike the radar, is not sensitive to small drops (<0.2 mm).

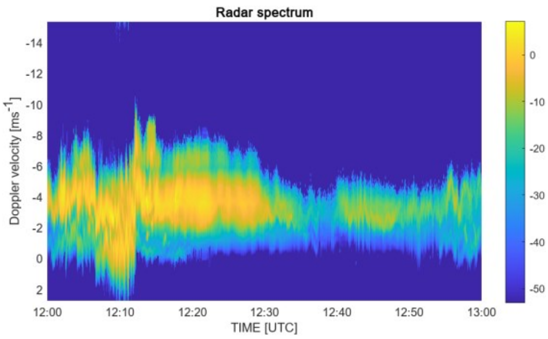

Fig. 1. Doppler spectrum measured by W-band radar.

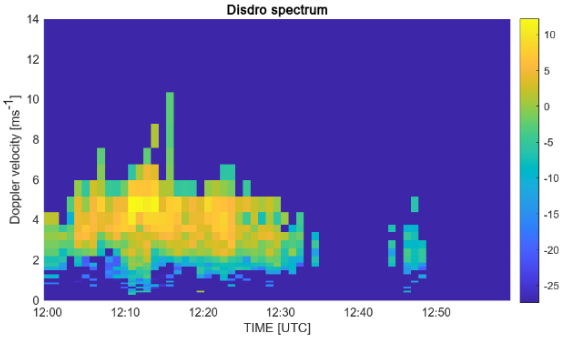

Fig.2. Doppler spectrum measured by disdrometer

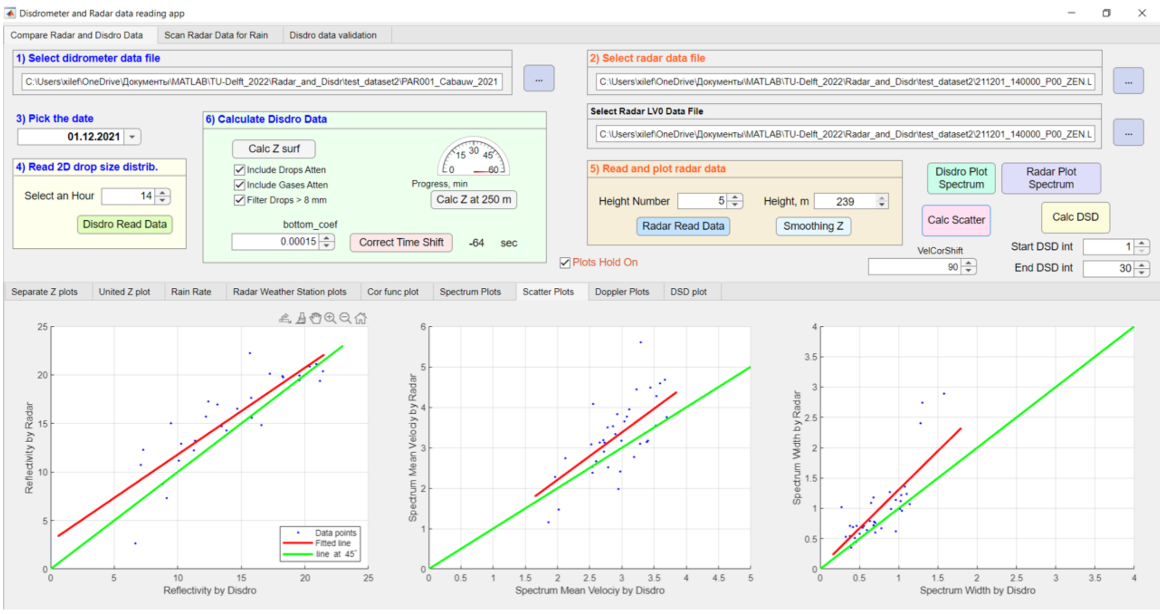

Fig.3. Scatter diagrams of measurands 'disdrometer – cloud radar', in particular: reflectivity, mean velocity of droplets, and RMS droplet velocity.

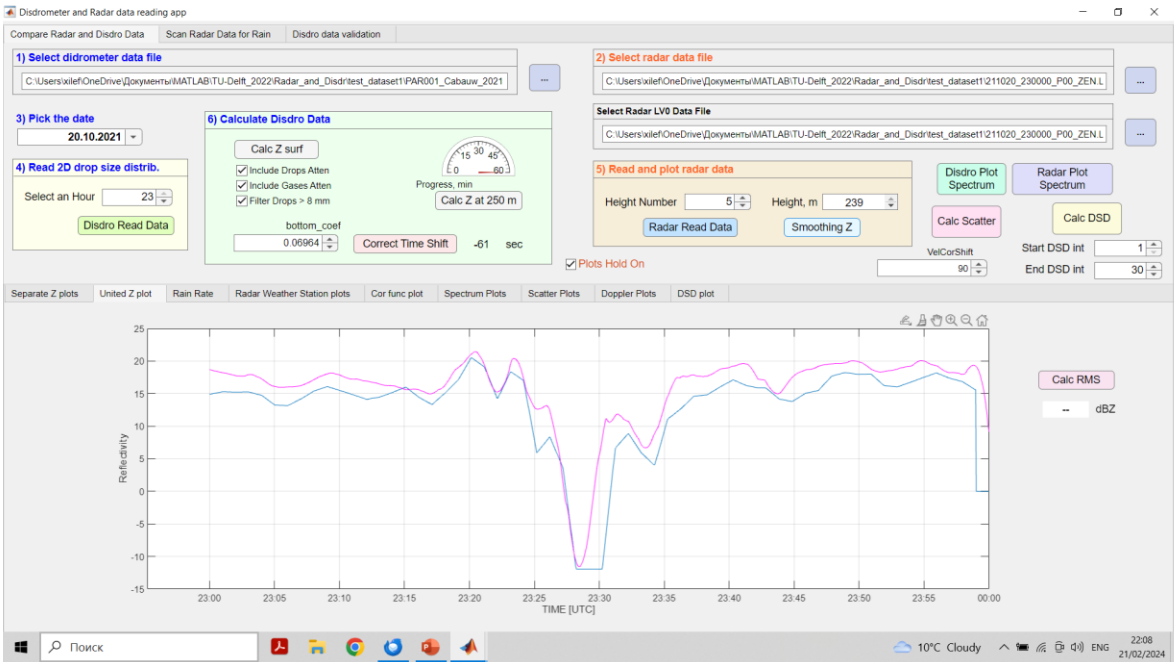

Fig.4. Combined measured radar reflectivity and calculated radar reflectivity from disdrometer data during one hour.

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 combined measured radar reflectivity and calculated radar reflectivity based on drop size distribution data measured by disdrometer are presented in Fig.4 during one hour.

It is also interesting to analyze statistical data for a selected period of time for objects characterized by certain parameters, for example, for rainfall with rain intensity within certain limits. The developed approach ensures the implementation of this option, which requires quite complex calculations. Period of 2021-2023 was covered. As an example, Fig. 5 shows the scatter plot of Z_{rad} and Z_{dis} for rain rates 3 to 10 mm/h during one month (October 2021).

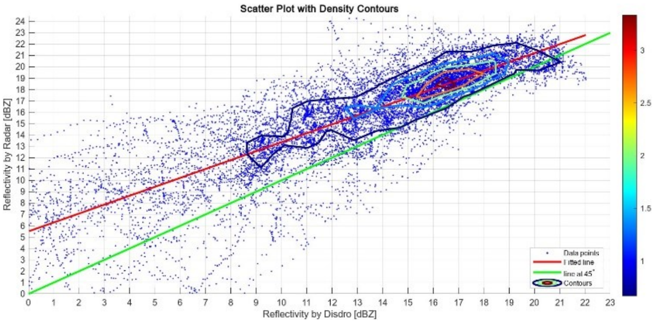

Fig.5. Scatter plot of Z_{rad} and Z_{dis} for October 2021, rain rates 3 to 10 mm/h.

Such comparative approach will be used not only to validate the effectiveness of disdrometer-based calibration but will also shed light on the limitation of the devices and intricacies of cloud/rain microphysics captured by W-band radars.

VI. Conclusion

Multi-instrument rain observations using W-band cloud radar, laser optical disdrometer, and weather station and radiometer have been analyzed. New friendly interface software has been developed and used as a tool for comparison and fusion of diverse sensors datasets. The results obtained have demonstrated the synergy of multi-instrument measurements, which correspond to the overarching trends of Big Data analysis. The intricacies of combining data from various sources to enhance calibration and improve the accuracy of remote sensing of atmosphere have been discussed, in particular the analysis of 94 GHz cloud radar calibration based on disdrometer rain measurements has been done.

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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 parsivel2,” 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] Rose, T., Crewell, S., Löhnert, U., Simmer, C., 2005. A network suitable microwave radiometer for operational monitoring of the cloudy atmosphere. Atmos. Res. 75, 183–200. https://doi.org/10.1016/j.atmosres.2004.12.005.

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

[18] 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.