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DOI
10.23919/SPSympo57300.2023.10302660

Publication date
2023

Document Version
Final published version

Published in
2023 Signal Processing Symposium, SPSympo 2023

Citation (APA)
Yanovsky, F. J., Pitertsev, A. A., Unal, C. M. H., & Russchenberg, H. W. J. (2023). Peculiarities and Experience of W-Band Cloud Radar Calibration. In *2023 Signal Processing Symposium, SPSympo 2023* (pp. 208-213). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.23919/SPSympo57300.2023.10302660

Peculiarities and Experience of W-band Cloud Radar Calibration

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***Abstract*— This paper is devoted to discussing peculiarities of W-band cloud radar calibration. After a brief overview of meteorological radar calibration methods for quantitative information retrieval, we focus on problems and their possible solutions with respect to mm-wave radar calibration. The experimental part of the research is based on multi-instrument measurements performed during several years in the Cabauw experimental meteorological site in the Netherlands. The accumulated data are used for comparison of 94 GHz radar rain measurements with non-radar droplet size distribution measurements, provided by laser disdrometers. Calculations are done taking into account data of other in situ meteorological measurements. A specialized MATLAB software tool for processing such complex data and radar calibration is developed and demonstrated.**

Keywords—radar remote sensing, signal processing, electromagnetic scattering, radar measurements, data integrity, data processing, sensor fusion

I. Introduction

The problem of meteorological radar calibration arose as soon as first attempts of quantitative measurements in radar meteorology began. First operational instruments in radar meteorology were S-band radars [1]. Moreover, they still are widely used in practice [2]. Later, C-band radars began to be also used, and then X-band radars, especially in some dual-wavelength systems were explored. Moreover, X-band became the basic and standard frequency range for airborne weather radars [3]. Millimeter wave radar systems of 8 mm and later 3 mm wavelength, first were just tested as experimental instruments for sounding of the atmosphere. Their operational application was at least difficult due to strong wave attenuation, especially in precipitation, as well as due to technological problems when generating and processing such high frequencies.

However, any disadvantage has also a back side: the strong scattering of millimeter waves by very small particles in the atmosphere makes millimeter-wave radars attractive tools for studying clouds, which weakly reflect lower-frequency signals. Fortunately, technological advances made in recent years have given a strong impetus to the emergence of operational radar systems in the 35 GHz and 95 GHz bands [4]. Often such radars used for atmosphere remote sensing are named as cloud radars to emphasize that their primary targets are clouds in contrast to precipitation.

Cloud radars differ from centimeter-band meteorological radars in significantly different models of scattering, absorption, and other effects that occur during propagation through the atmosphere. Moreover, the higher the operating frequency, the greater these differences. Having significant amount of measurement data at 94 GHz, in this article, we focus on the W-band, which is the shortest millimeter wave band used in practice.

The mentioned features of cloud radars lead to the fact that the known methods of calibration of weather radars cannot be directly applied to calibrate W-band radars.

In this article, we analyze the characteristics of cloud radars and feasible ways to calibrate them, and develop tools for processing signals and data from multi-instrument measurements in order to provide absolute calibration of W-band meteorological radars.

II. Known Calibration Methods

Absolute radar calibration is important for quantitative applications of radar measurements, such as estimating precipitation intensity or cloud hazard to aircraft. Many different parameters are measured by modern polarimetric radar, but the most important for absolute calibration is radar reflectivity of a weather object Z (reflectivity factor) [2]. Accurate estimation of Z is important itself for meteorology, and moreover, it influences strongly to measuring some other parameters. Under certain conditions, Z can be related to the microstructure of the weather object in the radar resolution volume. From the radar equation for meteorological objects, it follows that the received power P_r of the reflected signal, averaged over the sample, is proportional to the reflectivity Z:

$$\overline{P}_r = \frac{C_z Z}{R^2} \cdot |K|^2, \quad (1)$$

where R is the distance to the reflected volume, $|K|^2$ is a factor depending on the complex permittivity of the reflecting substance (for water equals to ≈0.93), and C_z is the dimensional coefficient depending on the radar parameters and different kinds of losses:

$$C_z = f(P_t, G_A, S_{r\min}, f_0, L_1 ... L_n, ...), \quad (2)$$

with P_t as transmitter power, G_A as antenna gain, $S_{r\min}$ as receiver sensitivity, f_0 as carrier frequency, $L_1 ... L_n$ as losses, etc.

By measuring the reflected power $\overline{P}_r$ the reflectivity Z can be measured, if $C_z = const$ is known. Calibration must ensure this condition. Internal calibration involves the use of a test signal that is circulated within the system to maintain critical parameters within proper limits. This is a task of radar designers. Our task is external calibration that covers the full cycle of receiving the reflected signal, including the formation of the sounding signal, propagation and the receiving channel.

Historically, the first method is the calibration using a reference target. Absolute calibration on a standard target by measuring the slant range and reflected signal power from a stable target with known RCS is capable of covering all parameters of the transmitter-medium-receiver tract and is quite accurate. Disadvantages are labor intensiveness and duration. Such measurements are difficult to organize: a pilot balloon with a winch or an UAV with a control system, GPS and communication means are required [5].

Another approach is a calibration using rain medium. The first idea is to compare the measurement of rain by radar and other means like rain-gauges, weather stations or disdrometers. This approach has many ramifications [6], [7]. Some of them have received significant development, especially with the advent of multiparameter polarization radars. In particular, the absolute calibration of a multiparameter meteorological radar using self-consistency of parameters [8]. Modern weather radars are mainly coherent and polarimetric, that is, multi-parameter systems. Among different radar parameters there are three following:

1) reflectivity $Z = Z_H$, where index H means horizontal polarization for definiteness;

2) differential reflectivity Z_{DR}=10lg(Z_H/Z_V), index V means vertical polarization;

3) specific differential phase $K_{DP}=[P_{DP}(R_2)-P_{DP}(R_1)]/(R_2-R_1)$, where $P_{DP}(R)$ is difference in phase between the horizontally and vertically polarized waves at distance R ($R_2>R_1$).

Theoretical analysis and natural radar observations of rainfall indicate that the measurement results of these three parameters are in a limited 3D space [9], more exactly:

$$K_{DP}^{*} = C Z_H^{\alpha} 10^{-\beta Z_{DR}}, \quad (3)$$

where the asterisk means calculated estimate of K_{DP} using measured values of two other parameters. Here Z_H [mm^6/m^{-3}] and Z_{DR} [dB]. The empirical coefficients C, α and β vary depending on the frequency and are well defined at least for S-band and C-band.

This self-consistency (3) can be used to determine calibration errors by comparing the measured K_{DP} with calculated K_{DP}^{*}. In the absence of measurement errors, the scatter diagram of measured K_{DP} and calculated K_{DP}^{*} should lie approximately on a straight 1:1 line. If the radar channels are not balanced, the scatter diagram deviates from the 1:1 line and its slope indicates the magnitude of the offset in the absolute calibration.

The obvious fact that Z_{DR} should be 0 dB when sounding into the zenith in a rainy medium, is additionally used for balancing polarization channels. Averaging is provided by rotating antenna around the vertical axis from 0 to 360°, maintaining the elevation angle of 90°. After such averaging, any non-zero averaged Z_{DR} directly indicates the asymmetry of the two polarization channels.

Even the radiation of Sun is useful for calibration [10]. First, solar radio-thermal radiation can be used to monitor radar antenna alignment and receiver stability. The calibration of the receiving path can be checked by comparing the radar data with the observations of the solar flux monitoring station. Moreover, Sun's noise powers at horizontal and vertical polarization are equivalent. This also can be used for calibration of Z_{DR}.

Finally, combined calibration methods of polarimetric meteorological radars can be reasonable. For example, combining self-consistency method (in case of rain) and ground-based passive clutter monitoring (at any weather) and intercomparing them for real-time monitoring can complement the limitations of each [11].

III. Problem of Millimeter Wave RadarCalibration

Millimeter-wave cloud radars (or simply cloud radars) are radar systems suitable for cloud monitoring. They operate at frequency range from 24 to 110 GHz, and most common around 35 GHz (Ka-band) and 94 GHz (W-band). The wavelength is 10-30 times shorter than that of X-band and S-band.

The delicate nature of mm-band components and the harsh conditions in which meteorological radars operate can lead to undetected performance changes even more often than in S-, C-, and X-band radars. That is why the calibration is especially important issue in case of mm radars in order to obtain meteorological object parameters with required accuracy.

The question arises: Can the methods developed for S-, C- and X-band radars be used to calibrate W-band radars? Obviously, known methods should be taken into account, but there is a significant difference in the processes of scattering and propagation that in some cases makes known methods inapplicable for the W-band.

The basic features of W-band taken into consideration are following:

- the attenuation is much stronger;
- the Rayleigh scattering model is inapplicable because wavelength and droplet sizes are of the same order;
- radar components can change characteristics uncontrollably to a greater extent;
- sensitivity to temperature is more pronounced;
- antennas and radomes should be protected from water;
- differential reflectivity Z_{DR} in the W-band is typically much less than in X-band for rain;
- estimating specific differential phase K_{DP} becomes more difficult in the W-band.

It is reasonable to assume that these features can be not only the sources of problems, but also encourage us for new engineering and technological solutions.

IV. Measuring Facilities and Data

Scientists, engineers and students at the Delft University of Technology have access to an impressive experimental base for research in radar meteorology. It includes: S-band and X-band radars and a weather station on the roof and in the attic of the 21-storey building of the Faculty of Electrical Engineering, Mathematics and Informatics; X-band and W-band radars, radiometers and weather stations at the research and teaching site of the Department of Geosciences and Remote Sensing on the University campus; a large meteorological research site in Cabauw, Utrecht in the center of the Netherlands, where various equipment is installed, including a 213-meter meteorological tower. This research site is the basic part of the Ruisdael Observatory, which is a national initiative in the Netherlands, a nationwide observatory for measurements of the atmosphere.

In this research, the W-band cloud radar, which is equipped with a weather station, and the laser disdrometer system were selected as the key sources of data. The radar and disdrometer are spaced by 60 m.

The RPG-FMCW-94-DP Doppler cloud radar [12] operates at a 94 GHz and is a dual-polarization radar system. The OTT Parsivel² laser precipitation disdrometer [13], [14] uses laser technology to capture information on particle size, velocity, and type in the place where it is installed. This sensor processes the raw data in real time, calculating parameters such as reflectivity and precipitation intensity using embedded algorithms.

Observations are made continuously and data from the output of all devices are recorded. For the analysis the data collected during 2021 – 2023 were selected. It is a huge amount of multi-instrument observations data, which include 94GHz radar sounding data at vertical sounding, laser disdrometer data corresponding to time, weather station data, and radiometer data. Radiometer data are not considered in this paper but can be useful for further research.

This brief overview of the instruments and data is taken into account for selecting a reasonable calibration method among the various possibilities considered in the next section.

V. Possible Approaches to Cloud Radar Calibration

Let us consider the applicability of calibration methods described in Section II, to W-band cloud radar. The traditional way of calibrating on a standard target is certainly universal and works accurately in all frequency bands. In principle, it is even possible to achieve high accuracy. But the shortcomings, noted above, in particular large organizational and labor costs, become even more acute in the W-band that limits its applicability. It is reasonable to carry out such calibration periodically, sometimes, but not as everyday instrument.

The self-consistency calibration method is attractive. However, this method is based on mathematical models that use Rayleigh scattering. Rayleigh model does not work in the W-band. The effect of non-Rayleigh scattering by raindrops destroys the self-consistency effect (3). It would be very interesting to find a way to adapt a similar approach for W-band radar, or should other advanced calibration methods be sought [15].

Remembering that the self-consistency method is not suitable at W-band since the effects of non-Rayleigh scattering by relatively large drops and strong wave attenuation destroy the self-consistency, it is attractive to transform this disadvantage to your advantage. Really, the greater the intensity of the rain, the greater the attenuation but also the greater the deviation from Rayleigh. That is why the reflectivity increases much more slowly with increasing rain rate in higher frequency bands. In [16] it was shown that at 94 GHz, these two effects are sufficient to cause Z measured at a short distance from the radar to have little dependence on rain intensity due to simultaneous action of these two effects. This feature allows to offer an original way to calibrate the 94 GHz cloud radar. Such calibration can be performed every time it rains.

Obviously, both self-consistency method and method of combining effects of wave attenuation & non-Rayleigh scatteringis are especially attractive, when there are no other sources of data except of the radar to be calibrated.

Comparison of rain measurements by radar and other means, in particular disdrometer, of course also works, but models and calculations become much more complex than for lower frequency bands. Given the availability of various devices for atmospheric research in our disposal and the accumulated data of multi-instrument measurements at TU Delft, we will dwell on this particular calibration approach in more detail below.

VI. Data Processing

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 Zrad, which is proportional to the received power (1) and presented in dBZ, that is, in logarithmic scale. Laser precipitation disdrometer directly determines drop size distribution (DSD) and drop velocity distribution, providing simultaneous measurement of 32 classes for drop sizes and velocities.

Radar reflectivity is provided by disdrometer from the DSD based on calculation using Rayleigh model, which is not applicable in W-band. That is why one of the data processing problems is calculation radar reflectivity from disdrometer data, based on Mie scattering. However, there are many other issues, which should be taken into account as is illustrated in the generalized algorithm in Fig.1.

Let us characterize these issues that should be fixed by data processing. 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 several tens of meters, 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 antenna far 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.

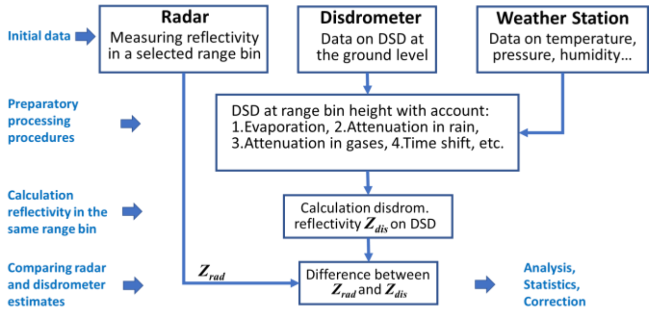

Fig. 1. Generalized procedures of data processing for absolute Z calibration by comparison radar and disdrometer measurements.

This affects the results of data comparison for two reasons: firstly, the disdrometer data series is late in respect to the radar data series, and secondly, during this falling time, the droplet's water may evaporate a little, i.e., droplets in the reflecting volume of the radar may be slightly bigger than at the level of the disdrometer.

Naturally, when processing, it is necessary to take into account the attenuation of W-band radiation in rain and in atmospheric gases, when propagating and scattering.

The normally unpleasant effect of a wet radome is minimized in this case by using an efficient system for blowing water off its surface.

Now we can proceed to the brief description of processing procedures. The most complex is calculation of the radar reflectivity estimate and other characteristics of radar signals from laser disdrometer data on size and velocity of scatterers. This estimate must be relevant to W-band radar, that is, be based on Mie scattering. In Fig.1 this estimate of the reflectivity is indicated as Z_{dis}.

The most complete description of the reflected object in case of polarimetric radar is given by scattering matrix. It is necessary not only for reflectivity and other signal characteristics estimation but is important also for calculation of attenuation in rain medium.

Calculation of the scattering matrix for a non-spherical particle was done by [17], using T-matrix method. It gives backscattering $S_{jk}(D_i)$ and forward-scattering $F_{jk}(D_i)$ coefficients at different combinations of polarization for transmitting and receiving components, where $j = h;v$ and $k = h;v$ (horizontal and vertical correspondingly). Normally, when reflectivity is determined, the horizontal polarization is assumed for definiteness [15]. Then using $S_{hh}(D_i)$, the nonattenuated reflectivity Z_i for a single droplet of D_i diameter is expressed as:

$$Z_i = \frac{4\lambda^4 |S_{hh}(D_i)|^2}{\pi^4 |K|^2} 10^{18} \, , \left[\frac{mm^6}{m^3}\right] \tag{4}$$

and using forward-scattering coefficient $F_{hh}(D_i)$, the specific one-way attenuation due to liquid water drop is:

$$A_i = 8.686 \cdot 10^3 \cdot \frac{2\pi}{k} \cdot \mathrm{Im}[F_{hh}(D_i)] \, , \left[\frac{dB}{km}\right] \tag{5}$$

These two expressions are used to calculate the reflectivity Z_{dis} taking into account the attenuation in rain. The final nonattenuated reflectivity Z and the one-way attenuation A are calculated from the Parsivel disdrometer data as the sum over the DSD distribution [15]:

$$Z = 10\log\left(\frac{1}{60}\frac{|K|^2}{|K_0|^2}\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{C_{i,j}Z_i}{v_i S_i}\right), \ [dBZ] \tag{6}$$

$$A = \frac{1}{60}\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{C_{i,j}A_i}{v_i S_i}, \ \left[\frac{dB}{km}\right] \tag{7}$$

In expressions (6) and (7): index i runs over n diameter bins; index j runs over m velocity bins; $C_{i,j}$ is a cell of the disdrometer raw data matrix, that is, the number of drops at the ith size and jth velocity bin; v_i is terminal velocity in meters per second of a drop with the diameter D_i; Z_i and A_i are reflectivity (4) and attenuation (5) for one drop, with the diameter D_i in a unit volume, respectively; $|K|^2$ is the dielectric factor of water at a certain temperature. $|K_0|^2 = 0.74$ is the constant dielectric factor of water at 8°C set in the processing routine of the used radars. A value $S_i = L_b(W_b - D_i/2)$ in formulas (6) and (7) is the effective sampling area in square meters of the disdrometer with L_b and W_b being the length and the width of the disdrometer laser beam [13]. For OTT Parsivel² L_b= 18 cm and W_b=3 cm. Having all these intermediate results, it is possible to calculate the radar reflectivity factor Z(r) along a path r of rainfall with constant properties as

$$Z(r) = Z_0(r) - 2\int_0^r [A(r) + A_g(r)]dr \, , \tag{8}$$

where Z_0 [dBZ] is the nonattenuated reflectivity; A [dB/km] is the one-way attenuation by rain, A_g [dB/km] is one-way attenuation by atmosphere gases; r is in distance [km].

Unlike for longer wavelength radars, gas attenuation cannot be neglected for the W band [18]. Content of water vapor and oxygen are the basic affecting components in the troposphere. Recommendations of ITU-R P.676-10 (09/2013), 'Radiowave propagation' were used for calculations using weather station measurements as initial parameters. Correction on drop evaporation during their falling down time from the height of radar reflecting volume down to sensitive area of a disdrometer is done based on the expression describing the rate of change of the drop radius due to evaporation [19]. After changing from the droplet radius to the diameter, the formula is:

$$vD\frac{dD}{dH} = 4\frac{S-1}{F_K + F_D}\, , \tag{9}$$

where v is the velocity of a drop; H is a vertical range traveled by the drop; S is the supersaturation with respect to liquid water. Coefficients F_K and F_D are related to heat conduction and vapor diffusion, respectively:

$$F_K = \left(\frac{L_v}{RT} - 1\right)\frac{L_v \rho_l}{f_h K T}\, , \tag{10}$$

$$F_D = \frac{\rho_l R_v T}{f_v D_v e_s(T)}\, , \tag{11}$$

where L_v is the latent heat of vaporization; R_v is the gas constant for water vapor; T is the air temperature; ρ_l is density of liquid water; K is the thermal conductivity of air; D_v is diffusivity of water vapor; $e_s(T)$ is the saturation vapor pressure as a function of T; f_v and f_h are the ventilation coefficients for vapor and heat [20].

Equation (9) relates a drop size at a certain altitude to the drop size at the surface. An opposite relation is needed: what would the drop size be at a H altitude if its size at the surface is known? To determine that, let us replace the derivative in equation (9) by the ratio of the corresponding increments, ΔD and ΔH, and solve the obtained equation relative to ΔD. Then we can define the drop size at the altitude H as:

$$D_H = D_S + \Delta D = D_S + \frac{4(S-1)}{v D_S (F_K - F_D)} H \, , \qquad (12)$$

where D_S is drop diameter at the surface; D_H is drop diameter at height H, in fact H=ΔH, if disdrometer is located on the surface; ΔD is difference between drop diameter at the height and the surface due to evaporation.

After making all the considered corrections into equations (4), (5), (8), the radar reflectivity calculated from the disdrometer data $Z(r)$, r=H (8) can be considered as Z_{dis}, which is prepared for comparison in absolute value with the reflectivity Z_{rad} measured by the radar in the radar bin corresponding to the altitude H.

The only additional comment is about time delay compensation because we must provide correct comparison of calculated $Z_{dis}(t)$ and measured $Z_{rad}(t)$ reflectivity time series. The time delay between the series Z_{rad} and Z_{dis} is estimated by calculating their cross-correlation function. The time shift (relative to 0) corresponding to the maximum correlation is used to correct the position of the disdrometer time series relative to the radar.

All mentioned data processing procedures as well as many others which deserve separate consideration are implemented in the software described in the next section.

VII. Software and Calculation Results

In our paper [21], the first version of a software tool was described for processing data to compare the radar reflectivity of rain measured by a radar and a disdrometer. This section presents the further development of this approach. The software presented here uses algorithms [21] for filtering raw data in the form of data files selected from extensive cloud databases in accordance with certain criteria. Further, these data are processed according to the described mathematical models. Other algorithms are significantly improved and a lot of new functions are added. The software was developed in the MATLAB environment.

A convenient and intuitive interface has been developed, and its primary panel is shown in Fig. 2. One can see that it provides selecting disdrometer and radar files, their date and time are synchronized automatically. Radar data can be selected from a desired radar bin (Height number) and Z_{rad} can be smoothed (Smoothing Z). Disdrometer DSD data is processed according to algorithms described in section VI to calculate Z_{dis}. The software gives a possibility to study separately the influence of different factors onto the estimation of the reflectivity Z_{dis}, as described above, namely: attenuation by rain, attenuation by gases, evaporation during falling down, and time shift by marking and pushing corresponding knobs: 'Include Drops Attenuation', 'Include Gazes Attenuation', 'Calc Z at 250 m', and 'Correct Time Shift'. After introducing all corrections, it is possible to represent Z_{rad}.and Z_{dis} in one field (united Z plot).

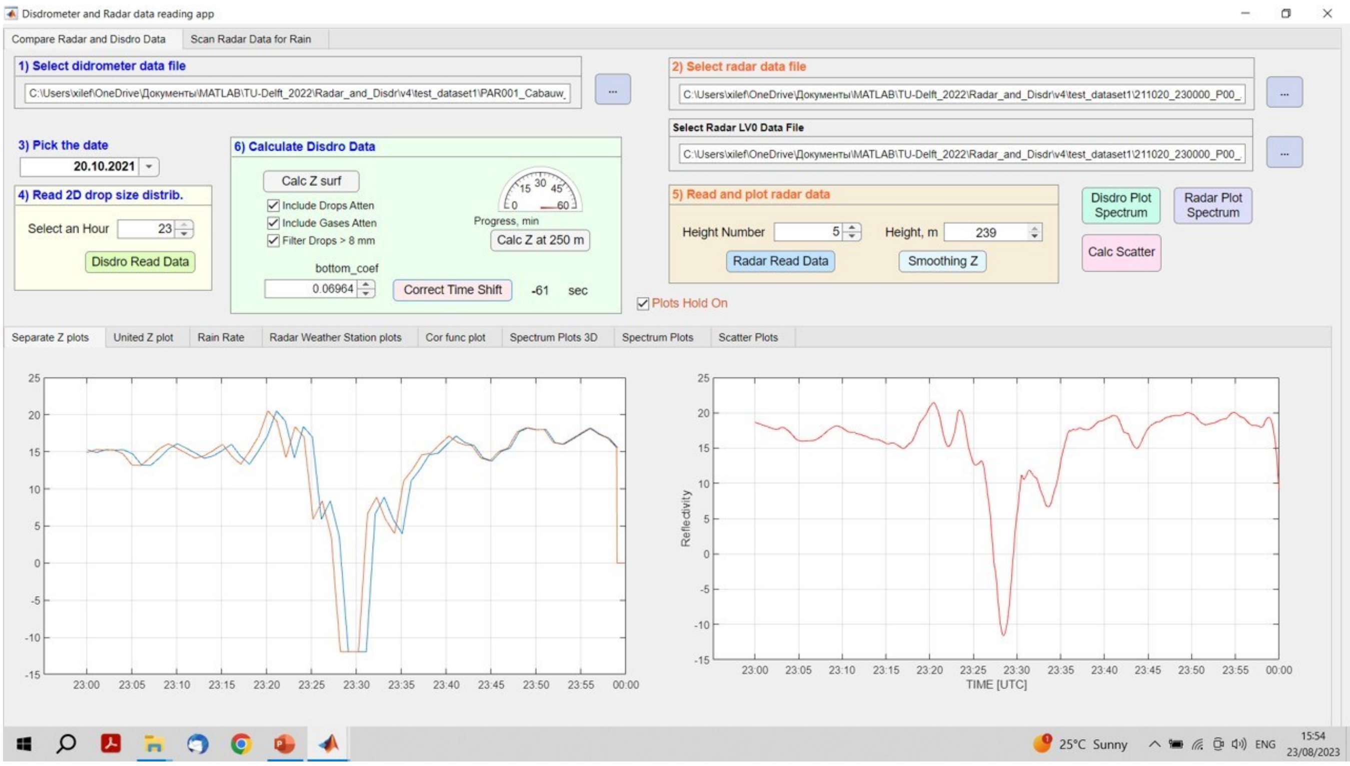

Fig. 2. The visual interface for file selections and processing of the multi-instrumental data, including 94 GHz radar and laser optical disdrometer.

In addition, the software calculates velocity spectrum from disdrometer data to compare it with radar Doppler spectrum (green and violet buttons in Fig. 2) as is shown in Fig.3. Scatter plots of Zrad.- Zdis, mean velocities and spectrum widths (Calc. Scatter) are also built as is shown in Fig.4.

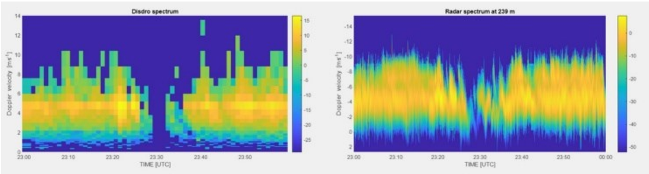

Fig. 3. Disdrometer velosity spectrum (left) and radar Doppler spectrum.

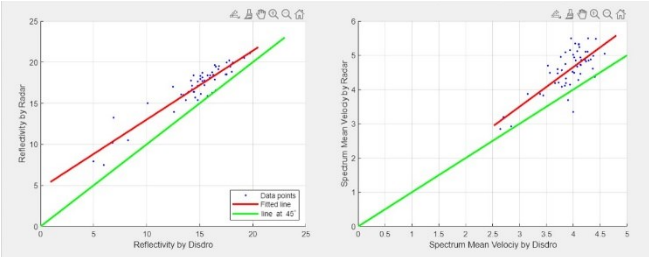

Fig. 4. Scatter plots for reflectivity Z (left) and mean velocity.

VIII. Conclusions and Future Work

In this paper, analysis of radar calibration methods for their suitability to absolute calibration of W-band meteorological radars has been carried out. The method of multi-instrument calibration using disdrometers and compact meteorological stations has been analyzed in detail. The issues related with data processing in case of W-band radar has been characterized and their solution discussed. The convenient friendly software has been developed for comparative analysis of the data obtained by W-band radar and disdrometer during continuous measurements of rain characteristics.

Experimental part of the research was based on multi-instrument measurements provided during several years in the Cabauw experimental meteorological site in the Netherlands. The accumulated data are used for comparison of 94 GHz radar rain measurements with non-radar droplet size distribution measurements, provided by laser disdrometers. Calculations have been done taking into account data of other meteorological in situ measurements. Specialized MATLAB software tool for processing, comparison, and fusion sophisticated multi-instrument data has been developed, tested and used for W-band radar calibration.

The developed software is suitable and has been tested as the tool for correct comparison of radar reflectivity factors, Doppler spectra, mean and root-mean-square velocities.

The T-matrix method that has been implemented in the developed MATLAB software provides possibility to calculate also polarimetric parameters for comparison with radar measurement. This should be done in the future research, which will include the case of slant radar sounding and additionally the available radiometric data.

Acknowledgment

This work was supported by the Ruisdael Observatory, a scientific research infrastructure co-financed by the Netherlands Organisation for Scientific Research (NWO), grant number 184.034.015.

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