A W-Band Radar–Radiometer System for Accurate and Continuous Monitoring of Clouds and Precipitation

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ABSTRACT

A new 94-GHz frequency-modulated continuous wave (FMCW) Doppler radar–radiometer system [Jülich Observatory for Cloud Evolution (JOYCE) Radar–94 GHz (JOYRAD-94)] is presented that is suitable for long-term continuous observations of cloud and precipitation processes. New features of the system include an optimally beam-matched radar–radiometer; a vertical resolution of up to 5 m with sensitivities down to $2.62 \text{ dBZ}$ at 100-m distance; adjustable measurement configurations within the vertical column to account for different observational requirements; an automatic regulation of the transmitter power to avoid receiver saturation; and a high-powered blowing system that prevents hydrometeors from adhering to the radome. JOYRAD-94 has been calibrated with an uncertainty of 0.5 dB that was assessed by observing a metal sphere in the radar’s far field and by comparing radar reflectivities to a collocated 35-GHz radar. The calibrations of the radar receiver and the radiometric receiver are performed via a two-point calibration with liquid nitrogen. The passive channel at 89 GHz is particularly useful for deriving an estimate of the liquid water path (LWP). The developed retrieval shows that the LWP can be retrieved with an RMS uncertainty (not including potential calibration offsets) of about $0.15 \text{ g m}^{-2}$ when constraining the integrated water vapor from an external source with an uncertainty of $0.2 \text{ kg m}^{-2}$. Finally, a dealiasing method [dual-radar dealiasing method (DRDM)] for FMCW Doppler spectra is introduced that combines measurements of two collocated radars with different measurement setups. The DRDM ensures high range resolution with a wide unambiguous Doppler velocity range.

1. Introduction

Clouds play a major role in Earth’s hydrological cycle and radiation budget (Boucher et al. 2013); thus, it is important to characterize them with high accuracy and spatial resolution. Reliable and robust ground-based Doppler radars and radiometers are key instruments for detailed observations of cloud processes, long-term data collection, and model and satellite evaluations. Here, we present a system [Jülich Observatory for Cloud Evolution (JOYCE) Radar–94 GHz (JOYRAD-94)] that combines frequency-modulated continuous wave (FMCW) Doppler radar with passive radiometer observations at millimeter wavelengths (94 and 89 GHz, respectively), providing new opportunities for cloud observations.

Radar operating at millimeter-wavelength can be used—among other applications—to determine cloud microphysical processes (e.g., Kollias et al. 2007a; Luke and Kollias 2013; Kneifel et al. 2011; Acquistapace et al. 2017; Tridon and Battaglia 2015) to estimate rain rates (Maahn et al. 2015), or to obtain information about in-cloud turbulence (e.g., Kollias et al. 2002; Borque et al. 2016). Moreover, radars are combined with other remote sensors in order to enhance the sensitivity and the
accuracy of the derived cloud properties. For example, Frisch et al. (1998) used microwave radiometer (MWR) and radar data to retrieve the liquid water content (LWC) profile of a cloud. The vertically integrated amount of liquid water [also liquid water path (LWP)] was constrained by the MWR, and the range-resolved radar signal was used to reconstruct the liquid water vertical distribution. Illingworth et al. (2007) exploited the synergy of collocated radar, microwave radiometer, and lidar observations to obtain further refined cloud properties, such as the hydrometeor phase, type, and position in the vertical column (Cloudnet algorithm).

Currently, the majority of cloud radars—especially at comprehensive observatories (e.g., Löhntert al. 2015; Kollias et al. 2007b; Haeffelin et al. 2005)—are pulsed systems. Illingworth et al. (2015) pointed out that FMCW radars can be a more economical solution, which then could further increase the number of observatories for comprehensive cloud studies that are needed for climate monitoring. However, FMCW radar requires two antennas, which could in turn increase system costs, especially when considering low-frequency radars where larger antenna diameters are required (Heijnen et al. 2000).

A further disadvantage of FMCW technology is that it requires a large bandwidth at great distance to sustain vertical and temporal resolution, which increases the background noise. Nevertheless, several publications showed that FMCW W-band radars are suitable for both ground-based (Yamaguchi et al. 2009; Huggard et al. 2008; Bennett et al. 2009; Thies et al. 2010; Delanoë et al. 2016) and airborne fog and cloud studies (Pazmany et al. 1994; Mead et al. 2003).

FMCW radars often allow greater flexibility of varying vertical resolution. For JOYRAD-94 a vertical resolution of 5 m can be used (note that in principal, even finer vertical resolutions are possible), which is beneficial for evaluating high-resolution model simulations such as large-eddy simulations (LES) (e.g., van der Dussen et al. 2013) or for investigating processes with strong vertical gradients (e.g., melting layer).

The increased time on target, because of continuous transmission, provides similar average output powers as pulsed systems and leads to comparable sensitivities. In general, FMCW systems are cheaper to build because of their simpler electronic design and lack of high-voltage components (Ligthart and Nieuwkerk 1980), which further leads to better long-term stability and easier calibration. Also, their smaller instrument dimensions and lower transmitter power facilitate their installation in various environments.

High-frequency radars operating in the W-band provide greater sensitivity to small hydrometeors, which allow, for example, for investigating thin liquid or ice clouds and their microphysical processes (Lhermitte 1987). The disadvantage of using high frequencies is increasing signal attenuation as a result of dry gases, water vapor, and frozen and liquid hydrometeors.

Figure 1 shows the W-band radar radiometer at JOYCE (Löhntert al. 2015) in Jülich, Germany, and at the Alfred Wegener Institute for Polar and Marine Research and the French Polar Institute Paul Emile Victor (AWIPEV) Arctic Research Base in Ny-Ålesund, Norway. At JOYCE (www.joyce.cloud) it is located next to a pulsed 35-GHz system (JOYRAD-35) for high-accuracy dual-frequency retrievals of liquid water content. The Arctic deployment (2016/2017) took place within the German research initiative Arctic Amplification: Climate Relevant Atmospheric and Surface Processes and Feedback Mechanisms [(AC³)] (http://www.ac3-tr.de/), where the objective is to detect, quantify, and model the feedback mechanism leading to the observed accelerated warming in the Arctic compared to global mean.

JOYRAD-94 is a very compact system with a horizontal extent of 1.0 × 1.1 m², a height of 1.3 m, and is installed and recoverable with two persons. It operates under all weather conditions as a result of two high-powered blowing systems that nominally keep the radomes free of liquid and ice. A dry radome is important because a thin liquid layer can contaminate the radar and radiometer measurements significantly; for example, Hogan et al. (2003) observed a two-way radome attenuation of 15 dB. Also, a thin liquid layer on the receiver radome can affect the radiometer brightness temperature measurements by several kelvins, biasing the retrieval of LWP.

As will be explained in detail later in the manuscript, the vertical resolution of JOYRAD-94 is adjustable within up to 10 different layers, making it possible to adapt the resolution and sensitivity to different measurement objectives at different heights. JOYRAD-94 receives the passive and active signals over the same antenna—that is, both sensors observe the same scene and have the same beamwidth of 0.53°—which reduces the uncertainty of retrievals when combining radar and radiometer measurements (Frisch et al. 1998). Such a synergetic instrument was design by Skou (1995) for airborne observations; however, it has not yet been used for ground-based studies.

Common radiometers have beamwidths between 3° and 6°, and therefore smooth out horizontally varying cloud structures (Huang et al. 2014). The passive channel of JOYRAD-94 provides new opportunities for observing spatial and temporal cloud variability, for example, questioning Taylor’s hypothesis of “frozen” turbulence, which was found to be valid for radiometers.
with beamwidths larger than 1° (e.g., Huang et al. 2008). Moreover, combining matched radar–radiometer measurements with small beamwidths and high vertical resolution can add information on processes at cloud edges, such as turbulence and evaporation induced by lateral entrainment (Heus and Jonker 2008). However, the latter and LWP variability will not be part of the following discussion; but it is left as a topic for future research.

In the following, we will introduce the instrument’s design, which enables continuous and unattended observations while receiving both the active and passive signals with the same antenna. In section 3, the signal processing is discussed, including the adjustable measurement setup for different atmospheric layers. The performance of the instrument is shown in section 4 followed by a comparison to a 35-GHz pulsed radar. In section 6, we introduce the novelties of JOYRAD-94 for cloud observations. The last section gives a summary and an outlook considering software and hardware updates that will be or have already been included in the system.

2. Instrument design

The instrument is designed for long-term unattended observations of cloud macro- and microphysical properties by combining passive and active microwave radiometry at center frequencies of 89 and 94 GHz, respectively. FMCW radar is used to provide high flexibility of range and Doppler resolution variation along the ranging path. Moreover, low transmitter power (typically 1.5 W) allows for solid-state technology, leading to a long lifetime and low costs.

The main components of the radar–radiometer are the transmitter with adjustable power to protect the receiver from saturation, the Cassegrain two-antenna system, and the receiver containing both the radar receiver channel at 94 GHz and the passive broadband channel at 89 GHz. Both channels are thermally stabilized within a few millikelvin (mK) to ensure accurate output power measurement and radiometric accuracy. A block diagram of the full system and technical specifications are given in Fig. 2 and Table 1, respectively.

a. Antenna

The Cassegrain antenna, which was recently measured using the solar sun scan technique (Reimann and Hagen 2016), produces a beam of 95% Gaussian shape. Moreover, the modeled and measured half-power beamwidths (HPWB) are 0.48° and 0.53°, respectively. The modeled and measured antenna gains are 51.8 and 51.5 dB, respectively. JOYRAD-94 was calibrated with the modeled values, which leads to an overestimation of reflectivity of 0.26 dB that has been accounted for in the data analysis. Future versions will use the measured parameters instead. The two antenna systems protect the receiver from saturation, as during continuous transmitter operation it is not possible to separate transmitted and received power. Transmitting and receiving antennas are separated by 568 mm, which leads to a signal loss of 10% at 300 m distance as a result of imperfect beam overlap. Because of the small antenna separation, backscattering theory is still fully
applicable. The far field of the antenna begins at about 50 m. The antenna system losses are dominated by subreflector blocking—that is, the subreflector shading the output beam—which was found to cause a power loss of 11%.

b. Transmitter

The maximum output power is continuously monitored by the radar with a retraceable precision Rhode and Schwarz W-band power head (accuracy of 0.1 dB). The feedhorn insertion loss is $0.3 \pm 0.05$ dB, which was determined by a Rhode and Schwarz network analyzer (accuracy of 0.05 W). To ensure linear detection while observing a high dynamic range of input power signals (from thin cirrus to precipitating liquid clouds), the radar’s transmitter power can be reduced in digital steps by a maximum of 16 dB. Sawtooth chirps are generated by a chirp generator module based on a direct digital synthesizer (DDS) that is clocked by a fundamental oscillator of frequency of 916 MHz. The chirp generator produces an output signal in the range of $7.79$–$7.88$ GHz that is then multiplied by 12 to become the transmitter signal between $94.48$ and $94.56$ GHz.

c. Receiver calibration

The radar receiver calibration maps the power at the analog-to-digital converter (ADC) board $P_n$ (W; for $n$ range gates) to the power spectrum incident on the radar antenna $P_m$—that is, it determines the receiver gain $G_m$ of the system—so that

$$P_n = G_m P_m.$$  \hspace{1cm} (1)

### TABLE 1. Radar specifications.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$94$ GHz $\pm$ $100$ MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power</td>
<td>$1.5$ W (solid-state amplifier)</td>
</tr>
<tr>
<td>HPWB</td>
<td>$0.53^\circ$</td>
</tr>
<tr>
<td>Antenna type</td>
<td>Two antennas with 500-mm aperture</td>
</tr>
<tr>
<td>Antenna separation</td>
<td>$568$ mm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>$51.5$ dB</td>
</tr>
<tr>
<td>System noise figure</td>
<td>$3$ dB</td>
</tr>
<tr>
<td>A/D sampling rate</td>
<td>$8.2$ MHz</td>
</tr>
<tr>
<td>Profile sampling rate</td>
<td>$0.2$–$30$ s</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>$1$–$100$ m</td>
</tr>
<tr>
<td>Doppler range</td>
<td>$\pm 10$ m s$^{-1}$</td>
</tr>
<tr>
<td>Size</td>
<td>$1.0$ m $\times$ $1.1$ m $\times$ $1.3$ m</td>
</tr>
<tr>
<td>Weight</td>
<td>$80$ kg (without stand)</td>
</tr>
</tbody>
</table>
Therefore, a so-called hot–cold calibration is performed using a blackbody at environmental temperatures as a “hot” reference and a liquid nitrogen–cooled blackbody as a “cold” reference. The integration time during the calibration is 60 s. Using the radiometer formula (Ulaby and Long 2014, p. 279), a single intermediate frequency (IF) bin of typically 4-kHz bandwidth and about 500-K system noise temperature has a root-mean-square (RMS) noise of 1 K, that is, a peak-to-peak noise of about 4 K.

During the “hot–cold” calibration, the radiometer channel at 89 GHz is calibrated too. The 89-GHz channel has an RMS noise smaller than 0.5 K when integrating on the hot calibration target for any integration times between 5 and 100 s. Küchler et al. (2016) found an uncertainty of ±0.5 K for direct detection radiometers of a similar type that were calibrated with liquid nitrogen. Maschwitz et al. (2013) suggested repeating absolute calibrations every 3–6 months to sustain measurement accuracy.

d. Calibration cross-check

A calibration cross-check with a metal sphere reflector showed an agreement within 0.5 dB between the expected power ratio of the transmitted and received signals and the measured power ratio. The sphere had a diameter of 48 mm; was lifted by a helium balloon to 104 m above ground at a horizontal distance of approximately 950 m to the radar, resulting in a radial distance of 960 m; and was strapped to the ground by three strings. The distance between the balloon and the metal sphere was about 10 m. The radar was mounted on a positioner that was manually operated using a telescope for precise pointing. To account for the horizontal swinging of the sphere, the integration time was set to 0.2 s and a peak-hold function in the radar software was run, which samples the maximum value observed within 60 s. The procedure was repeated 100 times, resulting in a standard deviation of 0.15 dB of the return signal. Atmospheric attenuation was found to be 0.6 dB over a path of 1920 m, which was determined from radiative transfer calculations assuming homogeneity on the radiation’s path and using surface data from the radar’s meteorological weather station.

3. Signal processing

In this section we briefly describe only the main processing steps and refer the reader to the cited literature (e.g., Strauch 1976; Delanoë et al. 2016; Ulaby and Long 2014, 615–621) for details of FMCW signal processing.

a. FMCW principle

Figure 3 illustrates the basic principle of a transmitted sawtooth chirp sequence over the bandwidth $B$ (Hz), which is backscattered by a single steady particle at distance $R$ (m). The delay $\Delta t$ (s) between the transmitted and received signals is determined by the particle’s distance and the propagation speed $c$ (m s$^{-1}$) of the transmitted electromagnetic wave:

$$\Delta t = \frac{2R}{c}. \quad (2)$$

Using $B$ and the chirp duration $T_c$ (s), $\Delta t$ is mapped to the measured intermediate frequency $f_{IF}$ (Hz; i.e., the difference between the transmitted and received signals) to

$$f_{IF} = \frac{R}{cT_c}. \quad (3)$$

Furthermore, the range resolution $\delta R$ (m) is determined by $B$ over
\[ \delta R = \frac{c}{2B}. \]  

If the particle moves, there will be an additional frequency shift \( f_d \) (Hz; called Doppler shift) between the transmitted and received signals. This shift is much smaller than the IF difference between two range gates (e.g., Strauch 1976) and is determined by the transmitted frequency \( f_t \) (Hz) and the particle’s radial velocities \( v_d \) (m/s):

\[ f_d = \frac{2f_t v_d}{c}. \]  

The maximum Doppler shift \( f_{dm} \) (Hz) is related to \( T_c \) via

\[ f_{dm} = \frac{1}{2T_c}. \]  

As several parameters above depend on each other and cannot be chosen arbitrarily because of physical and technical restrictions, certain trade-offs must be considered when defining a measurement setup. This can be illustrated by the so-called Doppler dilemma: the maximum range to be sampled determines the minimum chirp duration; for example, the two-way propagation time of a transmitted signal backscattered at 10 km height is about 70 \( \mu \)s. For a full ranging via a fast Fourier transform (see the next subsection), additional sampling time is required (approximately 30 \( \mu \)s). Using Eqs. (6) and (5), the maximum unambiguous velocity \( v_N \) (also called Nyquist velocity) is about 8 m/s at 94 GHz. With a given minimum \( T_c \), \( B \) is also restricted by Eq. (3) and vice versa, since \( f_{IF} \) must not exceed certain limits for any \( R \) as a result of technical limitations (see section 3d). Therefore, increasing \( \delta R \) requires an increase of \( B \) [see Eq. (4)], which requires an increase of \( T_c \), leading to a decrease of \( v_N \).

b. Acquisition and processing

The IF signal from the mixer output is sampled by a fast ADC board, whereas the sampling clock of the ADC is also generated by the chirp generator to ensure an optimal synchronization of ramp generation and sampling. The ADC’s maximum sampling rate is 28.625 MHz. According to Parsivel’s theorem (Hughes 1965), the mean power of the voltage time series, being the sum of the squared sample voltages, equals the sum of the power spectrum over the sampling interval. Thus, applying a Fourier transform to the digitized mixer output voltage provides the power spectrum \( P_n \), where \( n \) corresponds to a certain IF that is linearly related to \( R \) where the scattering targets are located [see Eq. (3)].

A second Fourier transform of the time series of \( P_n \), at \( N_{IF} \) samples, yields the Doppler velocity spectrum \( S_n(v_d) \) (W) depending on the radial velocity \( v_d \) of the scattering targets. The spectrum contains \( N_{IF} \) points ranging between \( \pm v_R \) (m/s). The integral over the Doppler power spectrum equals \( P_n \):

\[ P_n = \sum_{v_d = -v_R}^{v_R} S_n(v_d), \]  

where \( P_n \) is then converted into the power incident on the antenna \( P_m \) using Eq. (1). The equivalent radar reflectivity factor \( Z_e \) (mm\(^6\)m\(^{-3}\); called reflectivity) is obtained from the ratio between \( P_m \) and transmitted power \( P_T \) (W) using the radar equation

\[ Z_e = \frac{P_m}{P_T} \frac{5.12 \times 10^{20} \ln(2) \lambda^2 R^2}{G^2 T \theta^2 \pi^2 |K_n|^2 \delta R}, \]  

where \( K_n \) is related to the dielectric constant of liquid water and is assumed to be 0.86 at 90 GHz. Furthermore, \( Z_e \) depends on the half-power beamwidth \( \theta \) (rad), the transmitter gain \( G_T \), the transmitted wavelength \( \lambda \) (m), and \( \delta R \). After subtracting the noise power from the spectrum, the moments, such as the reflectivity, the mean Doppler velocity \( v_m \) (m/s), and the spectral width \( \sigma \) (m/s), can be calculated (e.g., Acquistapace et al. 2017).

The radar software conducts “level 1” processing, that is, it determines the noise level of the spectra and calculates spectral moments. Moreover, visualization tools are available for instantaneous data monitoring. The detection threshold for a valid sample is a multiple of the noise density standard deviation above the mean noise density of the Doppler spectrum, which must be exceeded in the spectrum. For more details, we refer the reader to Görßdorf et al. [2015, parameter \( Q \) in Eq. (14)] is the “noise filter”.

c. Doppler spectra

Example spectra are shown in Fig. 4 at three different heights of a precipitating cloud. Particles moving toward the radar have a negative velocity. The noise level was determined using the Hildebrand–Sekhon scheme (Hildebrand and Sekhon 1974). The top panel illustrates a Gaussian-shaped power spectrum of a sample volume that contained ice particles exhibiting a mean Doppler velocity of \(-1\) m/s. The second power spectrum was sampled within the melting layer showing a negative skewness, a broadening of the spectrum, and a shift to more negative velocities, which indicate the acceleration of melting ice particles. The third panel exhibits a broad spectrum that is
typical for regions below the melting layer, where a mixture of liquid particles with different velocities was present.

The lhs of the third panel indicates that the sample volume contained particles whose fall velocities were close to the Nyquist velocity. At lower range gates, particles were present that exceeded the Nyquist velocity (not shown here). If particles move faster than $v_N$, then their spectral signal will occur in the upper or lower range gates at the opposite side of spectrum (folding of velocities), depending on whether their motions are toward or away from the radar. This process is the so-called aliasing. The spectra were recorded in a measurement mode that was not defined for precipitation studies. If studying precipitation is the main objective, then either the settings can be adjusted to increase $v_N$ or the Doppler spectrum can be dealiased in the postprocessing (e.g., Maahn et al. 2015). Moreover, in section 6 we will introduce a new method to dealias Doppler spectra that combines measurements of two collocated radars providing spectra in high vertical resolution (5 m) while enhancing the limits of $v_N$.

d. The chirp table

The current measurement modes that are operated on the radar run with a sampling rate of approximately 8 MHz. The Nyquist limit restricts the maximum IF, which can be sampled distinctly, to 4 MHz. Moreover, the chirp generator’s phase noise contaminates IFs below 300 kHz. Therefore, the usable IF signal band is limited to frequencies between 300 and 4 MHz. Because the IF bandwidth determines the maximum unambiguous range, a range from 0 to 12 km cannot be covered by a single chirp sequence. Therefore, several chirp sequences are executed consecutively, whereas for each chirp sequence the IFs between 300 kHz and 4 MHz span different ranges, for example, 100–400 m in the first chirp sequence, 400–2000 m in the second chirp sequence, etc. As a consequence, the final profile is a composite of several chirp sequences.

On the one hand, this is a disadvantage, since the data in different chirp sequences were recorded at different times. On the other hand, the sequence of different chirps provides the opportunity to define several parameters, such as $\delta R$ and $v_N$, for each chirp sequence individually. Thus, the observational settings can be adjusted to several atmospheric regions, for example, a large $v_N$ in the lower boundary layer to capture precipitation events and a high vertical resolution in regions where the melting layer is expected for studying phase conversion processes. The radar software allows for defining up to 10 different chirp sequences. The total duration of one full measurement cycle is mainly determined by the duration of the individual chirp sequences.

Currently, the radar is operated in two modes: the standard mode (SM) and the high-vertical-resolution mode (HRM). The former operates with vertical resolutions between 16 and 34 m, with Doppler velocity resolutions ($Dy$) between 3.9 and 1.7 cm s$^{-1}$ and with $v_N$ from 6.9.7 to 6.4.2 m s$^{-1}$. The latter runs with a vertical resolution of about 5 m between 100 and 3000 m, whereas the $v_N$ is minimum at $\pm 4.2$ m s$^{-1}$ in the lowest 1200 m. The parameter $\Delta v$ is about 2 cm s$^{-1}$ in all ranges. In both modes the maximum unambiguous range is 10 km, and the time differences between the first and last chirp sequences is smaller than 2 s. An overview is given in Table 2.

To avoid second-trip echoes, the maximum unambiguous range must be sufficiently large. However, increasing the maximum unambiguous range decreases the maximum unambiguous velocity (see section 3a). On the one hand, this can be a disadvantage, as aliasing becomes likely in lower layers, though it can be corrected, as will be shown in section 6b. On the other hand, it is likely that the transmitted signal at 94 GHz will be attenuated entirely before reaching regions above 10 km, if a convective precipitating cloud system is present. Nevertheless, there is the opportunity to define a measurement mode with two different chirp tables being executed alternatingly to enable observations of both high clouds and precipitation.

4. Radar–radiometer performance

Note that the data presented in the following were collected over a time frame (October 2015–May 2017) in which the sensitivity of JOYRAD-94 was decreased by two reasons: (i) the transmitter power chip
Table 2. Main attributes of two radar operation programs: SM and HRM. Several parameters, such as range resolution, $\Delta v$, and $v_N$, are adjustable for defined range gates. The selection of the former determines other parameters, such as $N_{\text{fft}}$, the number of spectral averages ($n_{\text{avg}}$), and integration time $\tau$. The HRM sensitivity was obtained from data collected in Ny-Ålesund. Total sample time for SM is 3 s and HRM 2.5 s. The maximum unambiguous range is in both modes: 10 km.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>$\Delta R$ (m)</th>
<th>$\Delta v$ (cm s$^{-1}$)</th>
<th>$v_N$ (m s$^{-1}$)</th>
<th>Sensitivity (dBZ)</th>
<th>$N_{\text{fft}}$</th>
<th>$n_{\text{avg}}$</th>
<th>$\tau$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 to 400</td>
<td>16</td>
<td>3.9</td>
<td>9.7</td>
<td>$-67$ to $-59$</td>
<td>128</td>
<td>8</td>
<td>0.34</td>
</tr>
<tr>
<td>400 to 1200</td>
<td>21.3</td>
<td>3.3</td>
<td>8.1</td>
<td>$-59$ to $-51$</td>
<td>256</td>
<td>8</td>
<td>0.40</td>
</tr>
<tr>
<td>1200 to 3000</td>
<td>26.9</td>
<td>2.5</td>
<td>6.2</td>
<td>$-51$ to $-43$</td>
<td>512</td>
<td>8</td>
<td>0.53</td>
</tr>
<tr>
<td>3000 to 10000</td>
<td>34.1</td>
<td>1.7</td>
<td>4.2</td>
<td>$-48$ to $-38$</td>
<td>1024</td>
<td>16</td>
<td>1.77</td>
</tr>
<tr>
<td>The high vertical resolution mode (HRM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 to 400</td>
<td>4</td>
<td>2.5</td>
<td>6.2</td>
<td>$-62$ to $-53$</td>
<td>512</td>
<td>8</td>
<td>0.53</td>
</tr>
<tr>
<td>400 to 1200</td>
<td>5.3</td>
<td>1.7</td>
<td>4.2</td>
<td>$-56$ to $-48$</td>
<td>512</td>
<td>6</td>
<td>0.59</td>
</tr>
<tr>
<td>1200 to 3000</td>
<td>6.7</td>
<td>2.1</td>
<td>2.5</td>
<td>$-49$ to $-42$</td>
<td>256</td>
<td>9</td>
<td>0.73</td>
</tr>
<tr>
<td>3000 to 10000</td>
<td>17</td>
<td>2.1</td>
<td>2.5</td>
<td>$-45$ to $-35$</td>
<td>256</td>
<td>7</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Degraded rapidly because of a production failure until it was replaced in April 2016, which caused a decrease in sensitivity; and (ii) the detection threshold (see section 3b) was calculated wrongly in the first software version, by not considering coherent averaging, which led to an additional loss of sensitivity by about 3 dB. The software was updated in February 2017.

a. Case study

The performance of the radar–radiometer is evaluated using a 24-h measurement period of 5 November 2015, which is shown in Fig. 5. Several precipitation events passed JOYCE during this day. These were mainly triggered by the southwestern inflow of warm and moist air over central Europe during the days before and an overpass of an elongated trough at 500 hPa from 4 to 6 November. The precipitation event in the morning was the tail of a convective system occurring the night before. The intensification of precipitation between 0100 and 0200 UTC is clearly visible by the increasing reflectivities in Fig. 5 (top).

The overlay of the ceilometer cloud-base height reveals a liquid cloud layer at the top of the cloud that was present between 0300 and 0500 UTC. It also shows the advantage of a radar in comparison to a ceilometer, as the radar captured ice particles below that were not detected by the ceilometer. JOYRAD-94 even detects clouds having a thickness of a few tens of meters; however, very thin liquid layers—for example, between 0800 and 0900 UTC—were beyond the sensitivity of the radar, mainly because of the too-conservative detection threshold in the first software version.

The second precipitating system crossed JOYCE between 2000 and 0200 UTC in night from 5 to 6 November. The transmitter power is automatically regulated to prevent the receiver from saturation when high reflecting particles, such as large raindrops, are present. Such events involve strong attenuation so that complete attenuation is possible at low altitudes, for example, as visible in Fig. 5 at 2230 UTC, where the reflectivity is significantly reduced after 2 km (yellow vertical stripe). Here, the transmitted power was decreased from 1.5 to 0.2 W between 2200 and 2300 UTC when precipitation produced an increased reflectivity signal. On the one hand, this causes a loss of information from higher cloud levels; on the other hand, it keeps the detector in its linear regime, thus, it increases data quality in lower levels.

The brightness temperature $T_B$, being the Planck equivalent temperature for the measured radiation, of the 89-GHz radiometer channel is also shown in the bottom panel of Fig. 5. The correlation between the liquid layers detected by the ceilometer and $T_B$ is evident. Even very thin clouds, such as occurring at 0530 and 0630 UTC, give a signature in the 89-GHz channel (because the $y$ axis of the brightness temperature plot spans a range of 250 K, small signatures of a few kelvins cannot be recognized in this illustration).

The $T_B$ signal responds strongest to the two precipitation events: (i) between 0100 and 0200 UTC and (ii) between 2200 and 2300 UTC. The amplitudes of $T_B$ suggest that the early morning event carried more liquid than the evening event. This is confirmed by the rain gauge measurement 100 m next to JOYRAD-94, which detected a peak rain rate of 1.2 mm (10 min)$^{-1}$ at 0200 UTC and only 0.2 mm (10 min)$^{-1}$ at 2300 UTC.

In this section, we showed that the passive channel complements the radar measurements while observing the same scene. In section 6, we will further discuss the performance of LWP retrievals using $T_B$ at 89 GHz.
b. Sensitivity

The sensitivity of JOYRAD-94 is illustrated in Fig. 6a. It shows the occurrence frequencies of observed reflectivities at each range bin when the radar has operated in the SM at JOYCE. Only signals that exceeded the reflectivity threshold were taken into account. The figure reveals several features that correspond to certain cloud types or specific positions within the cloud.

The area around the maximum at about 8.5 km and -25 dBZ corresponds to high-altitude ice clouds that were often connected to precipitating systems (e.g., as shown in Fig. 5) that occurred frequently during the observation period between November 2015 and March 2016. The occurrence of precipitating systems is reflected in the area around 10 dBZ between 0- and 2-km height when precipitation caused strong echoes. While combining Cloudnet data and synoptic maps, we found that the region of increased occurrences, connecting the maximum at the ground and at about 8.5 km, is mainly caused by cumulonimbus clouds associated with frontal passages over western Germany. Further cloud types that occurred frequently during the observation period were nonprecipitating cumulus and stratocumulus containing hydrometeors in the liquid phase. The fingerprints of these cloud events are evident in the local maximum between 500- and 2000-m altitude, exhibiting typical values from -40 to -20 dBZ (e.g., Frisch et al. 1995; Wang and Geerts 2003). The distinct bimodal signature in this region was also observed by a collocated 35-GHz pulsed radar, which is an interesting meteorological feature; however, a detailed analysis of the data and the synoptic conditions used to explain the bimodality is not part of this study.

A gap is visible at the sensitivity limit of JOYRAD-94 at about 7.8 km. It was found that a signal originating from ADC board electronics contaminates the signal processing. The signal’s frequency is equal to the IF frequency that corresponds to the range gate at about 7.8 km. To remove this contamination, the intrinsic noise underground in each IF bin was determined and stored. During operation, the contamination’s amplitude is subtracted from the monitored signal, which causes the gap in Fig. 6a, indicating that the logged value of the contamination signal was overestimated.

Fitting a curve to the lowest detected reflectivities (Fig. 6a) provides the sensitivity of the radar for the SM at JOYCE after filtering the data with the detection threshold discussed in section 3b. Moreover, the sensitivity was determined for each month of operation individually, showing a shift of the sensitivity curve toward larger reflectivities with advancing time. The loss of

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**Fig. 5.** The 24-h time series of JOYRAD-94 measurements at JOYCE on 5 Nov 2015. (top) Radar reflectivity. Cloud-base height from a collocated ceilometer at 3-m distance (black dots). (bottom) Brightness Temperature $T_B$ at 89 GHz (red) and transmitter power $P_T$ (blue).
sensitivity is due to the degradation of an erroneous transmitter power chip implemented in the prototype. The transmitter power chip was replaced in April 2016 and since then the transmitter power has been stable. Note that the curve of the HRM is also influenced by sensitivity losses caused by a higher vertical resolution.

In June 2016, the radar was installed in Ny-Ålesund (NyA), where the radar operated in the HRM and the SM. A software update in February 2017, with improved signal detection thresholds, further increased the sensitivity by 3 dB. The comparison of the resulting sensitivity profiles before and after the replacement, and the software update in Fig. 6a reveals that the sensitivity in the SM has improved with respect to the early time of installation at JOYCE when the power chip was still working properly. We find that the sensitivity loss in the HRM observed at JOYCE is mainly a result of the chip degradation and a too conservative detection threshold; the differences of the HRM and the SM with the new chip are smaller than 6 dB in the lowest 500 m and smaller than 4 dB above.

As clearly visible in Fig. 6a, jumps in the sensitivity occur at several heights. These are caused by different chirp sequences used for probing different altitude regions. In general, a finer vertical resolution leads to a lower sensitivity and vice versa. Because the vertical resolution often changes from chirp to chirp, the sensitivity changes accordingly. The sensitivity limits for all layers in both operation modes are summarized in Table 2.

We further assess the performance of JOYRAD-94 by comparing it to a pulsed 35-GHz radar (JOYRAD-35), as described by Görsdorf et al. (2015), which was located at 3 m distance to JOYRAD-94 at JOYCE. The sensitivity curve of JOYRAD-35 is also included in Fig. 6a as a reference. Clearly evident is the higher sensitivity of JOYRAD-35 in the lowest 3 km (Fig. 6b), which is due to the much higher average transmitter power of 24 W (Acquistapace et al. 2017, their Table 2) and the short integration times in the HRM and SM in the lowest layer. These differences in sensitivity are on the order of 10 dB (15 dB) in the lowest kilometer for the SM (HRM) but reduce to 3 dB (8 dB) above 3 km. These sensitivity differences also affect the analysis in the following section. Note that increasing the integration time of JOYRAD-94 by 0.5 s in the lowest layer would increase the sensitivity by about 3 dB.

5. Assessment of cloud detection

The following analysis is based on the Cloudnet product of Illingworth et al. (2007), combining several
remote sensing instruments (e.g., radar, lidar, and MWR) and reanalysis data to classify cloud properties such as vertical thickness, phase, and hydrometeor type. Cloudnet provides a target classification with a vertical resolution of 30 m, allowing for checking which hydrometeor types are present in the observed atmospheric column. We compared the performances of JOYRAD-94 and JOYRAD-35 for two cloud types: (i) single-layer non-precipitating liquid clouds with a cloud base higher than 200 m and (ii) single-layer nonprecipitating ice clouds with a cloud base higher than 200 m. These cloud types were selected to ensure that both radars operate in the Rayleigh regime so that a comparison of reflectivities is reasonable.

The minimum cloud base was selected to ensure that the clouds were observed in the far field of both radars. A cloud was considered to be precipitating if either drizzle, rain, or melting ice particles, or a combination of these three, were connected to the cloud or were detected within the cloud. Falling ice particles were not defined as precipitation (Illingworth et al. 2007).

The Cloudnet product is derived with 30-s temporal and 30-m vertical resolution. We considered only data that were recorded by both radars simultaneously and within ±10 s of a Cloudnet data point while either a single-layer liquid cloud or a single-layer ice cloud was present. The vertical resolution of JOYRAD-35 was 29 m. JOYRAD-94 was operated in the SM; that is, the resolution varied between 16 and 34 m (see Table 2). Height matching was performed using nearest neighbor comparison. The integration time of JOYRAD-35 was 2 s. The integration time of JOYRAD-94 varied with height between 0.34 and 1.77 s (see Table 2). No corrections concerning gaseous and liquid or ice attenuation were applied to the data, since neither measurements of humidity and temperature profiles nor measurements of integrated water vapor (IWV) are available for this period at JOYCE.

a. Liquid clouds

After selecting single-layer liquid clouds using the Cloudnet classification scheme (a total of 41 791 cases), we investigated the performance of both radars at the cloud center. The cloud center was chosen to exclude the effects of partial beamfilling at cloud edges. The position of the cloud center was calculated from the Cloudnet cloud base and cloud top. Only in 73% of the cases was a signal simultaneously detected by both radars. This is due to the higher sensitivity of JOYRAD-35 compared to JOYRAD-94, especially because of transmitter chip degradation in JOYRAD-94 during the initial deployment at JOYCE and the too conservative detection threshold. If JOYRAD-94 had observed continuously with its nominal reflectivity (see Fig. 6a, “NyA SM”), liquid clouds would have been detected simultaneously in 97% of the cases.

Figure 7 shows scatter histograms of the radar reflectivity and the mean Doppler velocity for simultaneously detected single-layer liquid clouds having a cloud base above 200 m.
b. Ice clouds

We classified 49,556 cases as single-layer ice clouds; 93% of the cases were observed simultaneously by JOYRAD-35 and JOYRAD-94. The higher percentage with respect to liquid clouds is due to higher reflectivities that are associated with these clouds, as can be seen in Fig. 8a; that is, the sensitivity limit of JOYRAD-94 was mostly exceeded. If JOYRAD-94 had measured with its nominal reflectivity, ice clouds would have been detected simultaneously in 99% of the cases.

The majority of reflectivities are found between 230 and 220 dBZ, which corresponds to the area of enhanced occurrence in Fig. 6a between 6 and 8 km. The values between 220 and 25 dBZ predominantly originate from the area in Fig. 6a connecting the maximum at 8.5 km and at the ground. The distribution in the scatterplot in Fig. 8a starts to deviate from the 1:1 line for Ze values larger than 210 or 25 dBZ. Here, the resonance-scattering regime is reached at 94 GHz, while the Rayleigh approximation is still valid at 35 GHz. The mean difference between the two radars is 0.11 dB with a standard deviation of 1.98 dB.

The mean Doppler velocities are concentrated between 21 and 0 m s\(^{-1}\), which are characteristic for ice particles in high altitudes (e.g., Heymsfield and Iaquinta 2000). Again, a positive offset is evident, but still both radars agree with a mean difference of 0.08 ± 0.15 m s\(^{-1}\).

c. Comparative uncertainty estimate

The velocity offset has the same sign for liquid and ice clouds. This indicates that the velocity offset is due to a relative mispointing, that is, either one of the radars or both were not exactly aligned to zenith. Kneifel et al. (2016) found that a slight relative mispointing of 1° elevation produces a velocity offset of 0.1 m s\(^{-1}\), which is already larger than the offset found here.

Since corrections for gaseous and liquid attenuation could not be applied, a quantitative estimate for calibration accuracies cannot be drawn from the comparison of the radars’ reflectivities. All attenuating effects—that is, liquid and gaseous attenuation effects, as well as differential scattering at large particles—cause positive reflectivity offsets, that is, \(Z_{e}^{35} - Z_{e}^{94} > 0\). Hence, a negative offset, as revealed in Fig. 8a, must be due to an offset in calibration.

When comparing Fig. 8a to Fig. 7a, the differential attenuation becomes larger by about 0.6 dB; that is, the offset turns positive. On the one hand, this offset could be explained by attenuation by liquid water. At JOYCE, nonprecipitating single-layer liquid clouds exhibit averaged LWC values of about 0.1 g m\(^{-3}\) and smaller while having vertical extents of about 500–1000 m (Löhnert et al. 2015). This induces a two-way attenuation from the cloud base to the cloud center of about 0.4–0.7 dB (Hogan et al. 2005). On the other hand, it is possible that the average magnitude of the gaseous attenuation differed between the liquid cloud and ice cloud cases. Because the mean altitudes of the cloud centers were 1.2 and 6.1 km for liquid and ice clouds, respectively, we assume that gaseous attenuation has been weaker during liquid cloud events, which could compensate for the differential attenuation by liquid water. The differential two-way attenuation by water vapor is about 1 dB for the lowest 5 km for values of about 10 kg m\(^{-2}\) IWV (Kneifel et al. 2015), being typical for fall and winter at JOYCE.

FIG. 8. Scatter histograms of (a) reflectivities and (b) mean Doppler velocities of JOYRAD-94 and JOYRAD-35, which were observed at the cloud center of single-layer ice clouds having a cloud base above 200 m.
(Löhnert et al. 2015). Further, attenuation by oxygen can be up to 0.5 dB for the entire atmosphere. We estimate the decrease in reflectivity difference from Fig. 8a to Fig. 7a to be smaller than 1 dB, though sufficient to compensate attenuation effects by liquid water; that is, we would expect a similar value for $Z_T^{\text{w}} - Z_T^{\text{d}}$ in both figures. Regarding the latter and that a calibration cross-check with a metal sphere was performed only for JOYRAD-94, the calibration offset between both radars is likely larger than 0.5 dB and perhaps as much as 2 dB.

6. New opportunities for cloud observations

This section presents the novelties for cloud observations that arise from JOYRAD-94 that have optimally matched active and passive components. Moreover, we show that it is possible to overcome the trade-off between Nyquist velocity and range resolution without losing temporal resolution when combining data from two radars with different settings.

a. Liquid water path retrieval at 89 GHz

Optimal beam matching between a radar and a radiometer provides instantaneous signatures as was shown in section 4. To make use of these signatures, retrievals are necessary that add information to the radar measurement. Frisch et al. (1998) demonstrated that the vertical distribution of liquid water can be obtained when combining the LWP from a radiometer and radar reflectivity measurements. The liquid water path can be derived from a microwave radiometer at window frequencies, where clear-sky attenuation is low, for example, at 31 or 89 GHz. However, because of the water vapor absorption continuum in the microwave (Rosenkranz 1998), additional information on IWV is needed to constrain retrievals.

The retrievals, presented in the following, are quadratic models:

$$\text{LWP} = a_0 + \sum_{i=1}^{k} (a_{i,1} \chi_i + a_{i,2} \chi_i^2),$$

where $\chi_i$ represents one of $k$ input parameters (e.g., using $T_B$ at 89 GHz and IWV: LWP = $a_0 + a_{1,1} T_B + a_{1,2} T_B^2 + a_{2,1} \text{IWV} + a_{2,2} \text{IWV}^2$). The coefficients $a_0$ and $a_{i,j}$ were obtained from a least squares regression. The training dataset contains 15,175 radiosonde launched in De Bilt, the Netherlands, which is located 160 km northwest of JOYCE. Clouds where added by applying a relative humidity threshold of 95% for cloud presence and were modeled with a modified adiabatic approach as done by Löhnert and Crewell (2003). The parameter $T_B$ was modeled after Rosenkranz (1998) using the water vapor continuum correction by Turner et al. (2009). The retrievals were performed for clouds with LWPs smaller than 1.5 kg m\(^{-2}\), since most single-layer liquids clouds at JOYCE have smaller LWPs (Löhnert et al. 2015). Note that the training datasets provide information representative of the atmospheric conditions close to the measurement location; however, it should not be considered as ground truth.

Figure 9 shows the performance of an LWP retrieval using only the 89-GHz channel as the input parameter in Eq. (9) (Fig. 9a) and using the 89-GHz channel with additional information on the integrated water vapor from an external source with a random uncertainty of ±2 kg m\(^{-2}\) (e.g., short-term model forecast; Fig. 9b). We assumed an uncertainty of 0.5 K for $T_B$ when deriving the regression coefficients, which accounts for the RMS uncertainty of the 89-GHz radiometric channel (see section 2c). The retrieval using only the 89-GHz channel has an RMS uncertainty (not including potential biases, i.e., calibration offsets) of about 44 g m\(^{-2}\). When including the IWV in the retrieval algorithm, this uncertainty decreases to about 15 g m\(^{-2}\).

For comparison we ran the retrieval algorithm using only seven frequencies between 20 and 31 GHz, which are commonly used for LWP (e.g., Löhnert and Crewell 2003). The RMS uncertainty of this retrieval was 25 g m\(^{-2}\), being 60% larger than the RMS uncertainty of the retrieval combining 89 GHz and the IWV from an external source. This is due to the 89-GHz channel being more sensitive to liquid water than the 31-GHz channel. Combining $T_B$ measurements along the water vapor absorption line at 22.235 GHz with measurements at 89 GHz would further improve the retrieval performance.

b. Dual-radar dealiasing of Doppler spectra

On the one hand, operating JOYRAD-94 in the HRM provides vertical highly resolved data; on the other hand, the Nyquist velocity is small; hence, aliasing is likely when observing strongly turbulent clouds or precipitation. Maahn and Kollias (2012) introduced a method to dealias Doppler spectra recorded by a rain FMCW radar operating at 24 GHz. A stand-alone pulsed radar must vary the pulse repetition frequency to obtain the real atmospheric signal, which decreases the effective observation time (e.g., Holleman and Beekhuis 2003; Sosnytskiy 2014). In FMCW radar data, aliasing produces a folding into the upper (lower) range gate for particles having an absolute radial velocity larger than $v_N$ toward (away from) the radar. Hence, unfolding can be simply applied by
concatenating spectra from neighboring range gates (Maahn and Kollias 2012). However, a robust first guess for the true radial velocity is needed, especially if $u_N$ is small and double folding may have occurred.

Using two radars that operate simultaneously, having opposite settings with respect to $u_N$ and vertical resolution, makes unfolding possible without creating a time mismatch (pulsed radars) and without selecting the wrong part of the concatenated spectrum (FMWC radar). Therefore, the mean Doppler velocities of JOYRAD-35 were used as an initial first guess when unfolding the spectra. Figure 10 shows a flowchart of the dual-radar dealiasing method (DRDM) that was applied to the HRM data of JOYRAD-94. First, the spectrum of JOYRAD-94 is quintupled, concatenating the spectra from the next two range gates on each side. In the next step, the maximum closest to the initial-guess velocity from JOYRAD-35 is identified. In the third and final step, the spectrum is centered so that the contributions of the neighboring range gates are minimized. Therefore, the center of the spectrum is shifted within $\pm 0.25N_{\text{fft}}$ until the minimum sum of the first and last spectral entries is found.

Figure 11 shows two comparisons of mean Doppler velocities of JOYRAD-94 ($v^2_{m}$) and JOYRAD-35 ($v^3_{m}$) based on one month of HRM data. In Fig. 11a, $v^2_{m}$ was calculated from raw spectra and in Fig. 11b from spectra that were preprocessed with the DRDM. The scatter around the one-to-one line is reduced so that mean Doppler velocities smaller than $-5\,\text{m}\,\text{s}^{-1}$ can also be detected. However, the DRDM does not work perfectly, which is visible in Fig. 11b, when the DRDM overestimates the absolute fall velocity in some cases.

The DRDM is simple and computationally inexpensive. Moreover, a prior evaluation of signal quality can further decrease the computing time (Maahn and Kollias 2012). The disadvantages are clearly that bimodal spectra with fully separated peaks could be cut when the third step of the DRDM is conducted. This can be compensated for when including a further processing step that looks for secondary peaks in the spectra. Moreover, if the spectrum is broader than the $2u_N$, a clean unfolding will not be possible anymore, since signal interference will occur in the neighboring range gates. Nevertheless, the results in Fig. 11 show that the DRDM improves the calculation of higher moments and therefore the quality of retrievals. Additionally, the DRDM now allows for obtaining vertically high resolved spectra while minimizing the restriction due to $u_N$.

The choice of the maximum unambiguous velocities ($u_{Nw}$ and $u_{Nn}$ with indexes “Nw” and “Nn” for wide and narrow mode, respectively) depends on the maximum mean Doppler velocities and the spectral widths that are expected at the observational site. To be able to reconstruct full spectra with the noise floor, $2u_{Nn}$ has to be larger than the velocity range covered by the spectra that are expected, which depends both on the particle size distribution and turbulence. Parameter $u_{Nw}$ should be chosen large enough to cover large fall velocities and small enough to have a range resolution that is not too coarse with respect to the $Nn$ mode to avoid that mean Doppler velocities of the two instruments differ by more than $u_{Nn}/2$ when comparing nearest range gates. Otherwise, dealiasing will not be unambiguous without additional information. In the dataset recorded in Ny-Ålesund, we found turbulence-induced changes in vertical velocity of more than $5\,\text{m}\,\text{s}^{-1}$ within 30 m.
To get a copy of the MATLAB code of the DRDM, please contact the corresponding author of this manuscript.

7. Summary and outlook

We presented a new 94-GHz FMCW cloud radar–radiometer (JOYRAD-94) suited for studying cloud microphysical processes and cloud macrophysical properties. JOYRAD-94 is a compact instrument for unattended long-term measurements in all weather conditions. A strong blowing system minimizes adherence of liquid and ice particles on the radome and therefore attenuation effects are avoided. Additionally, the transmitter power can be regulated to prevent the detector from saturation and therefore provide accurate measurements also when strongly reflecting particles are present in the observed column, for example, during precipitation. A further novelty is that the active and passive components receive over the same antenna; that is, optimal beam matching is accomplished.

The active component of JOYRAD-94 can be accurately calibrated with an uncertainty of ±0.5 dBZ. This was shown by observing a metal sphere in the far field of the radar and by a relative comparison to a collocated 35-GHz radar. The calibration of the receiver should be repeated every 3–6 months. The passive broadband channel at 89 GHz has an uncertainty of about ±0.5 K.

JOYRAD-94 was tested in two different measurement configurations: a standard configuration (SM) with vertical resolutions between 16 and 34 m and a high-vertical-resolution mode (HRM) resolving the lowest 3 km with about 6-m range resolution. In both modes JOYRAD-94 is sensitive enough to capture the majority of clouds. The sensitivity ranges from \(-67 (-61)\) dBZ at 100 m to \(-38 (-35)\) dBZ at 10 km when operating in the SM (HRM). The HRM particularly allows for improving observations of small-scale microphysical processes.

**FIG. 10.** Flowchart of the DRDM using \(v_{35}^m\) and the Doppler spectra of JOYRAD-94. A single spectrum contains \(N_{\text{fft}}\) points, which is concatenated with the next two range gates on each side. After identifying the maximum that is closest to \(v_{35}^m\), the spectrum is centered so that, in case of a broad spectrum, contributions from neighboring range gates are minimized.
and processes comprising a strong vertical gradient such as melting layer or riming within layers of supercooled liquid water.

It is also possible to adjust the measurement mode within up to 10 layers in the vertical column to account for different cloud particle properties at different heights. For example, it can be beneficial to run a coarse range resolution with a large unambiguous $v_N$ in the lowest layer where precipitation is expected while measuring with 5-m vertical resolution in the region of the melting layer to study conversion processes with high vertical resolution.

It was shown that the passive channel can provide accurate LWP estimates. A model study revealed that the liquid water path can be retrieved with an RMS uncertainty of about 15 g m$^{-2}$ when measuring brightness temperatures at 89 GHz and knowing the IWV from an external source with an uncertainty of $\pm 2$ kg m$^{-2}$. In addition, systematic offsets—for example, as a result of calibration offsets—have to be taken into account. The information of the 89-GHz channel can be used to identify liquid constituents within the vertical column and to retrieve vertical profiles of liquid water when including radar measurements. The impact of optimally matched beams on the retrieval quality is content of a current study.

We presented a new method to dealias Doppler spectra (DRDM) without losing temporal resolution by using the data of the collocated radar as the initial guess. The DRDM provides vertically highly resolved spectra with an increased $v_N$. The next step will be to investigate how the vertically highly resolved profiles help to understand microphysical processes within the cloud but also at cloud edges.

As JOYRAD-94 is a prototype, future versions of this instrument will have to overcome initial teething troubles: the first version of the transmitter power chip was degrading very fast, which caused a significant loss of sensitivity of 10 dB. However, this problem has already been solved and we showed that the new power chip produces a stable output power. Furthermore, the latest version of the manufacturer’s software includes an update of the threshold detection procedure, the optimization of the suppression of the ADC board electronics’ signal that contaminates the signal processing, and a dealiasing routine to provide accurate spectra. Next generations will also have the possibility of polarimetric detection and can be mounted on a scanner to derive three-dimensional cloud fields. Moreover, a frequent switching between the two measurement modes will be enabled so that the DRDM can also be applied to single radar measurements when assuming constant conditions within two data samples.

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REFERENCES


