European networks observing the atmospheric boundary layer: Overview, access and impacts

Chapter: Doppler cloud radar (DCR)

Document version	**1**
Version date	**12/2021**
PROBE deliverables	**3.1, 3.2, 4.1**
Authors	Document preparation conducted by Chris Walden with input from Alexander Myagkov, Gerrit Maschwitz.

COST Association AISBL | Avenue Louise 149 | 1050 Brussels, Belgium
T +32 (0)2 533 3800 | F +32 (0)2 533 3890 | office@cost.eu | www.cost.eu

Funded by the Horizon 2020 Framework Programme
of the European Union

Table of contents

Introduction

This report provides a short overview of operating Doppler Cloud Radar, including introduction to sensor, products, manufacturers, instrument types, instrument setup and required regular maintenance on site, calibration, measurement configuration, data formats, QA/QC methods and retrieval methods.

Part 1 General overview

Introduction

Millimetre-wavelength radars have established themselves as valuable tools for the study of cloud and precipitation processes and for long-term cloud monitoring (e.g., Illingworth et al., 2007; Kollias et al., 2020). Compared to classical weather radars, their higher operating frequencies make them especially sensitive to the small droplets and ice particles in clouds. These frequencies also mean that antenna gains giving favourable beam widths (e.g., 0.5-1.0°) may be achieved with a compact design. However, a disadvantage is the presence of atmospheric attenuation due to water vapour and molecular oxygen. To minimise this, cloud radars usually operate in one of two frequency windows, around 35 GHz (Ka-band) and 94/95 GHz (W-band).

While still regarded as specialist instruments, there are now standardized configurations available from a number of manufacturers, opening up the field to new user communities. Available systems use either (a) magnetron or klystron technology, delivering high power pulses of electromagnetic energy, or (b) lower power solid state technology, often based on frequency modulated continuous wave (FMCW) transmission using swept-frequency transmissions known as chirps. FMCW systems usually have bistatic antenna configurations with separate transmit and receive antennas, and readily allow retrievals at close range. Use of multiple chirp sequences means they may be tailored to provide different resolutions at different ranges. This can offer advantages for boundary layer observations including studies of fog (Delanoë et al., 2016). For fully coherent pulsed radars, such as those with klystron-based or solid-state transmitters, the use of so-called pulse compression can improve sensitivity without compromising range resolution. This involves intra-pulse modulation of phase or frequency (see e.g., Skolnik 2008), with the latter taking the form of a chirp. In this way more energy may be delivered to the cloud targets through use of longer pulses. However, it has the drawback of introducing a blind zone at close range. To compensate for this, it is common to interleave coded pulses with short uncoded pulses to sample the boundary layer, and to then merge the data to create a full profile. Within Europe this has been implemented on a klystron-based Ka-band radar (Copernicus) at Chilbolton Observatory in the U.K., though this is not a commercially available system.

A list of some of the commercially available instruments is shown in Table 1, though this is not intended to be exhaustive. At present only a subset of instrument models is operated in European networks. Mostly these are the compact or trailer-based systems, although in some cases these have been adapted and incorporated into multi-instrumented containerized platforms (Bühl et al., 2013). Whilst early models of cloud radar used only a single polarization, many systems now offer dual-polarization capability, and some (Küchler et al., 2017) also incorporate a passive channel for the parallel detection of liquid water path (LWP).

Products

To date, the majority of systems deployed across Europe are operated in zenith-pointing mode, delivering cloud-profiling data sets. However, the availability of systems for scanning in azimuth and elevation is offering new opportunities for sky mapping and wind profile retrievals.

The raw observed quantities typically include backscattered power, expressed as effective radar reflectivity factor (dBZ), radial Doppler velocity (derived from signal power spectra or via pulse-pair techniques), and spectral width. More sophisticated measures such as skewness and kurtosis of Doppler spectra are available on some systems, and many offer options to record raw spectra for post-processing, although this can present challenges in terms of data storage capacity. Recording of polarimetric variables such as linear depolarization ratio (LDR), differential reflectivity (ZDR) and co- and cross-polar correlation coefficients depends on the instrument capability and configuration.

For sites equipped with both 35 GHz and 94/95 GHz instruments, side-by-side operation provides opportunities for more advanced retrievals such as cloud particle size distributions. Some manufacturers are facilitating this by offering combined dual-frequency systems, including some with scanning capability.

Manufacturers/Instrument types

Table 1: Overview of some commercially available cloud radar instruments

Manufacturer	Instrument	Antenna/ scanning	Radar technology	Size/Format
Metek Meteorologische Messtechnik GmbH (Metek) https://metek.de/	MIRA-35 series	Zenith system with 1m, 1.2 m or 2 m Cassegrain antenna Hemispheric scanning option with 1 m or 1.2 m antenna.	Pulsed magnetron Frequency 33-37 GHz Power 30 kW peak / 30-60 W average PRF 2.5-10 kHz	Scanning model is built into custom trailer. Zenith model is in semi-compact enclosure.
	MIRA-35C compact model	Zenith system with 50 cm or 1 m Cassegrain antenna	Pulsed magnetron Frequency 34.8-35.2 GHz Power 3 kW peak / 3-6 W average PRF 2.5-10 kHz	Compact enclosure
RPG Radiometer Physics GmbH https://www.radiometer-physics.de/	RPG-FMCW-94 series	Bistatic (2 Cassegrain antennas with 500 mm aperture) Optional hemispheric scanning	Solid state FMCW Centre frequency 94 GHz ± 100 MHz typical Power 1.5 W typical	Compact 80-160 kg (zenith models) 1150x900x900 mm 250 kg (with scanner) 1500x900x1400 mm
	RPG-FMCW-35 series	Bistatic antenna (2 Cassegrain antennas with 700 mm aperture) Optional hemispheric scanning	Solid state FMCW Centre frequency 35 GHz ±100 MHz typical Power 10 W typical	Compact 80-160 kg (zenith models) 1150x900x900 mm 250 kg (with scanner) 1500x900x1400 mm
	Dual frequency (35 GHz/94 GHz) models also available	Twin bistatic antennas Optional hemispheric scanning		500 kg (with scanner) 1800x1700x1800 mm
Meteomodem http://meteomodem.com	BASTA mobile	Bistatic (2 Cassegrain 0.6m antennas) Optional scan positioner	Solid state FMCW Centre frequency 95 GHz ±90 MHz typical Power 0.5 W (1 W option) Single polarization.	Compact 1540x940x620 mm Approx. 70 kg
	BASTA mini	Bistatic (2 Cassegrain 0.3m antennas) Optional scan positioner	Solid state FMCW, Centre frequency 95 GHz ±90 MHz typical. Power 0.5 W (1 W option) Single polarization.	Compact 820x460x450 mm Approx. 35 kg
ProSensing https://prosensing.com	KAZR	Zenith Single 1.82 m Cassegrain antenna	Extended Interaction Klystron Amplifier (EIKA)	Shipping container

			Power 2 kW peak, 100 W average. 34.83 GHz (short pulse mode), 34.89 GHz (chirp mode) Range 200m-2km (short pulse), 2-17.5km (chirp)	
	KASPR	Full hemispheric scanning Single 1.2 m Cassegrain antenna	Options include solid state transmitter (100 W peak power, 25 W average), or EIKA (2.2 kW peak power, 80 W average) Frequency 35.29 GHz PRF up to 15 kHZ	Deployed from shipping container
	Zenith pointing W-band cloud radars	Zenith Single 1.2 m Cassegrain antenna	EIKA 1.8 kW peak power Frequency 95 GHz	Semi-compact enclosure
	WSPR	Full hemispheric scanning. Single 1.2 m Cassegrain antenna	EIKA (1.8 kW peak power, 15 W average) Frequency 95 GHz Solid state option also available	Deployed from shipping container
	Custom Ka/W-band Scanning ARM Cloud Radar (SACR) built for U.S. ARM program	Full hemispheric scanning		

Part 2 Practical considerations

<u>Instrument setup</u>

Installation

Cloud radars are frequently operated as part of long-term observation programmes, but most systems are also designed to allow easy deployment for field campaigns. Solutions for delivery to observational sites include custom shipping containers, towable trailers, or flight cases and boxes.

For installation, all radar instruments require a stable, levelled platform or rooftop with sufficient load-bearing capacity, together with adequate surrounding space for access by personnel. This is especially true for container-based systems, where the overall levelling is determined by that of the container. For smaller instruments and trailer mounted systems, it is possible to compensate for some unevenness using adjustable legs/feet. Careful consideration should be given to the stability of the radar in the presence of strong winds. Where possible, secure fixing of the radar to the underlying platform should be considered (e.g., using steel ropes or belts), especially in the case of rooftop mounted systems.

The deployment environment should be such that there is at least an open view within a cone of specified angle from zenith. This angle depends on the particular antenna configuration of the radar, which determines the beam width and sidelobe characteristics. For scanning systems, the ideal setup is a view to the horizon on all azimuths, unobstructed by trees, fences, buildings and any nearby objects that may lead to reflections that could damage the radar receiver. In addition, local regulations for the use of the RF spectrum should be reviewed before installation. When siting the radar, consideration should be given to safety issues to prevent prolonged electromagnetic field exposure (see below).

For scanning systems, it is important to cordon off the area surrounding the instrument to prevent injuries from the rotating hardware. This is especially true for unattended operations, in which case the cordon should be a secure fence.

To assist with quality control, collocated ancillary measurements are recommended. ACTRIS requirements in this respect are being refined, but are likely to include the need for a weather station and disdrometer.

Alignment
Alignment of scanning systems relative to a reference (usually North) should be determined during installation. To assist with this, many systems include a dedicated sun scan procedure in the operating software. Fine tuning of horizontal alignment (e.g., using adjustable feet) is aided by the inclusion in some systems of embedded high-precision inclination sensors with digital output. Deployments on unstable ground are not recommended as they may lead to gradual misalignment and degraded data quality. Recent community developments include methodologies for monitoring zenith alignment by making use of retrieved Doppler velocities and wind information from reanalysis data (Pfitzenmeier et al., 2021). These are being considered for adoption as standard operating procedures within ACTRIS, together with solar scan methods in the case of scanning radars.

Power Supply and Network Access
Power requirements are instrument dependent, but within Europe a standard 380-415V three-phase supply is typical. For example, RPG radars have a power line that uses one phase to supply the radar instrument including peripherals and one phase for the optional scanner. However, some systems require only a single phase.

Network requirements also differ between manufacturers. Some employ an external host PC that runs part of the operating software, and this communicates with an embedded PC using an ethernet connecton. In such circumstances a direct (peer-to-peer) configuration is recommended, in order to prevent data loss related to the demands of the local institutional network infrastructure. For operation as part of a network such as ACTRIS, a reliable internet connection is strongly recommended.

Radiation
The outdoor operation of radars requires permission of the national bureau responsible for the regulation of electromagnetic emission (frequency allocation). The user is responsible for the acquisition of all required permissions at the place of deployment. In addition, the user needs to take measures to ensure that people (personnel and public) cannot enter the main beam within a certain on-axis safety distance from the radar transmitter. This is particularly important for scanning systems. When observing in the zenith direction, a safety fence is usually sufficient, so long as there are no means for anybody to enter the beam from above. Users are advised to consult the manufacturer's recommendations and the International Commission on Non-ionizing Radiation Protection (https://www.icnirp.org/).

Required regular maintenance on site

The majority of instruments are capable of unattended operation, and can be run 24/7 for extended periods of time. Where antennas are fitted with a radome, this is subject to aging that degrades its hydrophobic coating. To preserve optimum data availability and quality, the radome should be replaced at regular intervals as indicated by the manufacturer. Other components such as amplifiers also degrade over time. They may require replacement after some years, depending on the radar hardware and operating conditions.

Calibration

End-to-end calibration involving both transmitter and receiver chains is recommended, and should be performed at regular intervals as often as means allow. In practice this means a hands-on calibration every 1-2 years, with interim monitoring to identify changes. Hands-on calibration involves the use of external targets, and procedures are being evaluated for adoption within ACTRIS (Toledo et al., 2020). These include the use of mast-mounted corner reflector targets, or similar targets flown on uncrewed aircraft systems (UAS), as well as intercomparison with a calibrated reference radar using ice clouds as targets. This latter method is helpful for fixed zenith pointing systems, where practical considerations such as altitude limitations on UAS flights make it difficult to locate targets in the far field. Other techniques involving rain as a natural target (Hogan et al., 2003; Myagkov et al., 2016) show promise, especially as they allow ongoing checks on calibration stability. There are also valuable lessons to be learned from the challenges of calibrating airborne cloud radars (Ewald et al., 2019).

End-to-end calibration should be supplemented, where possible, by ongoing monitoring of the gain of the receiver chain using a noise source. This is often implemented by manufacturers and measurements form part of housekeeping data. However, this does not include the antenna section of the receiver chain, and a full characterisation requires the use of hot and cold targets as absolute temperature standards. For example, in the case of RPG radars (Rose, 2016) the manufacturer provides means for mounting an absorber (black body) with ambient temperature as hot target and a liquid nitrogen (LN2) cooled absorber as cold target. The procedure requires at least two people, with appropriate health and safety measures being implemented when handling LN2. Alternatively, where a collocated multichannel microwave radiometer (MWR) is available, clear sky may be used as a cold target, with the brightness temperature derived from the MWR. This is readily facilitated at ACTRIS cloud remote sensing sites, where operation of an MWR is standard.

In addition, work is in progress within ACTRIS to develop procedures for routine monitoring of drifts or step changes in the end-to-end calibration, by the use of a collocated disdrometer. This allows comparison of observed effective reflectivity factor, Z, from the radar, with that predicted by the measured drop size distribution (DSD). There are limitations due to wet radome attenuation, but by suitable selection of events with moderate rain rates the technique shows promise, especially for systems with blowers that minimise radome wetting.

Measurement configuration

Radar systems generally have many configuration options. For example, with pulsed radars the user may select pulse repetition frequency (PRF), pulse duration, integration time and velocity resolution, while FMCW radars achieve similar customisation by the tailoring of chirp schemes, including customized multiple chirp sequences to optimize range resolution and sensitivity. The flexibility depends on the manufacturer.

For cloud profiling application the preferred measurement mode is vertically pointing, since this permits the direct use of Doppler velocities (after correction for the motion of the air) in microphysical retrieval and reduces the severity of attenuation due to gases and liquid. For systems with scanning capability, vertical dwells may be interspersed with scans. For example, azimuth scans at high elevation (typically 8 degrees from zenith) may be used to derive profiles of in-cloud wind. However, to preserve the time series of profiles such scans should not represent more than a few percent of the observation time.

Within ACTRIS a cloud-profiling station requires not only a Doppler cloud radar, but also an automatic lidar or ceilometer (ALC) and a microwave radiometer (MWR). These are used together for the geophysical retrievals. The cloud radar should be capable of providing profiles of radar reflectivity factor and Doppler velocity at the nominal resolution of 30 seconds and 60 metres. Minimum sensitivity should be about −50 dBZ at 1 km in the absence of attenuation. Cloud radars capable of measuring linear depolarisation ratio (LDR) provide significant advantages in insect discrimination, melting layer determination and ice crystal classification.

Other general operational recommendations include keeping the instrument powered up, as this helps to maintain temperature and humidity stability. An accurate system clock is also necessary, which can be achieved using a time server (ntpd) or a GPS reference. Most commercial systems now include an internal GPS reference as standard.

Data formats

Data formats differ between manufacturers. However, it is always recommended to store the raw (Level 0) data in the manufacturer's format. Pre-processed Level 1 data typically include spectral moments such as effective reflectivity factor, radial Doppler velocity and spectral width, and are mostly available in NetCDF format, but with manufacturer-specific content. Within ACTRIS these instrument-specific files are processed to produce Level 1b NetCDF files. These have a subset of variables that are common across all radar models, together with instrument specific variables, and are the starting point for further processing. Details of the file format are available alongside documentation for the CloudnetPy Python processing toolkit (see Tukiainen et al. 2020 and https://cloudnetpy.readthedocs.io).

QA/QC methods

All manufacturers provide housekeeping data to monitor instrument status. Precise details vary between systems, but generally include technical information such as transmitter power, receiver temperature and humidity as well as status and quality flags (e.g., on/off status of blower where fitted). It is recommended that all such data be stored. Within ACTRIS there are automatic housekeeping data checks that will be performed as part of the processing chain. Additionally, ACTRIS is developing near-real-time instrument status dashboard displays to allow early identification of hardware faults to assist with maximising uptime.

The quality of retrievals from precipitating clouds is hampered by presence of attenuation due to wetting of the radome. The use of an air blower and a hydrophobic coating helps to minimise this. It can also mitigate the effects of wet snow accretion, which can introduce significant attenuation. Such blowers have been used with both Meteomodem BASTA and RPG radars, in the latter case being an integral part of the instrument design. Ancillary measurements from a collocated weather station can also assist in the QA/QC process.

There is also merit in enabling remote monitoring via a webcam to allow visual checks of instrument operation. This is especially recommended in the case of systems with scanning capability.

Retrieval methods

Retrieval of geophysical parameters such as liquid and ice water content (Hogan et al., 2006), and drizzle microphysical properties (O'Connor et al., 2005) necessitates synergetic use of radar data and measurements from collocated instruments, in particular an automatic lidar or ceilometer (ALC) and microwave radiometer (MWR). The Cloudnet processing scheme used within ACTRIS is well established, and has been developed in a modular fashion to allow evaluation of new retrieval algorithms based on community developments. An open-source Python package, CloudnetPy (Tukiainen et al., 2020), is available that implements this scheme. In addition to data from the three core instruments the scheme requires thermodynamical (model or radiosonde) data, and produces vertical profiles and characterization of cloud properties.

There is an active cloud remote sensing community and new retrievals are under continual development. Some require higher temporal resolution, and depend on the instrument capability and configuration. Examples are the derivation of turbulence and drizzle products based on the skewness of the Doppler velocity spectrum. Other more sophisticated retrievals rely on availability of the full Doppler spectrum from the radar. For example, this allows analysis of situations where more than one distinct hydrometeor population is occupies the same volume (e.g., stratocumulus containing liquid droplets and drizzle drops). Ongoing engagement with community developments is facilitated through regular ACTRIS workshops.

Part 3 References

Bühl, J., Seifert, P., Wandinger, U., Baars, H., Kanitz, T., Schmidt, J., Myagkov, A., Engelmann, R., Skupin, A., Heese, B., Klepel, A., Althausen, D. & Ansmann, A., LACROS: the Leipzig Aerosol and Cloud Remote Observations System, Proc. SPIE 8890, Remote Sensing of Clouds and the Atmosphere XVIII; and Optics in Atmospheric Propagation and Adaptive Systems XVI, 889002, 2013. https://doi.org/10.1117/12.2030911

Delanoë, J., Protat, A., Vinson, J., Brett, W., Caudoux, C., Bertrand, F., Parent du Chatelet, J., Hallali, R., Barthes, L., Haeffelin, M., & Dupont, J., BASTA: A 95-GHz FMCW Doppler radar for cloud and fog studies, J. Atmos. Ocean. Tech., 33(5), 1023-1038, 2016. https://doi.org/10.1175/JTECH-D-15-0104.1

Ewald, F., Groß, S., Hagen, M., Hirsch, L., Delanoë, J. & Bauer-Pfundstein, M., Calibration of a 35 GHz airborne cloud radar: lessons learned and intercomparisons with 94 GHz cloud radars, Atmos. Meas. Tech., 12(3), 1815-1839, 2019. https://doi.org/10.5194/amt-12-1815-2019

Görsdorf, U., Lehmann, V., Bauer-Pfundstein, M., Peters, G., Vavriv, D., Vinogradov, V., & Volkov, V., A 35-GHz Polarimetric Doppler radar for long-term observations of cloud parameters—Description of system and data processing, J. Atmos. Ocean. Tech., *32*(4), 675-690, 2015. https://doi.org/10.1175/JTECH-D-14-00066.1

Hogan, R. J., Bouniol, D., Ladd, D. N., O'Connor, E. J., & Illingworth, A. J., Absolute calibration of 94/95-GHz radars using rain, J. Atmos. Ocean. Tech., 20(4), 572-580, 2003. https://doi.org/10.1175/1520-0426(2003)20%3C572:ACOGRU%3E2.0.CO;2

Hogan, R. J., Mittermaier, M. P., & Illingworth, A. J., The retrieval of ice water content from radar reflectivity factor and temperature and its use in evaluating a mesoscale model, J. Appl. Meteorol. Clim., 45(2), 301-317, 2006. https://doi.org/10.1175/JAM2340.1

Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Brooks, M. E., Delanoë, J., Donovan, D. P., Eastment, J. D., Gaussiat, N., Goddard, J. W. F., Haeffelin, M., Baltink, H. K., Krasnov, O. A., Pelon, J., Piriou, J.-M., Protat, A., Russchenberg, H. W. J., Seifert, A., Tompkins, A. M., van Zadelhoff, G.-J., Vinit, F., Willén, U., Wilson, D. R., & Wrench, C. L., Cloudnet: Continuous evaluation of cloud profiles in seven operational models using ground-based observations, B. Am. Meteorol. Soc., 88(6), 883-898, 2007. https://doi.org/10.1175/BAMS-88-6-883

Kollias, P., Bharadwaj, N., Clothiaux, E. E., Lamer, K., Oue, M., Hardin, J., Isom, B., Lindenmaier, I., Matthews, A., Luke, E. P., Giangrande, S. E., Johnson, K., Collis, S., Comstock, J., & Mather, J. H., The ARM Radar Network: At the leading edge of cloud and precipitation observations, B. Am. Meteorol. Soc., 101(5), E588-E607, 2020. https://doi.org/10.1175/BAMS-D-18-0288.1

Küchler, N., Kneifel, S., Löhnert, U., Kollias, P., Czekala, H., & Rose, T., A W-band radar-radiometer system for accurate and continuous monitoring of clouds and precipitation, J. Atmos. Ocean. Tech., 34(11), 2375-2392, 2017. https://doi.org/10.1175/JTECH-D-17-0019.1

Myagkov, A., Kneifel, S. & Rose, T., Evaluation of the reflectivity calibration of W-band radars based on observations in rain, Atmos. Meas. Tech., 13(11), 5799-5825, 2020. https://doi.org/10.5194/amt-13-5799-2020

O'Connor, E. J., Hogan, R. J., & Illingworth, A. J., Retrieving stratocumulus drizzle parameters using Doppler radar and lidar, J. Appl. Meteorol. Clim., 44(1), 14-27, 2005. https://doi.org/10.1175/JAM-2181.1

Pfitzenmaier, L., Kollias, P., & Löhnert, U.: Retrieving antenna mispointing for vertical pointing cloud radar and correcting the introduced Doppler velocity errors in the measurements, EMS Annual Meeting 2021, online, 6–10 Sep 2021, EMS2021-293, https://doi.org/10.5194/ems2021-293, 2021.

Rose, T. (Ed.), RPG-FMCW-94-SP/DP 94 GHz W-band cloud Doppler radar instrument installation, operation and software guide, Version 2.10-1, 2016.
https://www.radiometer-physics.de/download/PDF/Cloud%20Radar/RPG-FMCW-Instrument_Manual.pdf

Skolnik, M. I. (Ed.), Radar Handbook, 3rd Edition, McGraw-Hill, ISBN 978-0-07-1485447-0, 2008.

Toledo, F., Delanoë, J., Haeffelin, M., Dupont, J.-C., Jorquera, S., & Le Gac, C., Absolute calibration method for frequency-modulated continuous wave (FMCW) cloud radars based on corner reflectors, Atmos. Meas. Tech., 13(12), 6853-6875, 2020. https://doi.org/10.5194/amt-13-6853-2020

Tukiainen, S., O'Connor, E., & Korpinen, A., CloudnetPy: A Python package for processing cloud remote sensing data, J. Open Source Software, 5(53), 2123, 2020. https://doi.org/10.21105/joss.02123