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

Chapter: Doppler lidar (DL)

Document version	**1**
Version date	**10/2021**
PROBE deliverables	**3.1, 3.2, 4.1**
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Funded by the Horizon 2020 Framework Programme of the European Union

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Introduction

This report provides a short overview of operating Doppler lidar, 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

Doppler lidars observe the radial (line-of-sight) Doppler velocity of atmospheric tracers such as molecules or aerosol using direct detection methods, typically at UV wavelengths, or by coherent heterodyne detection, typically using near-IR wavelengths. Hence, the latter method offers advantages in the atmospheric boundary layer, while the former, using molecules as tracers, can measure radial velocities in the upper troposphere, stratosphere and mesosphere (Reitebuch, 2012).

Most commercial systems employ solid-state fibre-optic technology and coherent heterodyne detection, with the tracers being aerosol, cloud droplets or ice particles. Two implementations are available for these robust and low-powered systems: pulsed (Pearson and Eacock, 2002), and continuous-wave (CW) (Pitter et al., 2015). CW systems obtain the range information by adjusting the focus of the telescope to change the range-weighting function, and are suitable for operation up to about 300 m in altitude. Pulsed systems, similar to ALCs, use the time-of-flight to obtain range information. Pulsed systems are necessary to cover the full depth of the boundary layer. The fibre optic design allows a high degree of flexibility, and these instruments are available in a number of guises: vertical stare only, full all-sky scanning capability, scan within a conical zone, or optimised for winds only. Some systems operate at very high pulse rates and average many pulses to achieve the required sensitivity, whereas others may operate at lower pulse rates, but with larger per-pulse energies. Like ALCs, the commercial systems can operate autonomously and require little maintenance.

Products

The raw quantities typically retrieved by Doppler lidar systems are signal power and the radial Doppler velocity. Some systems can also be configured to provide the signal power spectrum (from Fast Fourier Transform, FFT, or from lagged-autocorrelation) from which Doppler spectra can be produced (Pearson et al., 2009). If the telescope function is known or calculated, the signal profile can be converted into a profile of attenuated backscatter coefficient (Pentikäinen et al, 2020).

The vertical profile of horizontal wind is then retrieved from a combination of scans using trigonometry. Scan types for single DL retrievalsinclude Doppler Beam swinging (DBS) similar to sodars and radar wind profilers or conical Velocity-Azimuth-Display VAD) scans at a constant elevation angle (Päschke et al., 2015; Teschke et al., 2017). Other possibilities include the use of two or three systems operating together to create virtual-towers (Debnath et al., 2017; Lane et al., 2013; Calhoun et al. 2006). The presence of wind shear and low-level jets can then be diagnosed from the retirved wind profiles (Tuononen et al., 2017; Pichugina et al., 2012).

Turbulent characteristics can be derived from the rapid velocity fluctuations, both from vertical and from scanning operation (Bonin et al., 2017; Smalikho and Banakh, 2017; O'Connor et al. 2010). Further, a boundary layer classification can be generated from the combination of the horizontal wind profiles, turbulent characteristics and attenuated backscatter profiles (Krishnamurthy et al., 2021; Bonin et al. 2018; Smalikho and Banakh, 2017; Manninen et al., 2018; Harvey et al., 2013; Tucker et al., 2009).

Manufacturers/Instrument types

All instruments considered in Table 1 transmit at a wavelength close to 1.5 µm.

Table 1: Overview of commercial long-range Doppler lidars

Manufacturer	Instrument	Scanning	size/weight	PRF
Leosphere	Windcube (100S, 200S, 400S)	Hemispheric	compact 250 kg	> 10 kHz Depends on operating mode
Halo Photonics	Streamline, Streamline XR	Hemispheric	compact 60 - 85 kg	> 10 kHz Depends on manufacturer setup
	Streamline Pro	Limited cone (20 degrees)	65 kg	> 10 kHz Depends on manufacturer setup
Mitsubishi Electronic	Terminal DL	Hemispheric	small container 2000 kg	250 Hz
Leonardo	Skiron 3D	Hemispheric	small container 3500 kg	4 kHz
Lockheed Martin	Wind Tracer	Hemispheric	small container 1600-2500 kg	750 Hz

Part 2 Practical considerations

Instrument setup

As can be seen from the list of manufacturers and instruments in Table 1, there are two size classes of instrument. Those which are container-based will require a levelled platform or rooftop capable of supporting significant weight and an access area approaching 5 by 5 metres. The smaller size class, compact, comprises standalone instruments for which a stable surface is required, but an uneven surface can be compensated for by the adjustable legs/feet. The small instruments may also need fixing to the surface with suspension straps.

The deployment environment surrounding should have at least an open view within a cone of specified angle from zenith, in order to perform conical scans for the retrieval of the horizontal wind profile, and ideally an open view to the horizon in all directions to enable low-elevation scans. The instrument should be aligned to a reference (e.g. North).

The instrument should be kept powered continuously as this will keep the instrument internal temperature stabilised. An accurate system clock is also necessary, which can be achieved using a time server (e.g. ntpd) or a GPS reference. Most commercial systems now include an internal GPS reference as standard. More considerations for standard operating procedures are given in Table 2.

The near-IR wavelength of operation permits eye-safe use, but operation may require permission in some locations.

Required regular maintenance on site

Preventive maintenance is limited to occasional cleaning of the telescope. Leosphere systems may need a regular change of dessicant to prevent the internal fogging of the telescope lens in damp conditions. Over longer-term operation (5-10 years), some components may need replacement, such as amplifiers and the scanning motors, bearings or housing.

Calibration

Co-located ceilometer for an extended period to determine telescope focus function if use of attenuated backscatter profile required (Pentikäinen et al., 2020). Regular hard-target measurements, e.g. using a nearby wind turbine or mast, to keep track of potential systematic biases in pointing angle or Doppler velocity.

Table 2: Considerations for standard operating procedures

Retrieval of Calibration Parameters	• **Calibration parameters**: absolute calibration, background correction, telescope function and variability • **Absolute calibration**: - Doppler velocity and range calibration: hard target check - Attenuated backscatter: liquid cloud technique, after telescope focus determination. • **Background correction** performed during standard processing. • **Telescope function determination** by comparison with co-located ceilometer. Required every time telescope focus changed, or instrument modified/upgraded.
Characterization of measurement uncertainties	• **Doppler velocity uncertainty sources:** - Offset uncertainty assessed during instrument calibration and hard target. - Signal to noise ratio (including variation in laser power) • **Wind uncertainty sources:** - Pointing angle uncertainty - Doppler velocity uncertainty - Turbulent and inhomogeneity uncertaint**y** • **Attenuated backscatter uncertainty sources**: - SNR uncertainty (including background correction uncertainty) - Telescope focus uncertainty - Cloud calibration method uncertainty
Calibration schedule (automatic and hands-on)	• Automatic processing for SNR and velocity uncertainty. Cloud calibration updated every event. Telescope focus can be continuous or periodic depending on co-located ceilometer availability
Azimuth and elevation pointing accuracy	• For scanning instruments (target and/or horizontal winds). Provide azimuthal correction from north. Ensure horizontal alignment of instrument.
Detecting systematic errors during instrument operation	• Hard target velocity calibration and pointing angle (target and/or horizontal winds). • Monitor instrument stability (background, telescope focus, cloud calibration)

Measurement configuration

The scanning capability of these instruments implies that the configuration can be optimised for the location and research requirements as detailed in the retrieval method section. Network operation may include specific requests, for example, ACTRIS recommends that these are included within the scan schedule:

- Vertical scanning
    - High temporal resolution (< 5 seconds if possible)
    - Provides
        - Vertical air motion
        - Turbulent parameters,
        - Diagnosis of aerosol, cloud, precipitation
- Conical scanning
    - VAD with at least 12 beams, or continuous scan mode (CSM)
    - At two elevation angles if possible
        - 15-40 degrees from zenith for full extent of boundary layer
        - shallow elevation angle for capturing shallow boundary layers
    - One full scan every 15 minutes or less
        - Provides winds

Data formats

The data formats vary from manufacturer to manufacturer. It is recommended to always store the data in the native manufacturer format in the first instance.

Figure 1 outlines the processing steps that are performed by a coherent Doppler lidar in order to obtain the calibrated data necessary for calculating meteorological parameters. Processing up to *Calibrated data* is usually performed by the instrument internally in real time. Access to *raw timeseries* is often not possible as these are discarded immediately after on-board processing; if stored, the typical daily volume would easily exceed 1 terabyte. Access to *Raw spectra* is usually possible from most instruments, although archiving of this data is often not switched on by default.

The ACTRIS network requires the *Calibrated data* in the native format for central processing at the ACTRIS data centre, and will use the housekeeping data for QA/QC. However, for use in an operational network that might include different system types and systems from different manufacturers, it may be more appropriate to archive data in a common format that is compatible with the CF-standard.

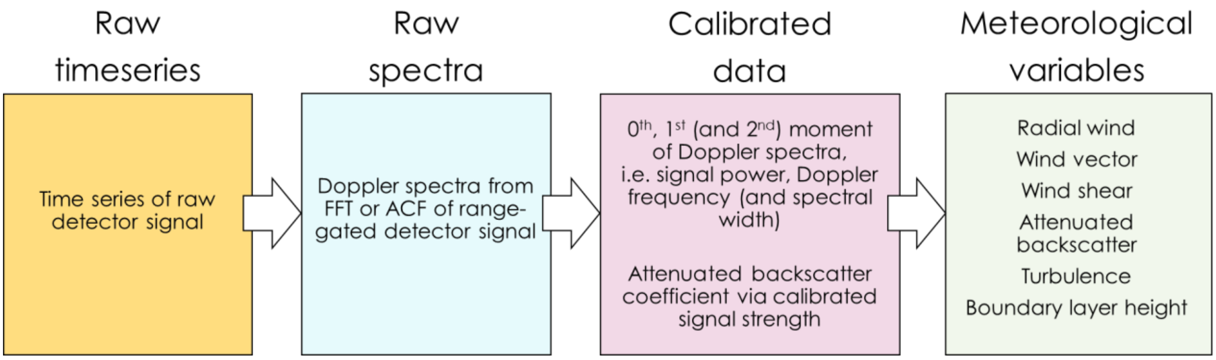

Figure 1: Processing steps for coherent (heterodyne) Doppler lidar systems

The current native *Calibrated data* formats are:

- Leosphere – long-range scanning windcube systems
    - .nc: calibrated signal and radial velocity files, including some housekeeping data
        - Note that these are in HDF5-netcdf4 format, which includes groups, see CF-radial
- Halo Photonics Streamline systems
    - .hpl: calibrated signal and radial velocity files
    - .txt: housekeeping data
        - system_parameters_*.txt
        - Time_sync_*.txt
        - Background_*.txt
    - .acf: raw spectra (complex autocorrelation function, ACF)

Spectral files are available from Leosphere systems, and from Halo Photonics systems (.acf files), but as stated previously, recording of these is not on by default due to the large data volume.

QA/QC methods

All instruments store the instrument setup specification data (transmission, acquisition, integration parameters) including those that can change with scan type and scanning parameters in the housekeeping data.

In addition, the instrument internal temperature and humidity logs, together with background noise files for certain instrument types, should also be recorded. Background noise data is used for automated quality control and correction, which can be augmented with internal temperature information. Temperature and humidity logs are also used in examining drifts and biases, and for identifying possible fogging/freezing of the telescope lens.

Retrieval methods

There are numerous methods in the literature for retrieving meteorological and other geophysical parameters from the Doppler lidar systems described in this document. A detailed description of the methodologies used for retrieving each meterological product is given in the references in Table 3.

Table 3: References for retrieval methods

Meteorological product	Description	References
Winds	DBS scan VAD or CSM VAD or CSM Virtual Tower	Lane et al., 2013 Päschke et al., 2015 Teschke and Lehmann, 2017 Calhoun and Heap et al., 2003 Debnath et al., 2017
Wind shear	From wind product	Pichugina et al. 2012
LLJ	From wind product	Tuononen et al., 2017
Turbulence	Vertical stare VAD, 6-beam, RHI VAD (CSM) VAD	O'Connor et al., 2010 Bonin et al., 2017, 2018 Smalikho and Banakh, 2017 Vakkari et al., 2015
ABL	Threshold retrieval Machine learning approach	Schween et al., 2014 Krishnamurthy et al., 2021
ABL classification	Combine winds, turbulence, skewness and attenuated backscatter coefficient	Manninen et al., 2018
Attenuated backscatter coefficient	Telescope focus function	Pentikainen et al., 2020

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