INTERNATIONAL STANDARD

ISO 28902-3

First edition
2018-11

Air quality — Environmental meteorology —

Part 3:
Ground-based remote sensing of wind by continuous-wave Doppler lidar

Qualité de l'air — Météorologie de l'environnement —

Partie 3: Télédétection du vent par lidar Doppler à ondes contenues basé au sol

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Reference number
ISO 28902-3:2018(E)

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Published in Switzerland

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Foreword

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This document was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology*.

A list of all parts in the ISO 28902 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

Lidars ("light detection and ranging"), used in this document to designate atmospheric lidars, have proven to be valuable systems for the remote sensing of atmospheric pollutants in various meteorological parameters, such as wind, clouds, aerosols and gases. Extensive optical and physical properties of the probed targets, such as size distribution, chemical composition, shape of the particles and gas concentration, and optical properties of the atmosphere, such as visibility, extinction and backscatter, can be retrieved using lidars. Atmospheric targets such as these can be spatially resolved along their line of sight by, for example, focusing the continuous-wave beam at the chosen specific range. The measurements can be carried out without direct contact and in any direction as electromagnetic radiation is used for sensing the targets. Lidar systems, therefore, supplement the conventional *in situ* measurement technology. They are suited for a large number of applications that cannot be adequately performed by using *in situ* or point measurement methods.

There are several methods by which lidar can be used to measure atmospheric wind. The four most commonly used methods are heterodyne pulsed Doppler wind lidar (see ISO 28902-2:2017[1]), heterodyne continuous-wave Doppler wind lidar, direct-detection Doppler wind lidar and resonance Doppler wind lidar (commonly used for mesospheric sodium layer measurements). For further reading, refer to References [2] and [3].

This document describes the use of (monostatic) heterodyne continuous-wave Doppler lidar.

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Air quality — Environmental meteorology —

Part 3: Ground-based remote sensing of wind by continuous-wave Doppler lidar

1 Scope

This document specifies the requirements and performance test procedures for monostatic heterodyne continuous-wave (CW) Doppler lidar techniques and presents their advantages and limitations. The term "Doppler lidar" used in this document applies solely to monostatic heterodyne CW lidar systems retrieving wind measurements from the scattering of laser light by aerosols in the atmosphere. Performances and limits are described based on standard atmospheric conditions. This document describes the determination of the line-of-sight wind velocity (radial wind velocity).

NOTE Derivation of wind vector from individual line-of-sight measurements is not described in this document since it is highly specific to a particular wind lidar configuration. One example of the retrieval of the wind vector can be found in ISO 28902-2:2017, Annex B.

This document does not address the retrieval of the wind vector.

This document can be used for the following application areas:

— meteorological briefing for e.g. aviation, airport safety, marine applications, oil platforms;

— wind power production, e.g. site assessment, power curve determination;

— routine measurements of wind profiles at meteorological stations;

— air pollution dispersion monitoring;

— industrial risk management (direct data monitoring or by assimilation into micro-scale flow models);

— exchange processes (greenhouse gas emissions).

This document can be used by manufacturers of monostatic CW Doppler wind lidars as well as bodies testing and certifying their conformity. This document also provides recommendations for users to make adequate use of these instruments.

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2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61400-12-1:2017, *Wind energy generation systems — Part 12-1: Power performance measurements of electricity producing wind turbines*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
data availability
ratio between the number of actual considered measurement data with a predefined data quality and the number of expected measurement data for a given measurement period

Note 1 to entry: In the wind industry, this term commonly applies to measurements averaged over a standard period of 10 min.

3.2
displayed range resolution
spatial interval between the centres of two successive range measurements

3.3
effective range resolution
application-related variable describing an integrated range interval for which the target variable is delivered with a defined uncertainty

[SOURCE: ISO 28902-1:2012, 3.14, modified — The example has been deleted.]

3.4
effective temporal resolution
application-related variable describing an integrated time interval for which the target variable is delivered with a defined uncertainty

[SOURCE: ISO 28902-1:2012, 3.12, modified — The symbol and the example has been deleted.]

3.5
extinction coefficient
α
measure of the atmospheric opacity, expressed by the natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length

[SOURCE: ISO 28902-1:2012, 3.10]

3.6
integration time
time spent in order to derive an independent value of the line-of-sight velocity

3.7
maximum acquisition range
R_{MaxA}
maximum distance at which a lidar signal can be recorded and processed

Note 1 to entry: It depends primarily on the laser wavelength and transmitter aperture size; also, to some extent, it depends on the number of acquisition points and the sampling frequency.

3.8
minimum acquisition range
R_{MinA}
minimum distance from which a lidar signal can be recorded and processed

Note 1 to entry: If the minimum acquisition range is not given, it is assumed to be zero. It can be different from zero, when the reception is blind by focusing limitations.

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3.9
maximum operational range
R_{MaxO}
maximum distance to which a wind speed can be derived with confidence from the lidar signal

Note 1 to entry: The maximum operational range is less than or equal to the maximum acquisition range.

Note 2 to entry: The maximum operational range is defined along an axis corresponding to the application. It is measured vertically for vertical wind profiler. It is measured horizontally for scanning lidars able to measure in the full hemisphere.

Note 3 to entry: The maximum operational range depends on lidar parameters but also on atmospheric conditions, particularly the extinction coefficient.

3.10
measurement period
interval of time between the first and last measurements

[SOURCE: ISO 28902-2:2017, 3.10]

3.11
minimum operational range
R_{MinO}
minimum distance where wind speed can be derived with confidence from the lidar signal

Note 1 to entry: The minimum operational range is also called blind range.

Note 2 to entry: In continuous-wave lidars, the minimum operational range is determined by the closest position of the focus achievable by the transceiver optical system.

3.12
physical range resolution
width [full width at half maximum (FWHM)] of the range weighting function

[SOURCE: ISO 28902-2:2017, 3.12]

3.13
probe length
width [full width at half maximum (FWHM)] of the spatial weighting function selecting the region in space that contributes to the wind speed computation

Note 1 to entry: The probe length is centred on the measurement distance.

3.14
range resolution
equipment-related variable describing the shortest range interval from which independent signal information can be obtained

[SOURCE: ISO 28902-1:2012, 3.13]

3.15
range weighting function
weighting function of the radial wind speed along the line of sight

[SOURCE: ISO 28902-2:2017, 3.15]

3.16
temporal resolution
equipment-related variable describing the shortest time interval from which independent signal information can be obtained

[SOURCE: ISO 28902-1:2012, 3.11]

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3.17
velocity bias
maximum instrumental offset on the velocity measurement

Note 1 to entry: The velocity bias has to be minimized with adequate calibration, for example, on a fixed target.

[SOURCE: ISO 28902-2:2017, 3.17]

3.18
velocity range
range determined by the minimum measurable wind speed, the maximum measurable wind speed and the ability to measure the velocity sign, without ambiguity

Note 1 to entry: Depending on the lidar application, the velocity range can be defined as the radial wind velocity (scanning lidar) or as horizontal wind velocity (wind profiler).

[SOURCE: ISO 28902-2:2017, 3.18]

3.19
velocity resolution
instrumental velocity standard deviation

Note 1 to entry: The velocity resolution is determined by the signal processing bin width.

3.20
wind shear
variation of wind speed across a plane perpendicular to the wind direction

[SOURCE: ISO 28902-2:2017, 3.20]

4 Fundamentals of heterodyne Doppler lidar

4.1 Overview

A CW Doppler lidar emits a narrow laser beam (see Figure 1). As it propagates in the atmosphere, the laser radiation is scattered in all directions by aerosols, molecules and other scattering material. Part of the scattered radiation propagates back to the lidar, it is captured by a telescope, detected and analysed. Since the aerosols and molecules move with the atmosphere, a Doppler shift results, changing the frequency of the scattered laser light.

At the wavelengths (and thus frequencies) relevant to heterodyne (coherent) Doppler lidar it is the aerosols that provide the principal target for measurement of the back-scattered signal.

The analysis aims at measuring the difference Δf between the frequencies f_t of the emitted laser pulse and f_r of the backscattered light. According to the Doppler equation, this difference is proportional to the line-of-sight wind component, as shown by Formula (1):

$$\Delta f = f_r - f_t = -2 v_r / \lambda \tag{1}$$

where

λ is the laser wavelength;

v_r is the line-of-sight wind component (component of the wind vector $\vec{v}$ along the axis of the laser beam, counted positive when the wind is blowing away from the lidar).

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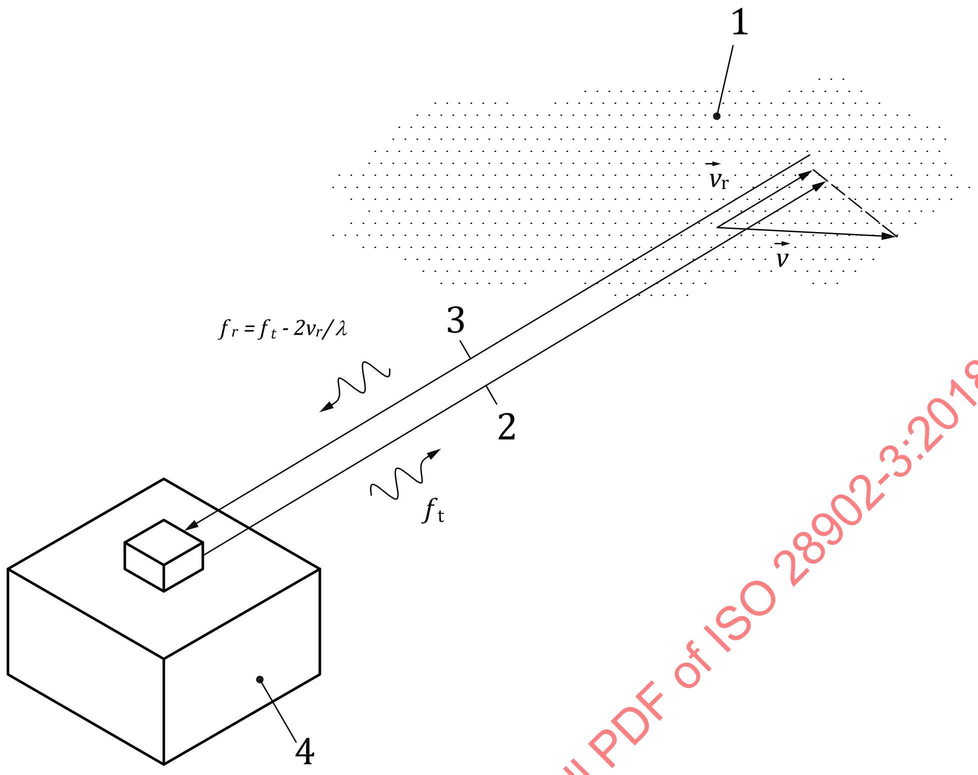

Key
1 scattering particles moving with the wind
2 optical path of the emitted laser beam
3 optical axis of the receiver
4 lidar instrument

Figure 1 — Measurement principle of a heterodyne Doppler lidar

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For a CW Doppler lidar system, the measurement range is usually determined by focusing the beam to create a waist at the chosen distance. Light backscattered from those regions in close proximity to the waist is efficiently re-imaged back into the receiver; light from a significantly closer or greater distance from the waist or focus is inefficiently gathered.

4.2 Heterodyne detection

In a heterodyne lidar, the detection of the light captured by the receiving telescope (at frequency $f_r = f_t + \Delta f$) is described schematically in Figure 2. The received light is mixed with the beam of a highly stable, continuous-wave laser called the local oscillator (LO). The sum of the two electromagnetic waves – backscattered and local oscillator – is converted into an electrical signal by a quadratic detector (producing an electrical current proportional to the power of the electromagnetic wave illuminating its sensitive surface). An analogue, high-pass filter is then applied for eliminating the low-frequency components of the signal, and a low-pass filter is also applied to avoid problems caused by aliasing in the subsequent signal processing.

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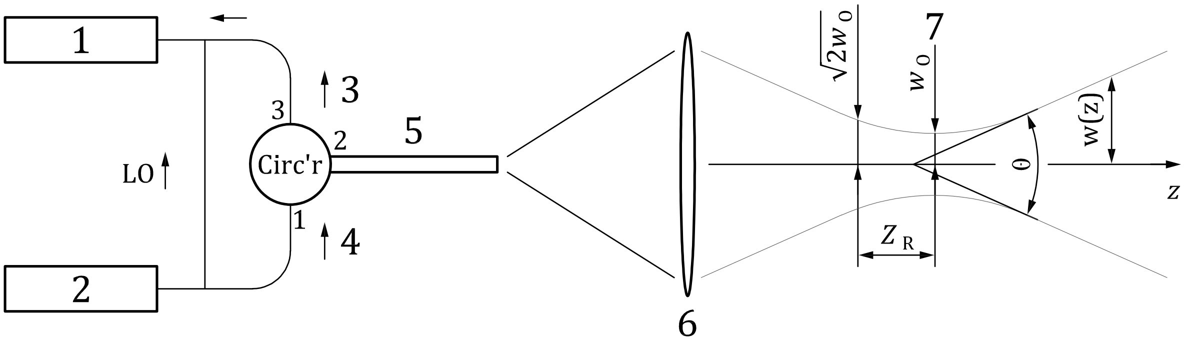

Key

1	detector	Circ'r	circulator
2	laser/local oscillator (LO)	w_0	beam waist
3	receive light	Z_R	Rayleigh length
4	transmit light	θ	total angular spread
5	single-mode fibre	w(z)	function of the axial distance
6	transmit/receiver aperture		
7	Gaussian profile transmitted beam and of backpropagated local oscillator (BPLO)		

Figure 2 — Principles of heterodyne detection, showing an example CW lidar architecture and focus geometry

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The result is a current $i(t)$ beating at the radio frequency $f_t + \Delta f - f_{lo}$, as shown by Formula (2) (derived from Formula (8) in Reference [5]):

$$\underbrace{i(t) = 2 \cdot \frac{\eta \cdot e}{h \cdot f_t} \cdot K \cdot \xi(t) \cdot \sqrt{\gamma(t) \cdot P_r(t) \cdot P_{lo}} \cdot \cos\left(2\pi\left(\Delta f + f_t - f_{lo}\right) \cdot t + \varphi(t)\right) + n(t)}_{i_{het}(t)} \tag{2}$$

where

t	is the time;
η	is the detector quantum efficiency;
e	is electrical charge of an electron;
h	is Planck's constant;
K	is the instrumental constant taking into account transmission losses through the receiver;
$\xi(t)$	is the random modulation of the signal amplitude by speckles effect (see 4.5.4);
$\gamma(t)$	is the heterodyne efficiency;
$P_r(t)$	is the power of the backscattered light;
P_{lo}	is the power of the local oscillator;
f_{lo}	is the frequency of the local oscillator;
$\varphi(t)$	is the random phase;
$n(t)$	is the white detection noise;
$i_{het}(t)$	is the heterodyne signal.

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The heterodyne efficiency $\gamma(t)$ is a measure for the quality of the optical mixing of the backscattered and the local oscillator wave fields on the surface of the detector. It cannot exceed 1. A good heterodyne efficiency requires a careful sizing and alignment of the local oscillator relative to the backscattered wave. Optimal mixing conditions are discussed in Reference [5]. The heterodyne efficiency is not a purely instrumental function, it also depends on the on the refractive index turbulence (Cn^2) along the laser beam[6]. Under conditions of strong atmospheric turbulence, the effect on varying the refractive index degrades the heterodyne efficiency. This can happen when the lidar is operated close to the ground during a hot sunny day.

For a CW coherent system, the time-averaged optical signal power, P_S, backscattered by the aerosols into the receiver is given to a good approximation[7][8] by Formula (3):

$$P_S = \pi P_T \beta(\pi) \lambda \tag{3}$$

where P_T is the transmitted laser power and $\beta(\pi)$ is the atmospheric backscatter coefficient in 1/(m·sr).

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It is notable that P_S is independent of both the focus range and the system aperture size. This approximation starts to break down as the system approaches its maximum operating range. With a value of 10^{-8}·1/(m·sr) for $\beta(\pi)$ in clear boundary-layer air, and a transmitted power of $P_T \sim 1$ W and $\lambda \sim 1{,}55$ µm, the received power P_S derived is of order 50 fW, emphasizing the need for extremely high sensitivity.

The signal-to-noise ratio (SNR) for a wind speed measurement by a continuous-wave coherent wind lidar is given by Formula (4):

$$\mathrm{SNR} = \frac{\eta P_S}{\frac{hc}{\lambda} \Delta\nu \left(1 + D(\nu) + R(\nu)\right)} \tag{4}$$

where η is an efficiency term incorporating optical losses and photodetector sensitivity (typically $\eta \sim 0{,}5$, approaching unity only for a “perfect” system), P_S is the input signal power and (hc/λ) is the light quantum energy, of order $1{,}3 \cdot 10^{-19}$ J at wavelength 1,55 µm. The signal bandwidth $\Delta\nu$ is determined by three contributions (instrumental width, transit time broadening and turbulence broadening), and the term inside the brackets denotes the various noise sources. $D(\nu)$ and $R(\nu)$ represent the power spectral density (at frequency ν) from dark noise and RIN, respectively, in units of the power spectral density of the local oscillator shot noise. Ideally $D(\nu)$ and $R(\nu)$ should both be << 1 over the range of Doppler frequencies of principal interest, so that shot noise is the dominant noise source.

The SNR as defined here is the power spectral density at the Doppler peak divided by that in the surrounding noise floor. The averaging of many spectra (described in the following clauses) ensures that good performance can be obtained even when the SNR is well below unity. For example, in a case where 4 000 spectra have been averaged at a SNR of 0,1, the resulting peak in the Doppler spectrum will easily exceed a 5 standard deviations (5σ) threshold level above the noise floor. From the above, it is possible to derive an approximate value of $\beta(\pi)_{min} \sim 10^{-9}$ m^{-1}sr^{-1} for the minimum detectable backscatter, assuming a transmitted intensity of 1 W and a 20 ms measurement time.

NOTE In the lidar community, SNR is commonly, and more properly, referred to as the carrier-to-noise ratio (CNR).

4.3 Spectral analysis

4.3.1 Signal processing for CW lidar

The retrieval of the radial velocity measurement from heterodyne signals requires a frequency analysis. This is conventionally done in the digital domain after analogue-to-digital conversion of the heterodyne signals. An overview of a possible processing scheme is given in Figure 3. An analogue to digital converter (ADC) with a sampling rate of 100 MHz permits spectral analysis up to a maximum frequency of 50 MHz, corresponding to a wind speed V_{LOS} of ~38,8 m/s for an upwardly pointing 30° scan (with λ = 1,55 µm). An analogue low-pass filter with a cut-off frequency of 50 MHz, inserted

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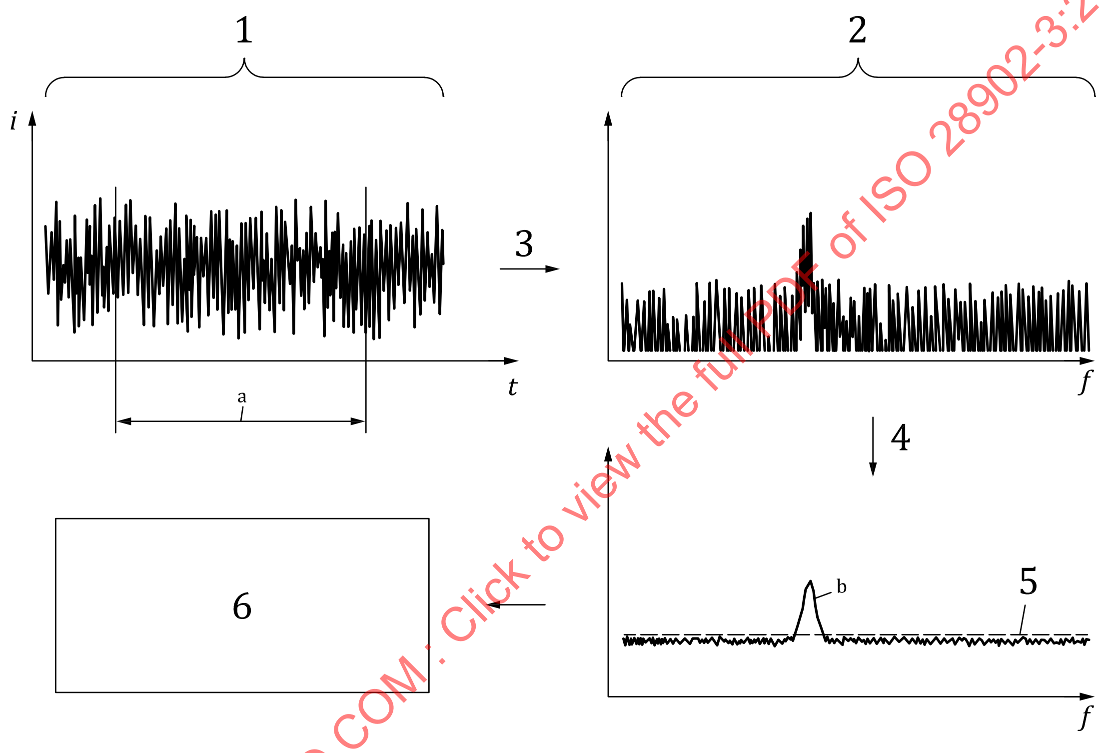
between the detector and ADC, eliminates aliasing. Spectra are calculated by digital Fourier transform (DFT) methods; a 512 point DFT gives rise to 256 points in the output spectrum with a bin width of ~200 kHz, corresponding to a line-of-sight velocity range of ~0,15 m/s. Each DFT represents ~5 µs of data; successive DFTs are then calculated, and the resulting "voltage" spectra are squared in order to generate a power spectrum. These power spectra are then averaged to find a mean spectrum for the averaging period. The random fluctuation in the shot noise floor of the spectrum reduces as the square root of the number of averages and hence the detection sensitivity increases by the same factor. For 4 000 averages, the measurement time amounts to ~20 ms (a data rate of ~50 Hz). This requires that the processing is capable of a 100 % duty cycle, which can be achieved, for example, with a fast Fourier transform (FFT) block within a field-programmable gate array (FPGA). It has been shown that a standard PC with no additional duties to perform can achieve a similar performance. It is possible to accommodate reasonable variations in any of the above parameters (sample rate, DFT length, number of averages) while maintaining the 100 % duty cycle.



Key

1 digitised detector output
2 spectral analysis of each block
3 DFT
4 averaging of many blocks
5 threshold applied
6 velocity estimation
a Split into blocks of ~5 µs.
b Wind signal.

Figure 3 — Stages in typical CW lidar signal processing: the DFT analysis is carried out by a computer integrated into the lidar system

From the preceding paragraph, it is apparent that each measurement of line-of-sight wind speed, obtained over a timescale of ~20 ms, generates a Doppler spectrum consisting of one or more peaks of variable width, superimposed on a noise floor that is predominantly white, but which can have spectral features originating from RIN and dark noise sources. The following subclause (4.3.2) outlines an example of a method to derive an appropriate estimate of the wind speed.

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4.3.2 An example of a wind speed estimation process

First, the noise floor is "whitened" so that each spectral bin contains the same mean noise level. This is achieved by dividing the power value in each frequency bin of the spectrum by a previously measured value for the same bin obtained with the shutter closed. A flat threshold is then applied at a pre-determined level above the mean noise (see Figure 3). A suitable and conservative choice for the threshold is 5σ above the mean noise level. In the absence of any wind signal (e.g. with the output of the lidar blocked), such a setting will give rise to negligible occurrences in which the noise alone exceeds threshold. It follows that any frequency bin for which the level exceeds the threshold is deemed to contain a valid contribution to the wind signal.

For each 20 ms measurement, the wind spectrum is reconstructed by subtracting the mean noise contribution from the contents of each bin that exceeds the threshold and applying a small correction for any distortion resulting from the noise whitening. In order to proceed to the next signal processing stage, a single velocity value is derived from the resulting spectrum. A number of options are available, including peak and median values; a common solution is to calculate the mean (or centroid) value $< V_{\mathrm{LOS}} >$.

4.4 Target variables

The aim of heterodyne Doppler wind lidar measurements is to characterize the wind field. In each range interval, the evaluation of the measured variable leads to the radial wind velocity.

There are potential additional target values like the variability of the radial velocity that are not discussed in this document.

The target variables can be used as input to different retrieval methods to derive meteorological products, such as the wind vector at a point or on a line (profile), in an arbitrary plane or in space as a whole. This also includes the measurement of shear winds, aircraft wake vortices, updraft and downdraft regions of the wind. An additional aim of the Doppler wind lidar measurements is to determine kinematic properties and parameters of inhomogeneous wind fields, such as divergence and rotation. Examples of applications are shown in ISO 28902-2:2017, Annex C.

4.5 Sources of noise and uncertainties

4.5.1 Local oscillator shot noise

The shot noise is denoted $n(t)$ in Formula (2). Its variance is proportional to the local oscillator (LO) power, as shown by Formula (5):

$$\left\langle in^2{}_{\mathrm{SN}} \right\rangle = 2eSP_{\mathrm{lo}}B \tag{5}$$

where

S is the detector sensitivity, $S = \dfrac{\eta e}{hf_{\mathrm{t}}}$;

B is the detection bandwidth.

It causes gross errors and limits the maximum range of the signal. If no other noise source prevails, the strength of the heterodyne signal relative to the level of noise is measured by the SNR, as shown by Formula (6) (derived from Formula (4) in Reference [9]):

$$\mathrm{SNR} = \frac{\eta \cdot K \cdot \gamma(t)}{\mathrm{h} \cdot f_{\mathrm{t}} \cdot B} P_{\mathrm{r}}(\mathrm{t}) \tag{6}$$

NOTE Some authors refer to carrier-to-noise ratio (CNR), defined here as SNR.

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4.5.2 Detector noise

Additional technical sources of noise can affect the SNR. As the shot noise, their spectral density is constant along the detection bandwidth (white noise). The variance in the detector current, denoted by $< in^2 >$, contains these contributions:

— dark noise is created by the fluctuations of the detector dark current i_D, as shown by Formula (7):

$$\langle in^2{}_{DN} \rangle = 2ei_D B \tag{7}$$

— thermal noise (Johnson/Nyquist noise) is the electronic noise generated by the thermal agitation of the electrons inside the load resistor R_L at temperature T, as shown by Formula (8):

$$\langle in^2{}_{TN} \rangle = \frac{4k_B T}{R_L} B \tag{8}$$

where k_B is the Boltzman constant.

4.5.3 Relative intensity noise

The relative intensity noise (RIN) (dB/Hz) is the LO power noise normalized to the average power level. RIN typically peaks at the relaxation oscillation frequency of the laser then falls off at higher frequencies until it converges to the shot noise level (pink noise). The RIN noise current increases with the square of LO power. See Formula (9):

$$in^2{}_{RIN} = (SPlo)^2 10^{0,1\text{RIN}} B \tag{9}$$

In a good lidar system, i_D, RIN, $1/R_L$ are low enough so that the LO shot noise is the prevailing source of noise. In that case only, Formula (5) is applicable.

4.5.4 Speckles

The heterodyne signal for a coherent Doppler wind lidar is the sum of many waves backscattered by individual aerosol particles. As the particles are randomly distributed along the beam in volumes much longer than the laser wavelength, the backscattered waves have a random phase when they reach the sensitive surface of the detector. They thus add randomly. As a result, the heterodyne signal has a random phase and amplitude. The phenomenon is called speckles[10]. It limits the precision of the frequency estimates.

4.5.5 Laser frequency

A precise measurement of the radial velocity requires an accurate knowledge of $f_r - f_{lo}$. Any uncertainty in this value results in a bias in $\hat{f}_r$. If the laser frequency f_t is not stable, it shall either be measured or locked to f_{lo}.

4.6 Range assignment

For an untruncated Gaussian beam the axial variation of sensitivity is centred at the beam waist, with half width at half maximum (HWHM) given by the distance over which the beam area doubles (Rayleigh range Z_R). A good approximation of the axial weighting function for a continuous-wave monostatic coherent lidar is given by a Lorentzian function[7][8], as shown by Formula (10):

$$F = \frac{\frac{\Gamma}{\pi}}{\Delta^2 + \Gamma^2} \tag{10}$$

where

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Δ is the distance from the focus position along the beam direction;

Γ is the half-width of the weighting function to the −3 dB point, i.e. 50 % of peak sensitivity.

Note that F has been normalized such that its integral from $-\infty$ to ∞ is unity. A good approximation of Γ is given by Formula (11):

$$\Gamma = \frac{\lambda R^2}{\pi A^2} \tag{11}$$

where

λ is the laser wavelength, here assumed to be the telecommunications wavelength $\lambda \sim 1{,}55 \cdot 10^{-6}$ m;

R is the distance of the beam focus from the lidar output lens;

A is the beam radius at the output lens.

The beam intensity profile is assumed to be an axially-symmetric 2D Gaussian and A is calculated for the point at which the intensity has dropped to $1/e^2$ of its value at the beam centre.

4.7 Known limitations

Doppler lidars rely on aerosol backscatter. Aerosols are mostly generated at or near the ground and are lifted up to higher altitudes by convection or turbulence. They are therefore in great quantities in the planetary boundary layer (typically 1 000 m thick during the day in temperate regions, 3 000 m in tropical regions), but in much lower concentrations at higher levels of the atmosphere. It follows that Doppler lidars hardly measure winds above the planetary boundary layer, except in the presence of higher altitude aerosol layers, such as desert dusts or volcanic plumes.

Laser beams are strongly attenuated in fogs or in clouds. The maximum range of Doppler lidars is limited in fogs (a few hundreds of meters at best) and these lidars cannot measure winds inside or beyond a cloud. They are able to penetrate into sub-visible clouds, such as cirrus clouds. Therefore, wind information at high altitude (8 km to 12 km) can be retrieved from ice-crystal particle backscattering.

Doppler lidars detect cloud water droplets or ice crystals when they are present in the atmosphere. As they are efficient scatterers, they tend to dominate the return from the atmosphere, in which case the Doppler lidar measures the radial velocity of hydrometeors rather than the radial wind. This can lead to incorrect measurement of the vertical wind component, since the hydrometeors tend to fall through the atmosphere, but the horizontal wind speed is usually measured correctly.

Rain downwashes the atmosphere, bringing aerosols down toward the ground. The signal strength for a Doppler lidar is commonly reduced significantly after rain.

The presence of rain water on the window of a Doppler lidar strongly attenuates the two-way transmission. Unless a lidar is equipped with a wiper or a blower, its window should be wiped manually.

As explained in 4.2, the efficiency of heterodyne detection is degraded by the presence of refractive index turbulence along the beam. Refractive index turbulence is mostly present near the surface during sunny days. The maximum range of Doppler lidar looking horizontally close to the surface may thus be substantially degraded in such conditions.

A general approach to quantify the effects of imperfect conditions, based on IEC 60825-1[11] for cup anemometers, is to perform a sensitivity analysis of the lidar against a high quality mast, assumed to provide "truth" data for comparison. The steps of this method are outlined below.

— The lidar is positioned adjacent to the mast for an extended period of at least three months.

— Differences between the lidar and mast for 10-min horizontal wind speed are investigated as a function of atmospheric parameters, such as shear, turbulence intensity, temperature and rain.

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— Their overall impact is summed to assess the overall impact of a range of conditions; care is needed to avoid double-counting of the effect of correlated parameters.

— By definition, the lidar cannot be better than the mast/cups against which it is compared; any mast imperfections (departure from “truth”) will therefore contribute to the lidar uncertainty.

5 System specifications and tests

5.1 System specifications

5.1.1 Laser wavelength

The laser wavelength depends mainly on the technology used to build the laser source. Most of the existing techniques use near-infrared wavelengths between 1,5 µm to 2,1 µm, even though other wavelengths up to 10,6 µm may be used. The choice of the wavelength takes into account the expected power parameters, but also the atmospheric transmission and the laser safety[11][12]. In fact the choice of the window between 1,5 µm and 2,1 µm is a compromise between technology and safety considerations (> 1,4 µm to ensure eye safety).

5.1.2 Transmitter/receiver characteristics

The transmitter/receiver is defined at least by the parameters given in Table 1.

Table 1 — Transmitter/receiver characteristics

Transmitter/receiver characteristics	Remarks
Aperture diameter	Physical size of the instrument’s aperture that limits transmitted and received beams.
Laser beam diameter and truncation factor	For a Gaussian beam, the laser beam diameter is defined as the diameter measured at $1/e^2$ in power at the lidar aperture. The laser beam diameter defines the illuminance level and so has some impact on eye safety considerations.
Focus point	Continuous-wave lidars typically bring the beam to a sharp focus.

Continuous-wave systems are commonly monostatic; however, bistatic setups are also possible.

5.1.3 Pointing system characteristics

The pointing system characteristics are given in Table 2.

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Table 2 — Pointing system characteristics

Pointing system characteristics	Remarks
Azimuth range	When using a pointing device, a lidar has the capability to point its laser beam at various azimuth angles with a maximum angular capability of 2π. For endless steering equipment, a permanent steering along the vertical axis is allowed. Other scanning scenarios should be followed for non-endless rotation gear.
Elevation range	The pointing device can be equipped with a rotation capability around the horizontal axis. Potential 360° rotation can be addressed. Typical elevation angles are set from 0° to 180° in order to observe the semi-hemispherical part of the atmosphere above the lidar. Anyhow, a nadir pointing can be used for the resting position of the equipment.
Angular velocity	The angular velocity is the speed at which a pointing device is rotating. A measurement can be performed during this rotation. In this case, the wind velocity information will be a mean of the various lines of sight in the probed area, between a starting angle and a stopping angle. Other scenarios of measurement can use a so-called step and stare strategy, with a fixed position during the measurement period.
Angular acceleration	The angular acceleration defines how fast the angular velocity can change. To be defined for complex trajectories with fast changes in direction. Angle overshoots can be observed when using high angular acceleration.
Pointing accuracy	The relative pointing accuracy is the standard deviation of the angular difference between the actual line-of-sight position (azimuth and elevation) and the position of the target (system of reference of the instrument). The absolute pointing accuracy needs prior calibration by angular sensors (pitch, roll, heading) (system of geographical reference).
Angular resolution	The angular resolution is the minimum angle step that the line of sight can move. It can be limited by a motor reduction factor, position, encoder or mechanical friction.

5.2 Figures of merit

System performance can be characterized by a figure of merit (FOM). Several options are available for CW wind lidar to address different aspects of performance. Two possible examples of FOM are given below.

For signal sensitivity, an appropriate FOM is $P_T\eta$, where P_T is the transmitted output power and η is a measure of the detection efficiency of the back-scattered photons, including factors such as the quantum efficiency of the detector and the level of shot-noise domination by the local oscillator.

For probe length and maximum range, the appropriate figure of merit is AS/λ, where λ is the wavelength, A is the aperture size (assumed to be filled by the transmitted beam) and S is the Strehl ratio indicating how close the optics performs compared to the diffraction limit.

5.3 Precision and availability of measurements

5.3.1 Radial velocity measurement accuracy

Radial velocity measurement accuracy is defined (in accordance with ISO 5725-1[13]) in terms of:

— trueness (or bias) as the statistical mean difference between a large number of measurements and the true value;

— precision (or uncertainty) as the statistical standard deviation of a series of independent measurements. It does not relate to the true value.

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Lidar data of good quality are obtained when the precision of the radial velocity measurements is better than a target value (e.g. within 1 m/s) with a predefined probability of occurrence (e.g. 95 %). This assessment can be made over different timescales, e.g. 10-min averages are commonly used in the wind industry.

An error value (1σ) of 0,5 m/s can be regarded as adequate for typical meteorological applications and for wind measurements to determine the statistics of dispersion categories for air pollution modelling[14]. For wind energy applications, the requirements may be higher (0,2 m/s).

5.3.2 Data availability

Data availability is defined as the ratio of data with precision to the total number of data during a measurement period. It is commonly assessed following a filtering process [quality control (QC)] defined by the lidar manufacturer. The filtering shall be automatically applied to avoid contamination of the data set with any sub-standard data. For wind energy applications, the availability is commonly assessed with regard to 10-min average values. A good 10-min average can still be obtained even when the availability is not 100 % within the 10-min period. The availability of measurement data, i.e. the determinability of the wind profile, is a function mainly of the aerosol concentration and the clouds. Other filtering criteria can be applied, depending on the required data accuracy; for example, data that exhibit significantly non-uniform flow around the scan disk shall be rejected.

5.3.3 Maximum operational range

For CW lidar, this concept is not appropriate because the beam can be focused at any range in principle, but it can only be brought to a clear waist at ranges up to a maximum value, as governed by the aperture size and the laws of diffraction. As mentioned previously, the SNR is almost independent of range, as shown by Formula (3) and in Reference [8].

5.4 Testing procedures

5.4.1 General

In order to assess the accuracy of the target variables, the manufacturer shall perform a set of validation tests for the focus range, beam direction and alignment, and velocity. Some tests can be performed under laboratory conditions. Certain other validation tests can only be performed by a comparison with other reference instruments, such as cup or sonic anemometers.

5.4.2 Hard target return

A moving target is used to provide a Doppler-shifted back-scattered signal; a rotating disk or moving belt are both common choices. The measured velocity from the lidar can be directly compared with the known velocity of the target. Such comparisons can conveniently be carried out at very short range, < 1 m, since the beam does not require focusing on the target surface itself to generate a clear signal.

5.4.3 Assessment of accuracy by intercomparison with other instrumentation

5.4.3.1 Sonic anemometer test

This test consists of directing the lidar beam very close to a sonic anemometer on a mast or platform without vibration and comparing lidar radial velocities with the projection of the three-dimensional wind vectors acquired by the sonic anemometer on the beam direction.

Lidar and sonic anemometer data shall be averaged over a suitable timescale, e.g. 1 min.

The direction of the lidar beam shall be determined with a good accuracy (of the order 1° or better) and as close as possible to the horizontal plane. The lidar beam shall be at the height of the sonic anemometer (height difference of the order of 1 m or less).

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