
Kakovost zraka - Okoljska meteorologija - 4. del: Daljinsko zaznavanje meteoroloških parametrov s tal z lidarjem na osnovi povratnega sipanja na delcih

Air quality - Environmental meteorology - Part 4: Ground-based remote sensing of meteorological parameters by particle backscatter lidar

Qualité de l'air - Météorologie de l'environnement - Partie 4: Télédétection basée sur le sol des paramètres météorologiques par lidar à rétrodiffusion des particules

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International Standard

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Air quality — Environmental meteorology —

Part 4:

Ground-based remote sensing of meteorological parameters by particle backscatter lidar

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CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Contents

Page

Foreword	v
Introduction	vi
1 Scope	1
2 Normative references	2
3 Terms and definitions	2
4 Symbols and abbreviated terms	4
4.1 Symbols	4
4.2 Abbreviated terms	6
5 Fundamental principles of the backscatter lidar	7
5.1 General	7
5.2 Choice of suitable wavelengths	9
5.2.1 General	9
5.2.2 Overlap function	10
5.3 Attenuated backscatter coefficient	11
5.4 Backscatter coefficient	11
5.4.1 General	11
5.4.2 Determining the boundary condition for the derivation of the particle backscatter coefficient	11
5.5 Particle extinction coefficient	12
5.6 Optical depth	13
5.7 Shape classification / linear depolarisation ratio	13
5.8 Obtaining information on particle size distribution	14
6 Measured and target variables of the backscatter lidar	14
6.1 Introduction	14
6.2 Measured variables	15
6.3 Target variables	15
6.3.1 Backscatter profiles	15
6.3.2 Identification of layers and their boundaries	15
6.3.3 Cloud base, cloud penetration depth and vertical extension	16
6.3.4 Shape classification by analysing the linear depolarisation ratio	17
6.4 Lidar Ratio	17
6.5 Auxiliary variable	19
6.6 Definition of performance characteristics	19
6.6.1 General	19
6.6.2 Temporal resolution	19
6.6.3 Range resolution	19
6.6.4 Spatial averaging	20
6.6.5 Signal-to-noise ratio	20
6.6.6 Operating range	22
6.6.7 Completeness, POD, FAR	23
6.7 Conventional ranges	23
7 Systems and system components	24
7.1 General	24
7.2 Radiation source(s)	24
7.3 Transmitting and receiving optics	25
7.4 Filters	25
7.5 Detectors	26
7.5.1 General	26
7.5.2 Photon counting	26
7.5.3 Analogue data acquisition	27
7.6 Data acquisition, control system	27
7.7 Mechanical structure, infrastructure	28

ISO/FDIS 28902-4:2026(en)

7.8	Additional system components	28
7.9	Typical lidar design	28
7.9.1	General	28
7.9.2	Bistatic and monostatic lidars	29
7.9.3	Ceilometers	33
7.9.4	Single wavelength lidar systems	33
7.9.5	Multi-wavelength systems	33
7.9.6	Polarisation lidar	34
8	Measurement planning and site requirements	35
8.1	General considerations	35
8.2	Safety	36
8.3	Adjusting the measurement system to atmospheric conditions	36
8.4	Limiting conditions for general operation	36
8.5	Maintenance and operational test	37
8.5.1	General	37
8.5.2	Maintenance	37
9	Factors and uncertainty considerations	37
9.1	General	37
9.2	“Frozen” atmosphere	40
9.3	Uncertainty considerations related to β_{att} and cloud base	41
9.4	Uncertainty considerations relating to the particle backscatter coefficient	42
9.5	Depolarisation lidar uncertainty considerations	43
9.6	Effect of atmospheric pressure and temperature	44
10	Quality assurance and system monitoring	44
10.1	Adjustments	44
10.2	Functional tests	45
10.3	Maintenance	45
10.4	Calibration	45
10.5	Quality assurance of the attenuated backscatter lidar	46
10.6	Performance tests in the laboratory or at test sites	47
10.6.1	General	47
10.6.2	Depolarisation	50
10.7	Individual or specific parameter tests	50
	Annex A (informative) Examples and theory	52
	Annex B (informative) Mathematical considerations	62
	Bibliography	65

ISO/FDIS 28902-4:2026(en)

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology*, and by the World Meteorological Organization (WMO) as a common ISO/WMO Standard under the Agreement on Working Arrangements signed between the WMO and ISO in 2008.

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

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ISO/FDIS 28902-4:2026(en)

Introduction

Lidar (light detection and ranging) is an active remote sensing method. The special advantage of lidar methods consists in the fact that they permit spatially resolved observations, the measurements are non-contact and can be conducted in arbitrary directions.

In meteorological and environmental applications light in the ultraviolet to infrared spectral range is used to probe the atmosphere and measure different parameters depending on the task the specific lidar for which the system has been designed. The measured quantities result from the scattering and absorption process of the emitted light on aerosols and molecules. Atmospheric lidar systems are designed to provide range-resolved profiles of target parameters like humidity and wind speed and provide target parameters like aerosol optical properties and cloud base heights derived from the actually measured backscatter signal.

This makes lidar systems suitable for several measurement tasks that cannot be carried out adequately with point-like measuring in-situ methods. The applications include e.g. measurements where spatially resolved information is important; measurements in which large areas and angular ranges are to be sampled rapidly and representatively; and measurements at sites and in directions that are difficult to access using conventional techniques. Examples that illustrate these applications are discussed in [Annex A](#).

This technology has made considerable strides since the first lidar applications in the 1960s. There now exist commercial systems that can be used in the meteorological field for a variety of measurement tasks.

This document describes atmospheric backscatter lidar, which is based on elastic scattering. It explains the lidar's mode of operation and discusses how reliable results can be obtained. In addition, the method's parameters are described, and typical applications are discussed. Theoretical and mathematical considerations for some parameters listed in this document are defined in [Annex B](#). Technical, safety and operational issues for specific applications that are not covered in detail; the reader is referred to relevant reference standards (see References [1]-[7]).

NOTE To improve readability within the text, "backscatter lidar" is used instead of "atmospheric backscatter lidar".

The following remote sensing standardized methods are presented in the following documents:

- ISO 28902-1: *Ground-based remote sensing of visual range by lidar*^[8]
- ISO 28902-2: *Ground-based remote sensing of wind by heterodyne pulsed Doppler lidar*^[9]
- ISO 28902-3: *Ground-based remote sensing of wind by continuous-wave Doppler lidar*^[10]
- ISO 19926-1: *Meteorology - Weather radar - System performance and operation*^[11]
- VDI 4210 Part 1: *Remote sensing - atmospheric measurements with LIDAR - measuring gaseous air pollution with DAS LIDAR*^[12]

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Part 4:

Ground-based remote sensing of meteorological parameters by particle backscatter lidar

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document specifies the determination of height-resolved profiles of atmospheric backscattering by means of active optical sounding. The measurements allow the following properties of the atmosphere up to several kilometres above ground to be derived:

- Cloud bases.
- Upper boundaries of optically thin clouds.
- Upper and lower boundaries and internal structures of particle layers:
 - The height of structures, e.g. inversions, boundary layer height, mixing layer height (under suitable conditions).
 - Attenuated backscatter of the particles.
 - Particle backscatter and extinction coefficients (requires further assumptions).

The document also addresses the depolarisation lidar and the use of multi-wavelength systems. This allows further parameters to be determined:

- Particle size classification (Ångström exponent, colour ratio).
- Shape classification (linear depolarisation degree).

The following fields of application are particularly important:

- Air quality monitoring (vertical structure of the boundary layer).
- Aviation safety (cloud base and visual range) (see ISO 28902-1[8]).
- Particle content and transport (e.g. volcanic dust).
- Weather forecasting and climate modelling (e.g. atmospheric boundary layer, cloud base, cloud microphysics).
- Satellite remote sensing (validation).

Examples that illustrate these applications are discussed in [Annex A](#).

The benefits of scanning systems for parameters mentioned above are also discussed in [Clause A.7](#).

In addition, particle backscatter lidars that measure at least two carefully selected wavelengths can be used to determine atmospheric gas concentrations. This is known as the differential absorption lidar “DIAL” technique. This technique is not part of this document and has been described in VDI 4210 Part 1[12].

ISO/FDIS 28902-4:2026(en)

This document does not specify extended lidar techniques that monitor the following parameters quantitatively: inelastic scattering effects such as, Raman scattering, Doppler broadening, Doppler shift, multiple scattering, modulation techniques, and spectral separation of molecular and particle backscattering (HSRL = high spectral resolution lidar). Some of these extended techniques have been or will be described in other parts of the ISO 28902 series. This document does not address special features of airborne or satellite-borne systems.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

lidar

light detection and ranging

active distance-resolving remote sensing method, in which the travel time of light from the source to scattering objects and back is used for distance measurement and the backscattering intensity is analysed

Note 1 to entry: In this document, only atmospheric applications are presented.

3.2

lidar system

measurement system based on lidar technology that uses at least one pulsed light source and one detection instrument with suitable temporal resolution

Note 1 to entry: In this document, ceilometers are also referred to as lidar systems.

[SOURCE: Reference [13]]

3.3

laser divergence

angle defined by the beam diameter at a particular distance

3.4

field of view

FOV

ϕ

field seen by the receiver (per channel) or region of atmospheric volume (object field) from which the channel detects radiation

Note 1 to entry: Usually quoted as a solid angle. It is determined by the diameter of the field aperture and the focal length of the receiving optics.

3.5

particle

aerosol particle

airborne (or only very slowly descending) particles that are either solid, liquid, or both, and whose number, size, shape and material can vary greatly in space and time

Note 1 to entry: Particles can be of either natural or anthropogenic origin.

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Note 2 to entry: Primary particles enter the air; secondary particles form in the air through condensation or coagulation of inorganic or organic molecules. Solid particles include swirled-up dust, ash particles from volcanoes and fires, sea salt, ice and snow crystals, and organic particles such as pollen, spores, viruses, or bacteria. Liquid particles can be small water droplets forming on condensation nuclei, or sulphuric acid droplets forming in volcanic gases.

Note 3 to entry: The term “particulate” is generally used in the context of several separate particles, a particle ensemble. Particulate matter (PM) is used to classify particles in air quality. Since it is more common to use particles in atmospheric *lidar systems* (3.2), such as particle backscatter lidar, the term “particulate” is not used in this document.

3.6

elastic scattering of photons

form of scattering in which the wavelength of the scattered photon is conserved in the centre-of-mass frame, but its direction of propagation is modified.

3.7

inelastic scattering of photons

fundamental scattering process in which the wavelength of scattered photon is not conserved.

Note 1 to entry: In an inelastic scattering process, some of the energy of the incident particle is lost or increased.

3.8

particle scattering

elastic scattering of photons (3.6) of electromagnetic radiation by atmospheric particles (e.g. desert dust, ice crystals, cloud droplets)

Note 1 to entry: For spherical particles, the Mie theory applies^[14].

3.9

molecular scattering

elastic scattering of photons (3.6) of electromagnetic radiation by air molecules

Note 1 to entry: Usually Rayleigh scattering of ‘light’, wavelengths between approximately 300 nm and 3 µm.

3.10

backscatter coefficient

wavelength-dependent fraction of the light that is scattered backwards elastically by atmospheric particles and air molecules per unit of solid angle and per unit of distance

3.11

extinction coefficient

wavelength-dependent fraction of the light intensity that is lost through scattering and absorption processes along the light path, per unit of distance

3.12

lidar ratio

ratio of the *extinction coefficient* (3.11) and the *backscatter coefficient* (3.10)

Note 1 to entry: Quoted separately for particles and air molecules.

3.13

backscatter ratio

ratio of the *backscatter coefficient* (3.10) and the molecular backscatter coefficient

3.14

Ångström exponent

parameter describing the wavelength-dependence of the extinction coefficient

Note 1 to entry: Usually quoted for particles.

ISO/FDIS 28902-4:2026(en)

3.15

linear depolarisation ratio

ratio of parallel and cross polarised backscattered light

Note 1 to entry: The emission from the lasers used for backscatter lidar is normally linearly-polarised.

Note 2 to entry: The backscattered light from non-spherical particles will have a modified polarisation that is strongly dependent on particle size, shape and laser wavelength.

Note 3 to entry: Measurements are made of the backscatter signal in two planes, one parallel to the plane of polarisation of the emitted laser pulse and the other perpendicular to that plane.

3.16

penetration depth

measure of how deep light can penetrate a material

Note 1 to entry: It is defined as the depth at which the intensity of the radiation inside the cloud or fog falls to 1/e (about 37 %) of its original value at (or more properly, just behind) the surface.

Note 2 to entry: The penetration depth will generally be a function of wavelength.

Note 3 to entry: The Beer-Lambert law describes the exponential decrease of the intensity of an electromagnetic wave within the atmosphere when absorption or scattering is present.

4 Symbols and abbreviated terms

4.1 Symbols

A	Effective area of the receiving telescope	m^2
c	Speed of light	m/s
$C_s(\lambda)$	System constant (lidar constant)	J m^3
$k_{\text{pol}}(\lambda)$	Calibration constant	–
$LR(x, \lambda)$	Lidar ratio	sr
$LR_{\text{eff}}(x, \lambda)$	Lidar ratio that is affected by multiple scattering	sr
$LR_{\text{m}}(x, \lambda)$	Lidar ratio for air molecules	sr
$LR_{\text{p}}(x, \lambda)$	Lidar ratio for particles	sr
N_{p}	Number of laser pulses	–
N_{x}	Number of samples per laser pulse (function of time)	–
$O(x, \lambda)$	Equipment-specific overlap function	–
$P(x, \lambda)$	Total backscatter signal	J
$\Delta P_{\text{sig}}(x, \lambda)$	Noise of the useful signal	J
$P_{\text{h}}(x, \lambda)$	Background signal	J
$P_{\text{sig}}(x, \lambda)$	Useful signal	J
$P_0(\lambda)$	Energy (mean power times pulse duration) of the emitted laser pulse	J

ISO/FDIS 28902-4:2026(en)

$P_{ }(x, \lambda)$	Fraction of the backscatter signal polarised parallel to the polarisation of the emitted laser pulse	J
$P_{\perp}(x, \lambda)$	Fraction of the backscatter signal polarised perpendicular to the polarisation of the emitted laser pulse	J
$p(x)$	Air pressure	hPa
$R(x, \lambda)$	Backscatter ratio	–
R_d	Gas constant for dry air	J/(kg·K)
$S(x, \lambda)$	Lidar signature	J m ²
$T(x)$	Temperature	K
$T_v(x)$	Virtual temperature	K
$q(x)$	Specific humidity	g/kg
Δt	Temporal resolution	s
t_1	Travel time after emitting the light pulse	s
Δt_s	Temporal width of the receiving window	s
V_{MOR}	Meteorological optical range	m
x	Distance to the backscatter location	m
Δx	Range resolution	m
x_{CRi}	Conventional range, index $i=\{a, b, c\}$	m
x_{Ref}	Reference height determined by the boundary condition for the Klett inversion of the backscatter signal	m
x_{max}	Maximum detection range	m
$\alpha(x, \lambda)$	Extinction coefficient (total extinction coefficient)	1/m
$\alpha_m(x, \lambda)$	Molecular extinction coefficient	1/m
$\alpha_p(x, \lambda)$	Particle extinction coefficient	1/m
$\beta(x, \lambda)$	Backscatter coefficient (total backscatter coefficient)	1/(m·sr)
$\beta_m(x, \lambda)$	Molecular backscatter coefficient	1/(m·sr)
$\beta_p(x, \lambda)$	Particle backscatter coefficient	1/(m·sr)
$\beta_{att}(x, \lambda)$	Attenuated backscatter coefficient	1/(m·sr)
$\delta_L(x, \lambda)$	Laser divergence	rad
$\delta_m(x, \lambda)$	Molecular depolarisation ratio	–
$\delta_p(x, \lambda)$	Linear depolarisation ratio of the particles	–
$\delta_v(x, \lambda)$	Linear depolarisation ratio of the backscatter volume	–
$\eta(\lambda)$	Total efficiency of the lidar system	–

ISO/FDIS 28902-4:2026(en)

η_{ms}	Multiple scattering factor	–
$\kappa(x, \lambda_1, \lambda_2)$	Ångström-Exponent	–
$\kappa_{\beta}(x, \lambda_1, \lambda_2)$	Parameter analogous to the Ångström exponent, which takes into account the wave-length-dependence of the backscatter coefficient	–
λ	Wavelength	m
ξ	Distance variable	m
ρ	Air density	kg/m ³
$\tau(\lambda)$	Optical depth of the atmosphere	–
$\tau_{\text{m}}(\lambda)$	Molecular optical depth of the atmosphere	–
$\tau_{\text{p}}(\lambda)$	Particle optical depth of the atmosphere	–
$\chi(x, \lambda_1, \lambda_2)$	Colour ratio	–

4.2 Abbreviated terms

ADC	Analogue-to-digital converter
AOD	Aerosol optical depth
APD	Avalanche Photo Diode
ATC	Air Traffic Controller
CBH	Cloud Base Height
CPD	Cloud Penetration depth
FAR	False Alarm Rate
FOV	Field of view
HSRL	High Spectral Resolution Lidar
IR	Infrared spectral range
MOR	Meteorological optical range
NIR	Near infrared spectral range
POD	Probability of Detection
PMT	Photomultiplier tube
SNR	Signal-to-noise ratio
UV	Ultraviolet spectral range
VIS	Visible spectral range
VOR	Vertical optical range

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5 Fundamental principles of the backscatter lidar

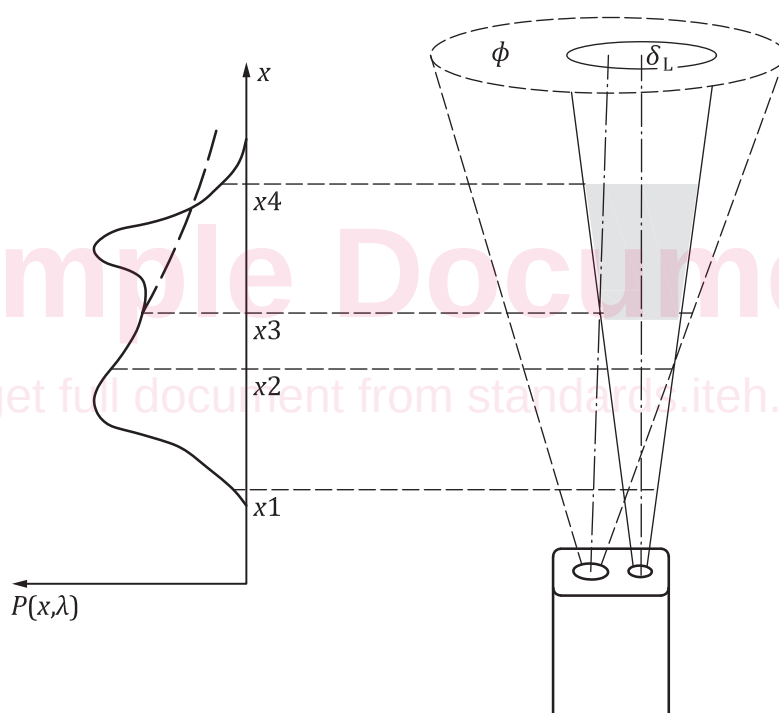
5.1 General

All lidar methods discussed here have in common that a short laser light pulse is emitted into the atmosphere, and the light scattered backwards is detected, temporally resolved, and analysed. Using the travel time t_1 from the light pulse's emission and the speed of light c , allows the distance to the backscattering location x to be calculated:

$$x = t_1 \cdot \frac{c}{2} \quad (1)$$

The factor $\frac{1}{2}$ arises from the forward and back path travelled by emitted light before being detected by the lidar system.

In the arrangement shown schematically in [Figure 1](#), after emitting a laser pulse of wavelength λ , the detector records successive signals $P(x, \lambda)$ given by [Formula \(2\)](#) (lidar equation) for elastic (simple) backscattering (see Reference [\[13\]](#)).



Key

x_1	start of the overlap between the laser pulse region and the receiver's field of view (FOV)
x_2	distance at which the geometric overlap is complete (see also 5.2.2)
x_3	bottom height of an aerosol layer
x_4	top height of an aerosol layer
δ_L	laser divergence (corresponds to the angle of aperture of the emitted radiation)
ϕ	FOV

Figure 1 — Schematic diagram of the lidar principle for a bistatic system

It is assumed that a photon recorded by the lidar's receiving system has experienced exactly one scattering event (in the backward direction). Multiple scattering occurs when the medium probed by the laser beam is dense. Then the probability becomes significant that a photon scattered by a first scatterer is further scattered by a second and additional scatterers. Multiple scattering typically happens in clouds. The detection of multiple scattering is enhanced by a large field-of-view. The result is an underestimate of the