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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



DRAFT International Standard

ISO/DIS 28902-4

Air quality — Environmental meteorology —

Part 4: Ground-based remote sensing of meteorological parameters — Particle backscatter lidar

ICS: 07.060; 13.040.20

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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.

The committee responsible for this document is ISO/TC 146/SC 5/WG 6 Lidar.

ISO 28902 consists of the following parts.

- *Part 1: Ground-based remote sensing of visual range by lidar*
- *Part 2: Ground-based remote sensing of wind by heterodyne pulsed Doppler lidar*
- *Part 3: Ground-based remote sensing of wind by continuous-wave Doppler lidar*

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.

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, in general, designed to provide range resolved profiles of the target parameters which can include humidity, wind speed, aerosol or cloud layers heights for example.

This makes lidar systems suitable for several measurement tasks that cannot be carried out adequately with point-like measuring in-situ methods. Lidar systems can complement conventional point-like measuring 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, e.g., in the vertical direction. 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 standard 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. 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]) and to laws, regulations, and administrative national provisions.

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
- ISO 28902-2: Ground-based remote sensing of wind by heterodyne pulsed Doppler lidar
- ISO 28902-3: Ground-based remote sensing of wind by continuous-wave Doppler lidar
- ISO 19926-1: Meteorology - Weather radar - System performance and operation
- VDI 4210 Part 1: Remote sensing - atmospheric measurements with LIDAR - measuring gaseous air pollution with DAS LIDAR

Air quality — Environmental meteorology —

Part 4:

Ground-based remote sensing of meteorological parameters — Particle backscatter lidar

1 Scope

This document describes 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
 - Backscatter coefficients of particles, extinction coefficients (requires further assumptions).

The document goes on to discuss 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 Part 1)
- Particle content and transport (e.g., volcanic dust)
- Weather forecasting and climate modelling (e.g., atmospheric boundary layer, cloud base)
- Satellite remote sensing (validation)

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

The benefits of scanning systems for parameters mentioned above are also discussed in Annex [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 technique “DIAL”. This technique is not part of this document and has been described in VDI 4210-1.

This document does not describe extended lidar techniques which 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

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.

ISO 28902-1:2012, *Air quality — Environmental meteorology — Part 1: Ground-based remote sensing of visual range by lidar*

ISO 28902-2:2017, *Air quality — Environmental meteorology — Part 2: Ground-based remote sensing of wind by heterodyne pulsed Doppler lidar*

ISO 28902-3:2018, *Air quality — Environmental meteorology — Part 3: Ground-based remote sensing of wind by continuous-wave Doppler lidar*

3 Terms and definitions

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

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 good temporal resolution^[8]

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

3.3

laser divergence

angle defined by the beam diameter at a particular distance

3.4

field of view (FOV)

Φ

the field seen by the receiver (per channel) or the 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 telescope.

3.5

particle (aerosol particle)

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

Note 1 to entry: Since a mixture of air and particles is referred to as an aerosol, the term 'aerosol particle' is used synonymously.

Note 2 to entry: Particles can be of either natural or anthropogenic origin.

Note 3 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 4 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, such as particle backscatter lidar, the term particulate is not used in this document.

3.6 elastic scattering

is a form of particle scattering. In this process, the kinetic energy of a particle is conserved in the center-of-mass frame, but its direction of propagation is modified (by interaction with other particles and/or potentials).

3.7 inelastic scattering

is a fundamental scattering process in which the kinetic energy of an incident particle or photon is not conserved (in contrast to elastic scattering). In an inelastic scattering process, some of the energy of the incident particle is lost or increased.

3.8 particle scattering

elastic scattering 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^[9].

3.9 molecular scattering

elastic scattering of electromagnetic radiation by air molecules

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

3.10 atmospheric scattering

both, molecular scattering and particle scattering together

3.11 backscatter coefficient

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

3.12 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

3.13 lidar ratio

ratio of the extinction coefficient and the backscatter coefficient

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

3.14 backscatter ratio

ratio of the backscatter coefficient and the molecular backscatter coefficient

3.15 Ångström exponent

parameter describing the wavelength-dependence of the optical depth or the extinction

Note 1 to entry: Usually quoted for particles.

3.16**linear depolarisation ratio**

The emission from the lasers used for backscatter lidar is normally plane-polarized. The backscatter from non-spherical particles will have a modified polarization that is strongly dependent on particle size, shape and laser wavelength. Measurements are made of the backscatter signal in two planes, one parallel to the plane of polarization of the emitted laser pulse and the other perpendicular to that plane. The effect is described as the linear depolarisation ratio.

3.17**penetration depth**

is a measure of how deep light can penetrate a material. 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.

The penetration depth will generally be a function of wavelength.

The Beer-Lambert law, describes 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**

Symbol	Name	Unit
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
$LR_m(x, \lambda)$	Lidar ratio for air molecules	sr
$LR_p(x, \lambda)$	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
$P_h(x, \lambda)$	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
$P_{ }(x, \lambda)$	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_L	Gas constant for dry air	$\text{J}/(\text{kg}\cdot\text{K})$
$S(x, \lambda)$	Lidar signature	J m^2
$T(x)$	Temperature	K
Δt	Temporal resolution	s
t_l	Travel time after emitting the light pulse	s

Symbol	Name	Unit
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	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	1/(m·sr)
$\beta_m(x, \lambda)$	Molecular backscatter coefficient	1/(m·sr)
$\beta_p(x, \lambda)$	Particle backscatter coefficient	1/(m·sr)
$\beta_{\text{att}}(x, \lambda)$	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	–
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_L	Air density	kg/m ³
$\tau(\lambda)$	Optical depth of the atmosphere	–
$\tau_m(\lambda)$	Molecular optical depth of the atmosphere	–
$\tau_p(\lambda)$	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
CBH	Cloud Base Height
FAR	False Alarm Rate
FOV	Field of view
IR	Infrared spectral 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

5 Fundamental principles of the backscatter lidar

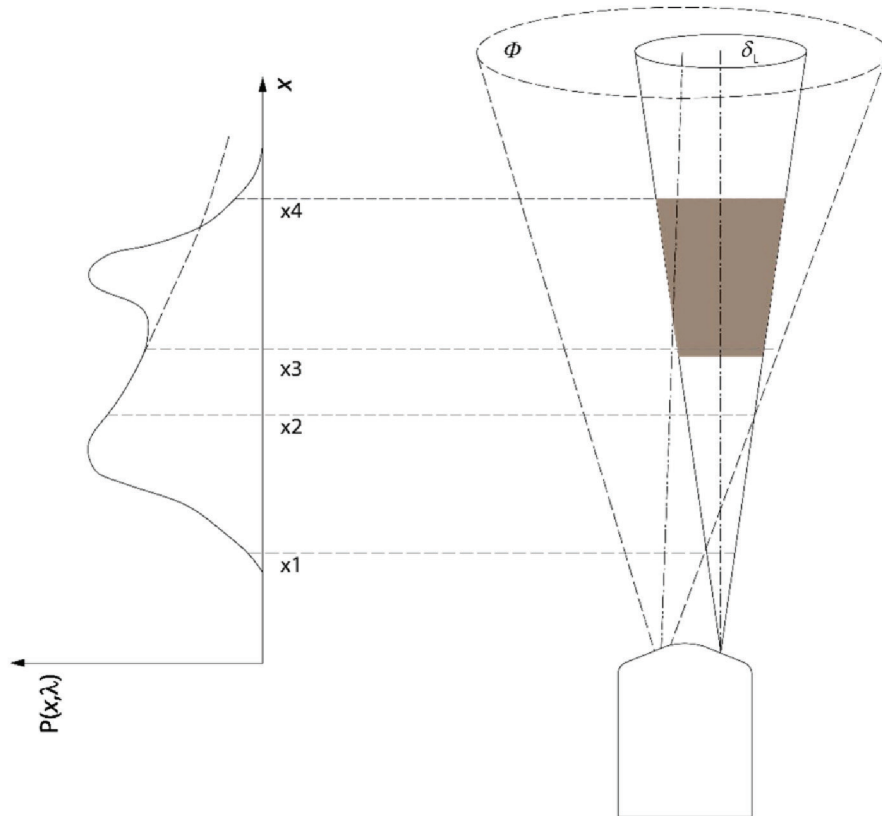
5.1 Introduction

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_l from the light pulse's emission and the speed of light c , allows the distance to the backscattering location x to be calculated:

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

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 (Reference [\[8\]](#)).



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 5.2.1 (overlap function))
- 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 field of view (FOV)

Figure 1 — Schematic diagram of the lidar principle for a bistatic system (Reference [79])

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 medium's optical depth if the analysis assumes single scattering. The determination of cloud bases, however, is not significantly impaired by this assumption.

For the usual small fields of view in concert with the high spatial resolution and the small optical depths of the atmosphere, makes neglecting multiple scattering reasonable. The lidar equation is then simplified to (Reference [10]):

$$P(x, \lambda) = \Delta t_s \cdot \frac{c}{2} \cdot P_0(\lambda) \cdot \frac{A \cdot \eta(\lambda) \cdot O(x, \lambda)}{x^2} \cdot \beta(x, \lambda) \cdot \left\{ -2 \int_0^x \alpha(\xi, \lambda) d\xi \right\} + P_h \quad (2)$$

where

x	Distance (m)
λ	Wavelength (m)
Δt_s	Temporal width of the receiving window (s)
c	Speed of light (ms^{-1})
$P_0(\lambda)$	Energy (mean power multiplied with pulse duration) of the emitted laser pulse (often polarised) (J) ¹⁾
A	Effective area of the receiving telescope (m^2)
$\eta(\lambda)$	Overall efficiency of the lidar system (can be polarisation-dependent, see 9)
$O(x, \lambda)$	Distance-dependent overlap function between transmitted beam and field of view
$\beta(x, \lambda)$	Backscatter coefficient (scatter coefficient for backscattering, i.e., at 180° based on the solid angle) ($\text{m}^{-1}\text{sr}^{-1}$)
$\alpha(\xi, \lambda)$	Extinction coefficient (m^{-1})

The signal consists only of a background component P_h and the useful signal P_{sig} .

Thus,

$$P = P_{sig} + P_h \quad (3)$$

Both the background components and signal components have their own noise components. This is further discussed in 6.6.4 and Clause 9.

The exponential term goes into Formula (2) to the second power since the extinction of the transmitted beam takes place both in the forward journey (from the laser to the scattering volume) and on the return journey (from the scattering volume to the receiving telescope).

The optical depth $\tau(x, \lambda)$ between the lidar and the backscattering volume at a distance x is obtained from the extinction coefficient of the atmosphere $\alpha(x, \lambda)$ by integrating over the distance variable ξ :

$$\tau(x, \lambda) = \int_0^x \alpha(\xi, \lambda) d\xi \quad (4)$$

Formula (2) and (4) yield the distance-corrected lidar backscatter signal which is referred to in the following as the lidar signature $S(x, \lambda)$:

NOTE The lidar signature $S(x, \lambda)$ was used differently in the ISO 28902-1:2012, as the background signal was ignored.

$$S(x, \lambda) = P_{sig}(x, \lambda) x^2 = C_s(\lambda) \cdot O(x, \lambda) \cdot \beta(x, \lambda) \cdot \exp(-2\tau(x, \lambda)) \quad (5)$$

1) Energy is power multiplied by time. In the emitted signal, the pulse duration is relevant, and in the received signal, the temporal width of the receiving window Formula (2) is expressed in units of energy, nevertheless the usual letter P is retained.

$$C_s(\lambda) = P_0(\lambda) \cdot A \cdot \eta(\lambda) \cdot \Delta x \quad (6)$$

with $C_s(\lambda)$ a wavelength-dependent system parameter. The distance-dependent and equipment-specific overlap function $O(x, \lambda)$, defined between 0 and 1 (see 5.2.1), is close to 0 for small distances, increases in a transition zone, and for large distances should reach a constant value of 1.

[Formula \(2\)](#) does include the complex and significant aspect of background radiation. This is particularly important under daytime conditions. The background light and noise contribution are further discussed in [Clause 9](#).

It is important to distinguish between the performance of ceilometers based on laser-diode transmitters and the more powerful lidar systems based on the use of Diode-Pumped Solid-State lasers or flash-lamp pumped lasers. Ceilometers are specifically designed to measure the cloud-base and aerosol layers. The more powerful lidars can measure detailed atmospheric structure, such as aerosol content, up to the cloud base.

It is also assumed that the laser pulse duration is shorter than the equipment-based temporal width of the receiving window Δt_s , with which the signal $P(x, \lambda)$ can be recorded. If this condition is not met, to use [Formula \(2\)](#), it shall be formulated differently, and this makes a deconvolution procedure necessary (References [11], [12], [13]).

5.2 Choice of suitable wavelengths

Backscatter lidar systems commonly use wavelengths in the range from 350 nm to 10 µm. The following factors determine the choice of wavelength:

- Target variables and required accuracies
- Atmospheric transmission
- Fields of application and ambient monitoring conditions
- Lasers and eye safety
- System costs, availability, maintenance intensity.

All systems use elastic backscattering by air molecules and particles (aerosols or hydrometeors).

In general, the amount of backscattered light from droplets, crystals, and particles depends on the relation between their size and the laser wavelength. The relationship is most sensitive when wavelength and particle size are close together, and in these cases it can be actively used to characterize particles, when several wavelengths are used (multiwavelength lidars). By using short wavelengths in the UV spectral range, it is possible to detect smaller anthropogenic particles with particular sensitivity, whilst wavelengths in the range from 900 nm to 1 500 nm are more suitable for clouds and sand dust.

The overall radius of particles lies between a few nanometres for small soot particles and 100 µm for large volcanic ash and mineral particles. The droplet sizes in clouds and fog are approximately above 1 µm in diameter; ice crystals are typically above 10 -100 µm in diameter.

The UV wavelength range below 350 nm is not commonly used in backscatter lidars, since decreasing wavelengths are associated with a rapid increase in molecular (Rayleigh) scattering and below 320 nm trace gases such as ozone exhibit strong absorption (see VDI 4210 Part 1). Moreover, there is a limited availability of permanently operating laser sources. The 350 to 355 nm UV range is used by several backscatter and Raman lidars. For this range, eye-safety restrictions are less restrictive while availability and quality of laser sources and suitable detectors is high.

In the visible spectral range eye-safety regulations are, in general, more restrictive, but the short reaction time that can be used between 400 and 700 nm due to the eye shut reflex has been used to develop specific eye-safe backscatter lidar systems. Data generated using visible laser wavelengths is more comparable to that obtained by the human eye, e.g., when making visibility measurements, unlike in the NIR, or UV range, where correction factors might be required.

In the NIR region, the wavelength range between approx. 800 nm and 1 064 nm is commonly used. The availability of laser diodes and detectors in this spectral range permits the construction of compact and economical instruments which provide acceptable eye safety. These systems are commonly used for measuring altitudes of clouds, for analysing the stratification of the atmospheric boundary layer, for detecting aerosol layers and their depths, and for determining visibility (see ISO 28902-1) (Note that these designs include ceilometers and micro-pulse lidars). The user is advised to consider carefully the laser manufacture's recommendations and implement advised safety measures.

These systems are ideally designed to minimize gas absorption by other atmospheric components. For systems where this is not the case, the absorption of gases shall be accounted for as a component of extinction. For example, water vapour absorption in the wavelength range between 900 nm and 940 nm shall be accounted for in instruments operating within this wavelength band.

5.2.1 Overlap function

In the near field of view for any backscatter lidar, the signal quality is limited due to an incomplete overlap of the transmitting and receiving beam (geometric overlap) (see [Figure 1](#), distance x_2) and due to automatic lens focusing where a near object will result in a focus point behind the detector (optical overlap). These two effects result in a distance and wavelength dependent overlap function $O(x, \lambda)$ which is specific to each lidar system (see [Figure 1](#)).

- Geometric overlap describes the overlap between the laser beam and the field of view of the telescope/receiver. It is determined by the laser beam's divergence described by the separation between the sending and receiving axes and by the receiver's field of view.
- Optical overlap describes the situation where the image plane of an object in the near field is larger than the detector area such that only part of the backscattered light in the overlap region is imaged by the detector.

The overlap function of a bi-static system has the value 0 immediately in front of the measurement system. It is only where there is complete overlap between the outgoing laser beam and receiver field of view does it reach the value of 1.

Mono-static systems start with an overlap value which is small, but greater than 0, the exact value depends on the mono-static setup as shown in example 2 in [7.8.1](#).

Additional, time depend effects on the overlap function are due to the properties of the laser (warming-up process, laser or laser diode aging, alignment stability (beam-pointing stability)), and of the receiving telescope (variations in focal length and beam path due to changes in temperature).

The reason for these time dependant effects is that the telescope's field of view (FOV) is chosen in accordance with the laser beam's divergence (δ_L) and therefore is sensitive to small changes in the properties described above. It is desirable to choose the smallest telescope field of view possible to minimise scattered daylight impacts.

5.3 Attenuated backscatter coefficient

Attenuated backscatter coefficient $\beta_{att}(x, \lambda)$ is a first target variable, which includes the initially unknown attenuation of the radiation over its path through the atmosphere, can be computed from the lidar signature $S(x, \lambda)$ ([Formula \(5\)](#)) and from system parameters. The background and noise signals are estimated as accurately as possible and subtracted from the lidar signal $P(x, \lambda)$. It is then distance-corrected and the signal is corrected for the system constants and functions $C_s(\lambda)$ and $O(x, \lambda)$:

$$\beta_{att}(x, \lambda) = \frac{S(x, \lambda)}{C_s(\lambda) \cdot O(x, \lambda)} = \beta(x, \lambda) \cdot \exp(-2\tau(x, \lambda)) \quad (7)$$

When the system constants are accurately known, when using a calibration methodology like Rayleigh calibration (see [5.4.1](#)), or where optically deep clouds are present (Reference [\[14\]](#)), the term $\beta_{att}(x, \lambda)$ is known as 'calibrated attenuated backscatter'. The adjective 'total' is sometime s appended at the front of

this phrase to express that the backscattering arises from molecular as well as particle scattering and that no further differentiation takes place.

Calibrated backscattering is commonly used in simple lidar systems such as ceilometers, in order to identify aerosol and cloud layers (see 7.8.2) and in order to obtain the extinction coefficient by means of a simplified inversion approach that ignores molecular scattering in the determination of visibility from the calibrated backscatter (see ISO 28902-1).

A description of the backscatter coefficient is covered in the next subclause.

5.4 Backscatter coefficient

The backscatter coefficient $\beta(x, \lambda)$ is the fraction of the light that is scattered elastically by atmospheric particles and air molecules in the backward direction, based on the solid angle and per distance unit (Reference [10]). In contrast with the attenuated backscatter coefficient $\beta_{att}(x, \lambda)$, it is an absolute physical quantity.

The backscatter coefficient results additively from the backscatter coefficients of all the individual components in the detected air volume. In practice, one differentiates between backscattering due to particles $\beta_p(x, \lambda)$ and those due to molecules $\beta_m(x, \lambda)$, which yields:

$$\beta(x, \lambda) = \beta_p(x, \lambda) + \beta_m(x, \lambda) \quad (8)$$

In addition to wavelength dependence, the backscatter coefficient also depends on the distance x : whereas $\beta_m(x, \lambda)$ is proportional to air density which decreases continuously with altitude, $\beta_p(x, \lambda)$ can change by several orders of magnitude over a few metres at the lower or upper boundaries of clouds and thus commonly exhibits high spatial and temporal variability. The same factors apply to a lesser degree to particle layers (mixing layer, detached aerosol layers).

5.4.1 Determining the boundary condition for the derivation of the particle backscatter coefficient

Both the Klett-Fernald (KF) method (Annex B.1.1) and the iterative method require a boundary condition for determining the particle backscatter coefficient. In the KF method, an atmospheric layer that can be assumed to be particle-free is commonly chosen. In this case, a boundary condition $\beta_p(x_{\text{Ref}}, \lambda) = 0$ can be selected.

Rayleigh calibration^[15] is used as the criterion for determining whether an atmospheric layer is particle-free. A hypothetical lidar profile of a particle-free atmosphere is calculated from the air density profile (Formula (B.1) and (B.2)), and the gradient of this signal is compared with that of the measured signal. In particle-free layers, the gradients match. The so-called Rayleigh calibration assumes that the measured signal in the supposedly particle-free layer has a sufficiently high SNR, an assumption that may be difficult to achieve and becomes impossible with increasing wavelength (e.g. 1 064 nm).

In such cases, it is possible to use data from other wavelengths. If, for example, the backscatter coefficient at a cloud level is known (cirrus clouds are particularly suitable here), one can consider that the backscattering is wavelength independent. This can be a good approximation in determining the boundary condition. This also applies to particle layers provided that the particles are sufficiently large (Sahara dust layers).

The second method for estimating the boundary condition consists of using simultaneous measurements of the optical depth – e.g., with a sun photometer – as an additional parameter characterizing an inversion. In this case, it is possible to extend the estimate of the backscatter profile to the near field of view (where there is incomplete overlap function) with low uncertainties.

These two are ‘fine weather methods’; hence, their use has significant limitations when low or mid-altitude clouds are present in the atmosphere. One can use as a third method which makes use of the calibration in optically dense water clouds^[14] (see 10.7). Optically dense clouds, in this discussion, are those in which the measured lidar signal is completely attenuated by the cloud. The integral of the distance-corrected lidar signal between the cloud base and the altitude of complete extinction is always exactly twice as large as the effective lidar ratio $LR_{\text{eff}}(x, \lambda) = LR(x, \lambda) \cdot \eta_{\text{ms}}$. Here η_{ms} is the multiple scattering factor. It can be estimated from the cloud height and the lidar geometry (see e.g. References [16] or [17]); since the value for the lidar

ratio of stratocumulus clouds is well-known (approx. 19 sr). When using this method, care shall be taken to ensure that the measured lidar signals returning from the cloud do not go into saturation leading to non-linear effects due to detector overloading.

Since $\beta_p(x_{\text{Ref}}, \lambda)$ is critical to the accuracy of $\beta_p(x, \lambda)$, reasonable checks should be carried out for the following quantities: spectral characteristics of the filter, spectral sensitivity of the detector, and values of the calculated backscatter coefficient at the altitude range around the assumed reference values.

5.5 Particle extinction coefficient

In analogy with the backscatter coefficient, the extinction coefficient is obtained according to [Formula \(9\)](#):

$$\alpha(x, \lambda) = \alpha_p(x, \lambda) + \alpha_m(x, \lambda) \quad (9)$$

The fraction of the air molecules $\alpha_m(x, \lambda)$ can be calculated using [Formulae \(B.1\)](#) and [\(B.2\)](#), as described in [Annex B.1](#). Given a lidar ratio of the particles $LR_p(x, \lambda)$, the profile of the extinction coefficient of the particles $\alpha_p(x, \lambda)$ can be derived from the estimated $\beta_p(x, \lambda)$. The assumptions with respect to $LR_p(x, \lambda)$ leads to uncertainties in $\alpha_p(x, \lambda)$. In most situations, the relative uncertainty for $\alpha_p(x, \lambda)$ is greater than for $\beta_p(x, \lambda)$.

Raman lidars and high spectral resolution lidars allow the extinction coefficient $\alpha_p(x, \lambda)$ to be determined directly and without the assumption of a lidar ratio. This results in a higher accuracy than for other systems.

5.6 Optical Depth

The optical depth of the atmosphere $\tau(\lambda)$ as defined in [Formula \(4\)](#) is obtained from the extinction coefficient. It can be split into molecular and particle components similar to the extinction coefficient in [Formula \(9\)](#).

$$\tau(\lambda) = \tau_m(\lambda) + \tau_p(\lambda) \quad (10)$$

Instruments like solar photometers measure the total optical depth column from ground to the upper atmosphere. This value is defined as aerosol optical depth AOD. The AOD can be used to calibrate backscatter lidar instruments measuring $\tau_p(\lambda)$, when the molecular components can be neglected as, for example, in the NIR spectral range.

5.7 Shape classification / linear depolarisation ratio

Measurement of the linear depolarisation ratio is the main method for classifying particle shapes since spherical particles do not modify the polarization of light during scattering. In contrast, some modification almost always takes place with non-spherical particles. Nearly spherical particles include swollen aerosol particles (hygroscopic particles at high relative ambient humidity), supercooled cloud droplets, and aged anthropogenic aerosol. Furthermore, non-spherical particles include ice crystals, desert dust and volcanic ash.

The extension of measurements to determining linear depolarisation ratios can be performed using both simple backscatter lidar systems and more complex systems (Raman lidar, high spectral resolution lidar), and they can be performed using one or more wavelengths. If the backscatter signal of a linearly polarized laser is split into two polarization directions oriented at right angles to each other, with one oriented as in the emitted radiation ($P_{||}(x, \lambda)$, parallel channel) and the other oriented normal to it ($P_{\perp}(x, \lambda)$, perpendicular channel), the linear depolarisation ratio of the backscatter volume $\delta_v(x, \lambda)$ can be measured according to²⁾:

2) Formulae are also in use where the denominator in [Formula \(B.4\)](#) has the sum of $P_{||}(x, \lambda)$ and $P_{\perp}(x, \lambda)$ instead of $P_{||}(x, \lambda)$.

$$\delta_v(x, \lambda) = k_{\text{pol}}(\lambda) \cdot \frac{P_{\perp}(x, \lambda)}{P_{\parallel}(x, \lambda)} \quad (11)$$

However, it is necessary to perform a relative calibration (determining the constants $k_{\text{pol}}(\lambda)$ in [Formula \(11\)](#)) of both channels before performing this calculation (see [Clause 10](#) and, ^[18] for inclusion of uncertainty considerations). The calibration procedure should include ensuring the correct orientation of the two polarization directions within the lidar's receiving optics.

Note that $\delta_v(x, \lambda)$ is not a property of particles alone, but it is rather 'mixed information' that depends on the relative contributions of air molecules and particles to the total backscattered signal.

It is only possible to measure the linear depolarisation ratio accurately when there is a high backscatter ratio (cirrus clouds, boundary layer aerosol, desert dust layer, volcanic ash). It can then be used as an approximation to achieve differentiation between spherical and non-spherical particles.

When molecular backscatter is non-negligible and its relative contribution is known, the linear depolarisation ratio of the particles $\delta_p(x, \lambda)$ can be used for classifying particles by shape (Annex [B.1.2](#)). Note that often aerosol distributions do not occur as 'pure' morphological types, and a wide range of mixtures of different aerosol types are possible. The observed linear depolarisation ratio is then a weighted average of the depolarisation ratios of the pure morphological 'types'.

5.8 Obtaining information on particle size distribution

The discussion in this subclause will primarily be related to multi-wavelength elastic lidars. Such multi-wavelength lidars can obtain the colour ratio $\chi(x, \lambda_1, \lambda_2)$, which is derived from β .

The more precise approach to calculate the particle size is using the Ångström exponent $\kappa(x, \lambda_1, \lambda_2)$ that is derived from α . Note, multi-wavelength elastic lidars cannot provide α and β independently.

The colour ratio is calculated using a supplementary variable $\kappa_{\beta}(x, \lambda_1, \lambda_2)$, which expresses the wavelength-dependence of the backscatter coefficient:

$$\frac{\beta_p(x, \lambda_1)}{\beta_p(x, \lambda_2)} = \left(\frac{\lambda_2}{\lambda_1} \right)^{\kappa_{\beta}(x, \lambda_1, \lambda_2)} \quad (12)$$

The colour ratio $\chi(x, \lambda_1, \lambda_2)$ is defined as:

$$\chi(x, \lambda_1, \lambda_2) = \frac{P(x, \lambda_1) \cdot C_s(\lambda_2) \cdot \exp(2\tau_m(x, \lambda_1))}{P(x, \lambda_2) \cdot C_s(\lambda_1) \cdot \exp(2\tau_m(x, \lambda_2))} \quad (13)$$

It is a simplified approach for classifying particle sizes and interpreted in the same sense as the Ångström exponent. For a wavelength-independent lidar ratio, we have $\kappa(x, \lambda_1, \lambda_2) = \kappa_{\beta}(x, \lambda_1, \lambda_2)$.

The relation between κ and particle size is complicated. For particles much larger than the sounding wavelengths, scattering becomes wavelength independent. Most aerosol Raman lidars use vibrational-rotational Raman signals (rather than pure-rotational Raman) since the former are substantially spectrally separated from the laser line.

For more sophisticated lidar systems (multi-wavelength Raman lidar or high spectral resolution lidar), the extinction coefficient $\alpha_p(x, \lambda)$ can be derived for at least two wavelengths, then the Ångström exponent $\kappa(x, \lambda_1, \lambda_2)$ can be used as a parameter for the wavelength-dependence of the extinction:

$$\frac{\alpha_p(x, \lambda_1)}{\alpha_p(x, \lambda_2)} = \left(\frac{\lambda_2}{\lambda_1} \right)^{\kappa(x, \lambda_1, \lambda_2)} \quad (14)$$

The Ångström approach assumes that the extinction is proportional to $\lambda^{-\kappa}$. For large particles (e.g. ice crystals), $\kappa(x, \lambda_1, \lambda_2) = 0$. For particle distributions with a high proportion of large particles, e.g., desert dust layers, $\kappa(x, \lambda_1, \lambda_2)$ is between 0 and 1, whilst for typical aerosol in the boundary layer, in which smaller particles predominate, values up to approx. 2 are reached. Since $\kappa(x, \lambda_1, \lambda_2)$ itself is not necessarily wavelength independent, the relevant spectral range should always be stated when quoting an Ångström exponent.

6 Measurement and target variables of the backscatter lidar

6.1 Introduction

The raw signal strength from backscatter lidar, which is a function of range, is defined as the measurement variable. The measurement variable is used to derive a series of target variables. These target variables are the atmospheric parameters of interest to specific users.

At the end of this subclause measurement parameters are described to characterise the performance.

6.2 Measurement variables

In backscatter lidar based on elastic scattering, the scattered light is received and temporally resolved at the emitted laser wavelength λ . The primary measurand is thus the elastic backscatter signal $P(x, \lambda)$ as a function of distance x (lidar profile) and the wavelength from [Formula \(2\)](#).

In polarization-measuring lidar systems, the backscatter signal is obtained as a function of the polarization direction. This is usually measured in two planes oriented perpendicular to each other and parallel to the direction of the laser beam.

Multiple scattering processes can increase $P(x, \lambda)$. This needs to be considered as an uncertainty when deriving target variables.

6.3 Target variables

6.3.1 Backscatter profiles

In the data analysis of the backscatter lidar signals there are various primary target variables:

- Distance-corrected backscatter signal $S(x, \lambda)$ (lidar signature; see e.g., ISO 28902-1 and [5.1](#)) (see [Formula \(5\)](#))
- Attenuated backscatter coefficient $\beta_{att}(x, \lambda)$ ([Formula \(7\)](#))
- Particle backscatter coefficient $\beta_p(x, \lambda)$ (see [5.4](#))
- In polarization-measuring lidar systems $\delta_v(x, \lambda)$ ([Formula \(11\)](#)) is the next primary target variable.

Target variables can only be computed when the measurand is well defined. The signal-to-noise ratio (SNR) is used to define the quality of the measurand; see [6.6.4](#).