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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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Foreword

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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.

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

Light detection and ranging (lidar) is an active remote sensing method. The special advantage of lidar methods are 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 in this document; References [1] to [7] cover these aspects.

NOTE To improve readability within this document, "backscatter lidar" is used instead of "atmospheric backscatter lidar".

References exist for the following remote sensing standardized methods:

— ground-based remote sensing of visual range by lidar, see ISO 28902-1[8];

— ground-based remote sensing of wind by heterodyne pulsed Doppler lidar, see ISO 28902-2[9];

— ground-based remote sensing of wind by continuous-wave Doppler lidar, seeISO 28902-3[10];

— system performance of ground-based weather radar systems measuring the atmosphere using frequencies between 2 GHz and 10 GHz, see ISO 19926-1[11];

— gaseous air pollution measurement with DAS LIDAR, see VDI 4210-1[12].

Air quality — Environmental meteorology —

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:

  — 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 4210-1[12].

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 [high spectral resolution lidar (HSRL)]. Some of these extended techniques are 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.

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* (3.11)

Note 1 to entry: Ångström exponent is usually quoted for particles.

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
$k_{pol}(\lambda)$	Calibration constant	–
$LR(x,\lambda)$	Lidar ratio	sr
$LR_{eff}(x,\lambda)$	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
$\Delta P_{sig}(x,\lambda)$	Noise of the useful signal	J
$P_h(x,\lambda)$	Background signal	J
$P_{sig}(x,\lambda)$	Useful signal	J
$P_0(\lambda)$	Energy (mean power times pulse duration) of the emitted laser pulse	J
P_n	Normalized measured signal	–

$P_{\|\|}(x,\lambda)$	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)
R_{SN}	Signal-to-noise ratio	–
$S(x,\lambda)$	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_l	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	–
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 wavelength-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	–
$\tau_m(\lambda)$	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
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

5 Fundamental principles of the backscatter lidar

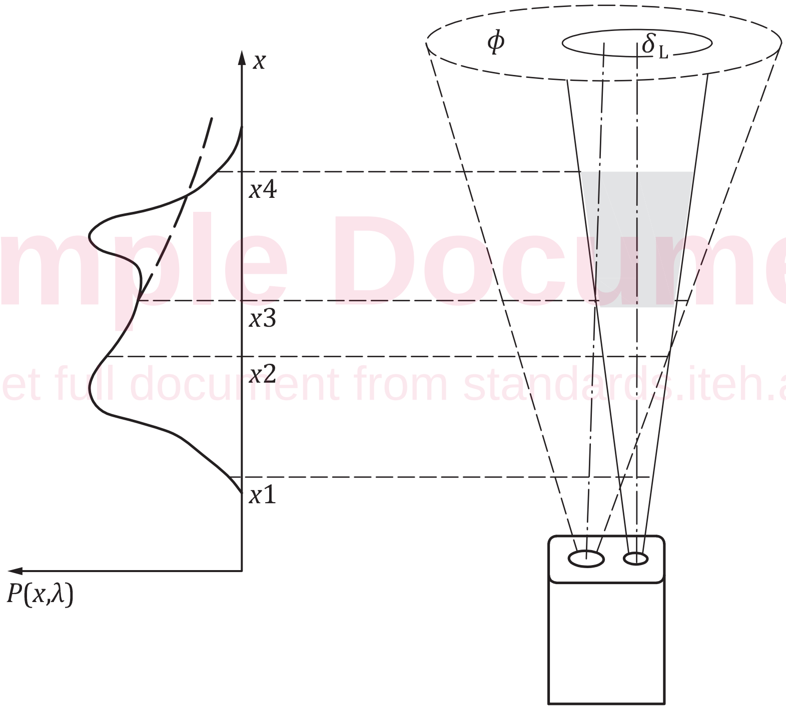
5.1 General

All lidar methods discussed in this document 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:

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

The factor ½ 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 $P\left(x,\lambda\right)$ 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 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 (see Reference [15]):

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

where

x	is the distance (m);
λ	is the wavelength (m);
Δt_s	is the temporal width of the receiving window (s);
c	is the speed of light (ms^{-1});
$P_0(\lambda)$	is the energy (mean power multiplied with pulse duration) of the emitted laser pulse (often polarised) (J);1)
A	is the effective area of the receiving telescope (m^2);
$\eta(\lambda)$	is the overall efficiency of the lidar system (can be polarisation-dependent, see Reference [9]);
$O(x,\lambda)$	is the distance-dependent overlap function between transmitted beam and FOV;
$\beta(x,\lambda)$	is the backscatter coefficient (scatter coefficient for backscattering, i.e., at 180° based on the solid angle) ($m^{-1}sr^{-1}$);
$\alpha(\xi,\lambda)$	is the extinction coefficient (m^{-1}).

The signal consists only of a background component P_h and the useful signal P_{sig}, see Formula (3).

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 6.6.5 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.

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

NOTE The lidar signature $S(x,\lambda)$ was used differently in the ISO 28902-1:2012,[8] as the background signal was ignored.

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.

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

$$S(x,\lambda) = P_{\text{sig}}(x,\lambda)\,x^2 = C_{\text{s}}(\lambda)\cdot O(x,\lambda)\cdot\beta(x,\lambda)\cdot\exp(-2\tau(x,\lambda)) \tag{5}$$

$$C_{\text{s}}(\lambda) = P_0(\lambda)\cdot A\cdot\eta(\lambda)\cdot\Delta x \tag{6}$$

with $C_{\text{s}}(\lambda)$ a wavelength-dependent system parameter. The distance-dependent and equipment-specific overlap function $O(x,\lambda)$, defined between 0 and 1 (see 5.2.2), 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 characterisation, up to much higher altitudes but still limited by the obstruction of optically thick clouds.

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 a deconvolution procedure shall be applied (see References [16], [17] and [18]).

5.2 Choice of suitable wavelengths

5.2.1 General

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 and 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 from 10 µm to 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