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Air quality — Environmental meteorology —

Part 1: Ground-based remote sensing of visual range by lidar

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

Partie 1: Télédétection de la portée visuelle par lidar basée sur le sol

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 28902-1 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology* in collaboration with the World Meteorological Organization (WMO).

ISO 28902 consists of the following part, under the general title *Air quality — Environmental meteorology*:

— *Part 1: Ground-based remote sensing of visual range by lidar*

The following part is under preparation:

— *Part 2: Ground-based remote sensing by Doppler wind lidar*

Introduction

This part of ISO 28902 describes the determination of the visual range via backscattering atmospheric lidar (“Light Detection And Ranging”). Lidars have proven to be valuable systems for remote sensing of atmospheric pollutants, of various meteorological parameters such as wind velocity and direction, cloud and aerosol distribution and composition, shape of the particles, gas concentration, and of optical properties of the atmosphere like extinction and backscatter. A specific feature of lidar methods is their ability to allow spatially resolved remote sensing. The measurements can be carried out without direct contact and in any direction as electromagnetic radiation is used for sensing. Lidar systems, therefore, supplement conventional measurement technology. They are suitable for a large number of tasks that cannot be adequately performed by using *in-situ* or point measurement methods.

Air quality — Environmental meteorology —

Part 1: Ground-based remote sensing of visual range by lidar

1 Scope

This part of ISO 28902 mainly specifies the requirements in order to perform visual range lidar measurements for the determination of direction-dependent meteorological optical range (MOR). The term "visual-range lidar" is used in this part of ISO 28902 to apply to the lidar systems making visual-range measurements, commonly referred to as "visibility measurements". Due to physical approximations, quantitative determination is limited to a meteorological optical range of between 30 m and 2 000 m. For this range, this part of ISO 28902 specifies the performance of visual-range lidar systems utilizing the method of range-integrated visual-range measurements based on light extinction. The following parameters can be calculated based on the direction-dependent meteorological optical range:

a) horizontal visual range;

b) vertical visual range;

c) slant visual range.

NOTE The measures for visibility are strongly related to the historical definitions of visibility, which are related to human observers. The lidar technique extends the definitions to various conditions, such as daylight and night-time conditions.

In addition, this measurement principle enables the user to retrieve information on cloud base height, boundary layer depth, fog banks and aerosol profiles due to the signal attenuation by water vapour and/or aerosols. Examples of these applications are given in Annex C.

This part of ISO 28902 can be applied in the following areas:

— meteorological stations;

— airports;

— harbours;

— waterways;

— roads and motorways;

— automotive;

— oil platforms.

2 Normative references

The following referenced documents are indispensable for the application 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 60825-1:2007, *Safety of laser products — Part 1: Equipment classification and requirements*

3 Terms and definitions

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

3.1
visual-range lidar
laser-based instrument using particle backscatter and extinction to measure visual range

3.2
visibility
meteorological visibility
greatest distance at which a black object of suitable dimensions (located on the ground) can be seen and recognized when observed against the horizon sky during daylight or could be seen and recognized during the night if the general illumination were raised to the normal daylight level

[WMO, 1992[1]; WMO, 2003[2]]

NOTE 1 ICAO (International Civil Aviation Organization) gives a different definition specified for aviation purposes) and makes a clear distinction with regard to daytime and night-time contrast (see ICAO, 2007[3]):

> Visibility for aeronautical purposes is the greater of:
>
> a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
>
> b) the greatest distance at which lights in the vicinity of 1 000 candelas can be seen and identified against an unlit background.

NOTE 2 In this part of ISO 28902, WMO's more general definition is used. The ICAO definition uses the luminous intensity of the runway lights for the night-time definition, which is not available in general cases.

3.3
visual range
greatest distance at which a given object can be recognised in any particular circumstances, as limited only by the atmospheric transmissivity and by the visual contrast threshold

[IEC 60050-845[4] and IEC ELECTROPEDIA 845-11-23[5]]

3.4
meteorological optical range
MOR
V_{MOR}
length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a colour temperature of 2 700 K, to 5 % of its original value

[WMO, 1992[1]; WMO, 2008[6]]

NOTE 1 The relationship between MOR and extinction coefficient (at the contrast threshold of α = 0,05) using Koschmieder's law is: $V_{\mathrm{MOR}} = -\ln(0{,}05)/\alpha$[6].

NOTE 2 If the contrast threshold is 2 %, the measurement quantity is called standard visual range V_{N}; this was initially used by Koschmieder[7].

NOTE 3 In this part of ISO 28902, MOR is used as a variable for horizontal measurements of the visual range; for slant measurements, the slant optical range (3.7) is used.

3.5
runway visual range
RVR
range over which the pilot of an aircraft on the centre line of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line

[ICAO, 2005[8]]

3.6
vertical optical range
VOR
V_{VOR}
meteorological optical range in the vertical direction

3.7
slant optical range
SOR
V_{SOR}
horizontal projection of the maximum distance out to which a black target in a plane can be recognized from an observer at height h above the plane with a contrast of 5 %

NOTE 1 The contrast threshold for the slant optical range is 5 % and is identical to the meteorological optical range (MOR) threshold.

NOTE 2 This definition is based on the standard definition of MOR [see Equations (5) and (8)] in order to enable a generally applicable mathematic evaluation procedure.

3.8
slant visual range
SVR
visual range of a specified object or light along a line of sight which differs significantly from the horizontal; for example, the visual range of ground objects or lights as seen from an aircraft on the approach

[ICAO, 2005[8]]

3.9
conventional range
maximum range measured under specified conditions in order to compare different systems

3.10
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

3.11
temporal resolution
equipment-related variable describing the shortest time interval from which independent signal information can be obtained

3.12
effective temporal resolution
Δx_{eff}
application-related variable describing an integrated time interval for which the target variable is delivered with a defined uncertainty

EXAMPLE The time resolution of consecutive extinction coefficient profiles or calculated values of the meteorological optical range (MOR) or vertical optical range (VOR).

3.13
range resolution
equipment-related variable describing the shortest range interval from which independent signal information can be obtained

3.14
effective range resolution
application-related variable describing an integrated range interval for which the target variable is delivered with a defined uncertainty

EXAMPLE The range resolution of consecutive extinction coefficient profiles or calculated values of the meteorological optical range (MOR) or vertical optical range (VOR).

3.15
fog
reduction of visibility caused by hydrometeors at a meteorological optical range $V_{MOR} < 1$ km and relative humidity near 100 %

3.16
mist
reduction of visibility caused by hydrometeors with a relative humidity ≥ 80 % or dew point differences ≤ 3 K for a meteorological optical range $V_{MOR} \geq 1$ km

[WMO, 1992[1]; WMO, 2003[2]; WMO, 2008[6]]

NOTE 1 The definition of an upper limit of 5 km is given by ICAO[3].

NOTE 2 National regulations specify differing upper limits due to different definitions of clear sky (e.g. Germany 8 km, Canada 6 miles).

3.17
haze
reduction of visibility caused by lithometeors with a relative humidity < 80 % or dew point differences > 3 K for a meteorological optical range $V_{MOR} \geq 1$ km

[WMO, 1992[1]; WMO, 2003[2], WMO, 2008[6]]

NOTE 1 The definition of an upper limit of 5 km is given by ICAO[3].

NOTE 2 National regulations specify differing upper limits due to different definitions of clear sky (e.g. Germany 8 km, Canada 6 miles).

4 Symbols and abbreviated terms

4.1 Symbols

Variable	Unit	Signification
A	m^2	area of the receiver optics
B	$W\ m^3\ sr$	system parameter depending on geometry and range
c	$m\ s^{-1}$	speed of light
E_0	J	laser pulse energy
h	m	height
K'	1	luminance contrast threshold of the eye
O	1	(range-dependent) overlap function between the transmitted beam and the field of view of the receiver (complete overlap if $O = 1$)
P	W	received detector power
P_0	W	average power of laser pulse

Variable	Unit	Signification
S	W m^2	lidar signature
T	K	temperature
t	s	time
Δt	s	laser pulse duration
Δt_{eff}	s	effective temporal resolution
x	m	range (distance from measuring system to scattering volume)
Δx_{eff}	m	effective range resolution
x_{CR}	m	conventional range for visual-range determination
x_{f}	m	starting distance for data evaluation by backward integration
x_{n}	m	starting distance for data evaluation by forward integration
x_{L}	m	baseline of a transmissometer
V_{MOR}	m	meteorological optical range
V_{N}	m	standard visual range
V_{SOR}	m	slant optical range
V_{VOR}	m	vertical optical range
α	m^{-1}	extinction coefficient
$\alpha(x_{\mathrm{f}})$	m^{-1}	initial value of extinction coefficient for backward integration
$\alpha(x_{\mathrm{n}})$	m^{-1}	initial value of extinction coefficient for forward integration
$\Delta\alpha$	m^{-1}	uncertainty of the extinction coefficient
β	m^{-1} sr^{-1}	backscatter coefficient
δ	rad	laser divergence
γ	rad	field of view
η	1	efficiency of the receiver optics
λ	m	wavelength
$\Delta\lambda$	m	spectral width
ξ	m	variable for range integration
τ	1	atmospheric transmittance between lidar and scattering volume

4.2 Abbreviated terms

ICAO	International Civil Aviation Organization
MOR	meteorological optical range
RVR	runway visual range
SOR	slant optical range
SVR	slant visual range
VOR	vertical optical range
WMO	World Meteorological Organization

5 Fundamentals of visual-range lidar

5.1 General

Lidar methods are active methods for measuring selected physical variables of the atmosphere[9]. Lidar requires a pulsed light source and a detection system with good time resolution[10]. The emitted light interacts with the atmosphere through scattering[11][12], and the backscattered fraction is measured. The backscatter signals are used to determine the physical variables that describe the atmospheric conditions. Depending on the process of physical interaction of the light with the atoms, molecules, or aerosol particles in the atmosphere, a distinction is made between different variants of the lidar principle.

The visual-range lidar uses elastic scattering on particles for the measurement.

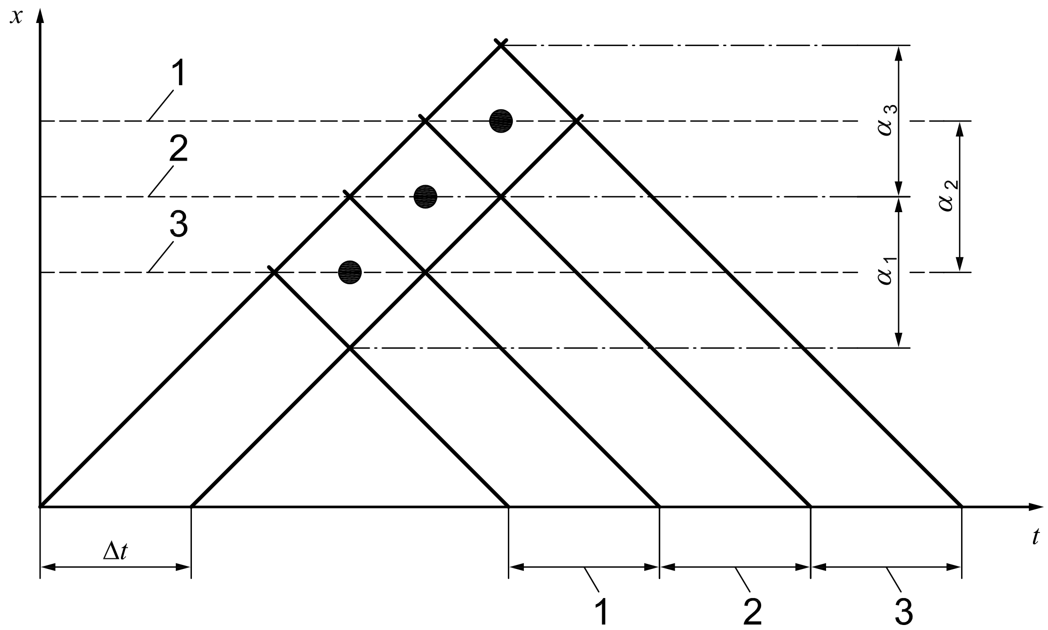
NOTE The wavelength is not changed during the scattering process.

In lidar, the propagation time of the light from the source to the object and back is used to determine distance. The distance x to the scattering volume is determined from the time t after emission of the laser pulse using the speed of light c:

$$x = \frac{c\,t}{2} \tag{1}$$

The factor 1/2 results from the doubled path traversed by the emitted light before it is recorded again by the lidar system.

After the emission of each individual laser pulse, the backscattering signal is detected in successive time bins. Each of these corresponds to a height or range interval and is characterized by its centre height or distance (see Figure 1).



Key

1, 2, 3	centre of the range or height interval and corresponding receiving time interval	t	time, in s
x	distance, in m	Δt	laser pulse duration, in s
α_i	extinction coefficient, in m^{-1}		

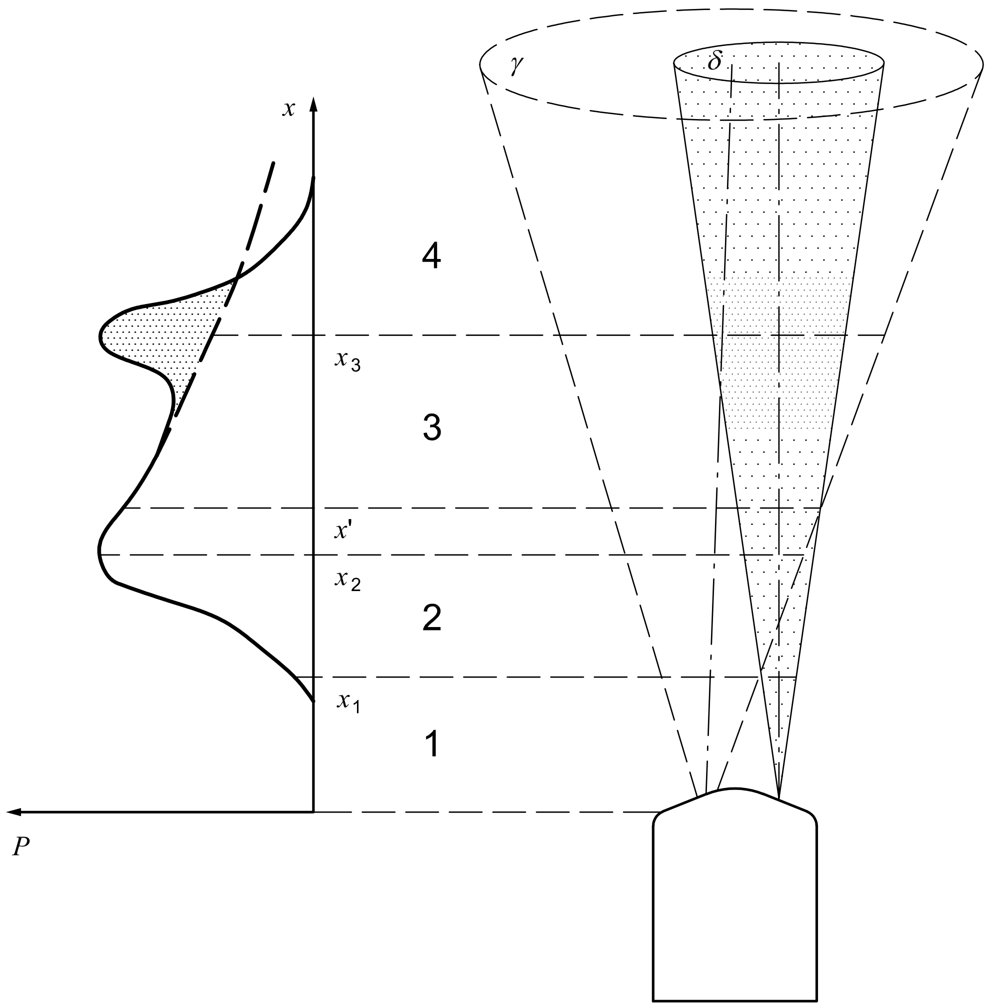
Figure 1 — Schematic relation between propagation time and range

In an arrangement such as that schematically represented in Figure 2, the detector records a signal $P(x,\lambda)$ after the emission of a laser pulse. The time profile of the signal is transformed into a spatial profile. Neglecting the duration Δt of the transmitted pulse, the spatial profile of the signal can be represented by Equation (2)[10]:

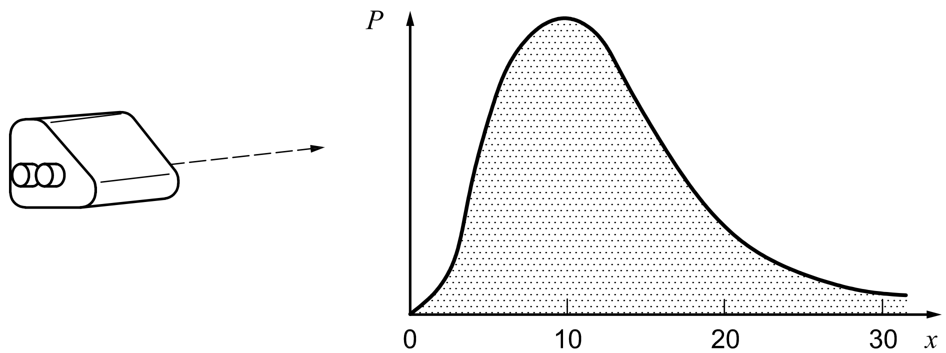
$$P(x,\lambda) = \frac{c\,\Delta t}{2}\,P_0\,\frac{A\,\eta\,O(x)}{x^2}\,\beta(x,\lambda)\,\tau^2(x,\lambda) \qquad (2)$$

where

c	is the speed of light;
Δt	is the (laser) pulse duration;
P_0	is the average laser power during the pulse;
A	is the area of the receiver optics;
η	is the efficiency of the receiver optics;
$O(x)$	is the range-dependent overlap function between the transmitted beam and the field of view of the receiver [complete overlap at $O(x) = 1$];
λ	is the wavelength;
$\beta(x,\lambda)$	is the backscatter coefficient;
$\tau(x,\lambda)$	is the transmittance of the atmosphere between the lidar and the scattering volume;
x	is the distance between lidar and scattering volume.



a) Typical receiver signal



b) Typical receiver signal in a homogeneous fog

Key

1,2,3,4	areas with differing backscatter and beam geometry
x_i	distance, in m
P	power, in W

NOTE Dashed cone: field of view of the detection system (γ); Solid cone: transmission cone of the laser (δ).

Figure 2 — Lidar measurement principle

In Figure 2 a), a typical receiver signal is depicted. Four areas can be distinguished assuming simplified laser beam geometry in near and far fields.

a) Up to a distance x_1, the receiver detects no radiation except from multiple scattering[1)], as the transmission cone has not yet entered the field of view of the receiver. The signal onset distance depends on the geometry of the transmitting and receiving optics. The overlap function $O(x)$ in this area is very small.

b) At a distance of x_2, a maximum signal develops which reflects the combined effect of overlap and extinction. At x', the overlap function equals 1: $O(x') = 1$. The full beam cross-section is imaged on the detector.

c) At x_3, another maximum signal appears which is caused by atmospheric inhomogeneity such as a fog bank or cloud. The signal would have followed the broken line if it had not been for this scattering inhomogeneity.

d) The cloud or fog bank causes a reduction of the light from the area behind the cloud, thus, the signal from the area beyond quickly drops to the noise level.

Figure 2 b) shows a typical receiver signal obtained in a homogeneous fog. To record visibility conditions in the immediate proximity of the lidar, a compact device with large transmitter and receiver aperture is used. Because of the different geometry of the lidar systems, the equivalent of areas 1 to 3 of Figure 2 a) is all contained in the first 30 m of Figure 2 b).

Three factors in the lidar Equation (2) are decisive for the profile of the received signal and require an adaptation of the signal dynamics in the data acquisition system:

— *the dependence on the distance*, $1/x^2$: This is a geometrical factor and stems from the fact that scattering is isotropic to the first approximation;

— *the backscatter coefficient* β: In general, a cloud scatters more strongly than the surrounding air molecules and aerosols, and, consequently, a cloud shows up clearly as an inhomogeneity in the signal profile;

— *the transmittance of the atmosphere* $\tau(x,\lambda)$: This is derived from the atmospheric extinction coefficient $\alpha(x,\lambda)$ by integration over the range variable ξ according to Equation (3). τ describes the transparency of the atmosphere to the light of the wavelength λ along the light path:

$$\tau(x,\lambda) = \exp\left[-\int_0^x \alpha(\xi,\lambda) \mathrm{d}\xi \right] \tag{3}$$

Equation (4) defines the range-corrected lidar backscattering signal, or lidar signature:

$$S(x) = P(x,\lambda)\, x^2 = B(x)\, \beta(x,\lambda)\, \tau^2(x,\lambda) \tag{4}$$

with $B(x)$ as a range-dependent system parameter determined by the geometry of the system.

The evaluation of Equation (4) is described in 9.1. In principle, other techniques, such as the high spectral resolution (HSR) method[13][14], can be used alternatively. The HRS method can resolve extinction and backscatter independently, but requires a small bandwidth laser and a high resolution receiver; it is not described in this part of ISO 28902.

5.2 Concept of visual-range lidar measurements

5.2.1 General

This subclause specifies the concept of visual-range lidar measurements.

1) If photons are scattered more than once on their way from the light source to the receiver, this is referred to as multiple scattering.

5.2.2 Meteorological optical range

Based on Koschmieder's visual-range theory[7], the meteorological optical range is defined as:

$$V_{\mathrm{MOR}} = -\frac{1}{\alpha}\ln K' = \frac{3}{\alpha} \tag{5}$$

where

V_{MOR} is the meteorological optical range;

α is the extinction coefficient;

K' is the luminance contrast threshold of the eye.

The value of K' was initially set by Koschmieder to 2 %. For practical applications (e.g. by an airport weather service and meteorological applications) a threshold value K' of 5 % is defined, both by ICAO[3] and WMO[1], to consider additional physiological and situational constraints. The meteorological optical range is thus defined for this threshold value of 5 %.

The conditions for the validity of Equation (5) are the following:

— the same illumination conditions prevail along the line from the observer to an object on the horizon;

— the extinction coefficient α is constant within the entire range;

— the object is black;

— the object is just visible.

MOR can be determined with a light transmissometer, or by use of the contrast-light method or the scattered-light method, or with a visual-range lidar.

If the extinction coefficient between the observer and the horizon is not constant, then the MOR in this direction is given by:

$$\int_0^{V_{\mathrm{MOR}}} \alpha(\xi)\,\mathrm{d}\xi = 3 \tag{6}$$

5.2.3 Vertical optical range

Using Equation (6) for the vertical direction, the vertical optical range is obtained as:

$$\int_0^{V_{\mathrm{VOR}}} \alpha(\xi)\,\mathrm{d}\xi = 3 \tag{7}$$

5.2.4 Slant optical range

For an observer at height h above the ground, the slant optical range is defined as the horizontal projection of the maximum distance out to which a black target in that plane can be recognized with a threshold of 5 %.

Based on Equation (6) and with the conditions $V_{VOR} > h$ and horizontal homogeneous distribution of the extinction coefficient, we obtain:

$$V_{SOR}(h) = h\sqrt{\left(\frac{3}{\int_0^h \alpha(\xi)\,\mathrm{d}\xi}\right)^2 - 1} \tag{8}$$

Equation (8) is only applicable if

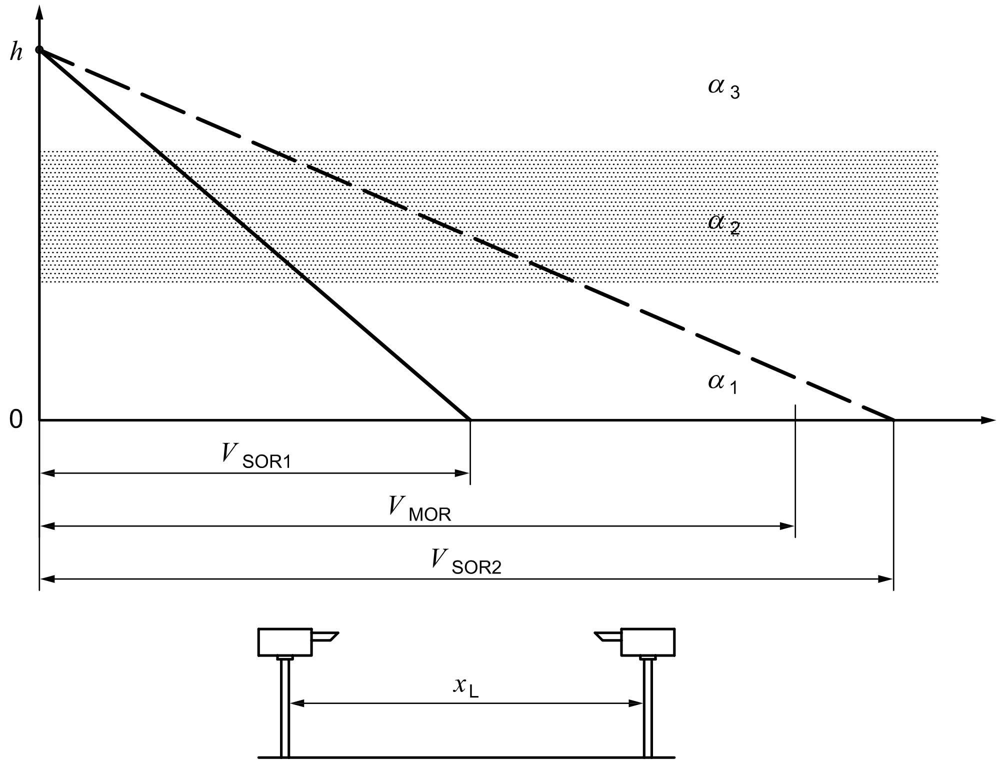
— $V_{VOR} > h$ and

— α is horizontally homogeneous and α is only a function of the height h.

If $V_{VOR} < h$, the SOR is not defined as a pilot at height h cannot see the ground.

If α is not horizontally homogeneous, the SOR determined by the instrument and the SOR perceived by the observer are not necessarily identical.

EXAMPLE Figure 3 shows schematically the situation during a landing approach at an airport. A light transmissometer at the ground (baseline x_L) measures V_{MOR} [Equation (5)] under the assumption of a horizontally homogeneous extinction coefficient α_1. In this example, V_{MOR} is larger than the baseline x_L. V_{SOR} requires integration over the vertically stratified extinction coefficient [Equation (8)]. Under low stratus ($\alpha_2 > \alpha_1$, α_3) conditions, a pilot at height h, thus sees the ground at a steeper angle (V_{SOR1}) than in ground fog ($\alpha_1 > \alpha_2$, α_3; V_{SOR2}) conditions.



The scheme illustrates that slant optical range, V_{SOR}, is defined as a distance at ground level and can be quite different from the meteorological optical range, V_{MOR}.

Figure 3 — Schematic representation of a situation with horizontally homogeneous visibilities corresponding to extinction coefficients $\alpha_1, \alpha_2, \alpha_3$

5.2.5 Visual-range determination with lidar

Koschmieder's theory assumes visible light. However, lidar methods for visual-range determination operate from the near UV region up to the near IR region, at wavelengths from 315 nm up to 1 600 nm [2].

The application of Koschmieder's theory to lidar methods is possible if wavelength-independent scattering is assumed. This condition can be met in different meteorological situations if backscatter particles are homogenous in shape and diameter (e.g. fog and mist or haze). If instead, there are particle mixtures or inhomogeneities, different theories have to be applied because wavelength independency is no longer a given.

According to Koschmieder's theory, the application of this part of ISO 28902 is therefore restricted by convention to $V_{\mathrm{MOR}} \leq 2\ 000$ m[3]. This meteorological optical range covers the applications described in 8.3. Examples for applications for $V_{\mathrm{MOR}} > 2\ 000$ m are given in Annex C.

The range-resolved measurement of the extinction coefficient α with lidar allows the meteorological optical range to be determined even in inhomogeneous stratification conditions. This is the essential difference with 5.2.2 and an advantage of visual-range determination with lidar compared to *in-situ* methods or point measurement methods or observers.

6 Requirements

6.1 Measurement variables

The measurement variable of a visual-range lidar is the power $P(x)$ backscattered from distance x [Equation (2)].

6.2 Target variables

With the described evaluation method in 9.1, the particle extinction coefficient $\alpha(x)$ is obtained from the measured backscatter signal $P(x)$. The following primary target variables can then be determined along the optical path if the minimum requirements listed in 6.3 are fulfilled:

— particle extinction coefficient, α;

— gradient of the particle backscatter coefficient, $\mathrm{d}\beta/\mathrm{d}x$;

— meteorological optical range, V_{MOR};

— standard visual range, V_{N};

— vertical optical range, V_{VOR};

— slant optical range, V_{SOR}.

The definitions of these primary target variables are given in Clause 5; their determination is described in 8.3.

6.3 Specifications and minimum requirements of performance characteristics

6.3.1 General

The extinction coefficient profiles, $\alpha(x)$, obtained from a measurement are determined by the values of several performance characteristics. Each of these characteristics depend on the choice of all the other variables. In order to attain the required performance of a lidar to determine visual range with a tolerable deviation from the true value, these characteristics shall be set within the range given in the following clauses.

---

2) Thermal radiation of the atmosphere can be neglected for $\lambda \leq 2$ µm. A correction is required if $\lambda > 2$ µm. This is why visual-range determination with IR-night-vision devices is not possible.

3) For wavelengths in the near UV region, molecular scattering cannot be neglected entirely. By restricting the meteorological optical range to $\leq 2\ 000$ m, the contribution of molecular scattering to the MOR uncertainty falls below the tolerated limits specified in Table 1.

Good resolution is synonymous here with a low numerical value of the corresponding variable. The reciprocal value or a quantity proportional to the reciprocal is denoted as a resolving power, i.e. good resolution corresponds to a high resolving power.

6.3.2 Basic requirements for visual-range lidar systems

Table 1 presents the requirements for visual-range lidar systems. The specified characteristics shall be met in order to obtain reliable visual-range lidar measurement results. The lidar system shall be eye-safe and shall meet the safety requirements specified in IEC 60825-1. Further information can be found in Reference [15].

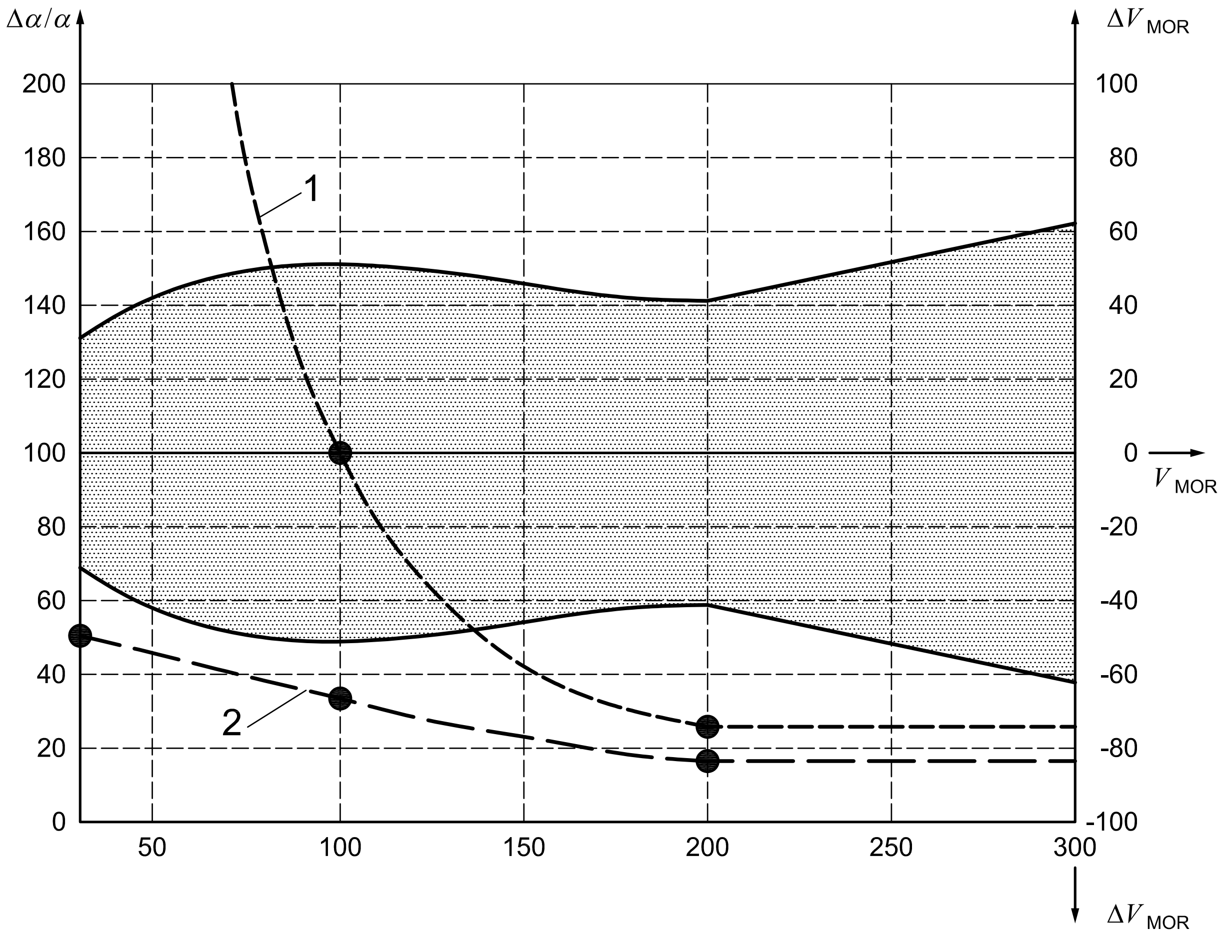
Table 1 — Requirements of visual-range lidar systems

	Symbol	Visual-range measurement	
MOR range/SOR range (normative)	V_{MOR}, V_{SOR}	30 m to 2 000 m	
Minimum range[a] (informative)	x_{min}	3 m (MOR – automotive) 50 m (VOR – meteorological application)	
Wavelength (normative)	λ	315 nm to 1 600 nm	
Effective temporal resolution[a] (normative)	Δt_{eff}	$<$ 1 s (automotive) 30 s to 60 s (traffic safety) 60 s (aviation) 600 s [meteorological (synoptic) applications]	
Effective range resolution (informative)	Δx_{eff}	$\leq$ 1/10 of the minimum MOR to be determined	
Relative uncertainty of extinction coefficient[b] (normative), see also Figure 4	$\Delta\alpha/\alpha$	$\alpha_{measured} > \alpha_{reference}$[c]	$\alpha_{measured} < \alpha_{reference}$[c]
		$<$ 1 000 % for V_{MOR} = 30 m $<$ 100 % for V_{MOR} = 100 m $<$ 25 % for $V_{MOR} >$ 200 m	$<$ 50 % for V_{MOR} = 30 m $<$ 33 % for V_{MOR} = 100 m $<$ 16 % for $V_{MOR} >$ 200 m
Relative uncertainty of MOR[b] (normative), see also Figure 4	$\Delta V_{MOR}/V_{MOR}$	$<$ 100 % for V_{MOR} = 30 m $<$ 50 % for V_{MOR} = 100 m $<$ 20 % for $V_{MOR} >$ 200 m	
Uncertainty of inclination angle (informative)	$\Delta\theta$	± 2°	

[a] Depending on the application.

[b] Includes all contributions of the system and atmosphere.

[c] $\alpha_{measured}$: extinction coefficient measured with visual-range lidar systems; $\alpha_{reference}$: extinction coefficient measured by a reference method, e.g. transmissometer; $\Delta\alpha = |\alpha_{measured} - \alpha_{reference}|$.



Key

$\Delta\alpha/\alpha$ relative uncertainty of the extinction coefficient α, in %

ΔV_{MOR} absolute uncertainty of MOR, in m

V_{MOR} meteorological optical range, in m

1 $\alpha_{measured} > \alpha_{reference}$

2 $\alpha_{measured} < \alpha_{reference}$

NOTE The dashed and dotted lines describe the relative uncertainty of the extinction coefficient related to the left-hand axis. The shaded area describes the tolerable absolute uncertainty of MOR related to the right-hand axis.

Figure 4 — Relative uncertainty of extinction coefficient α

6.3.3 Backscatter signal, $P(x)$

The signal-to-noise-ratio of the backscatter signal $P(x)$ shall exceed a value of 6 dB over the entire application-dependent range interval in which the range-resolved extinction coefficient α is determined. This is necessary in order to keep the noise-induced uncertainties related to the detection of α below a tolerable limit.

6.3.4 Temporal resolution and effective temporal resolution

Temporal resolution is an equipment-related variable. Effective temporal resolution (Δt_{eff}) is the time interval between two consecutive extinction coefficient profiles. For the application of visual-range lidar, the following typical effective temporal resolutions are recommended:

— $<$ 1 s for real-time measurement in a vehicle;

— 60 s for aviation and motorway monitoring;

— ≤ 600 s for meteorological (non-aeronautic) applications.

Effective temporal resolutions of < 1 s are typically only available for very short probe ranges (< 50 m), MOR values smaller than 500 m and a high uncertainty (50 % or 100 %). MOR values are calculated using calibrated backscatter signals and interpolation methods from smaller probe ranges. For meteorological applications, a clearly higher accuracy is required (uncertainty <10%). In order to reach this requirement, an effective temporal resolution of several minutes and a maximum probe range exceeding the calculated MOR values are necessary. In summary, depending on the application and measuring task, the specifications given in Table 1 shall not be exceeded.

6.3.5 Range resolution and effective range resolution

An abrupt change of the extinction coefficient (e.g. in the shape of a Heaviside step function) appears as a gradual change in the measured profile. The range interval over which the change from 25 % to 75 % of the total step height extends in the measured profile is defined as the range resolution. Range resolution is an equipment-related variable which is determined by the pulse duration, the upper bandwidth limit of the detectors and amplifiers and the temporal resolution in which one can digitize the signal.

In order to calculate a profile of the extinction coefficient α, an effective range resolution has to be defined. Averaging then takes place over as many primary range resolutions as fitting into the width of the effective range resolution. The averaging can be done in such a way that each original resolution is only considered once (box type or rectangular averaging). Successive averaged backscatter signal values are then independent from each other and vary as strongly as the corresponding averages in nature. If, on the other hand, the averaging takes place in such a manner that the backscattering signal value of a local resolution enters into several average values (sliding averaging), then the individual values of the averaged backscattering signals are not independent of one another and the graphical presentation of the average values results in a smooth curve even if, in reality, large differences exist between backscatter signals from adjacent bins.

The effective range resolution is the resolution of the first target variable, the extinction coefficient α, and usually corresponds to a multiple of the range resolution. For visual ranges below 200 m, the effective range resolution shall be $\Delta x_{\text{eff}} \leq 10$ m; for visual ranges between 200 m and 2 000 m, the effective range resolution shall be $\Delta x_{\text{eff}} \leq 50$ m.

6.3.6 Optimum effective range resolution

The uncertainty of calculated extinction coefficients and further target variables (see 6.2) can be optimized by optimizing the effective range resolution. The actual optimum effective range resolution depends on the atmospheric conditions (see Figure 5).

Limits due to detector intrinsic noise and additional optical background noises are not taken into account in this subclause.

For example, the variation of the effective range resolution, Δx_{eff}, at constant MOR affects the relative uncertainty of the optical range determination in two ways.

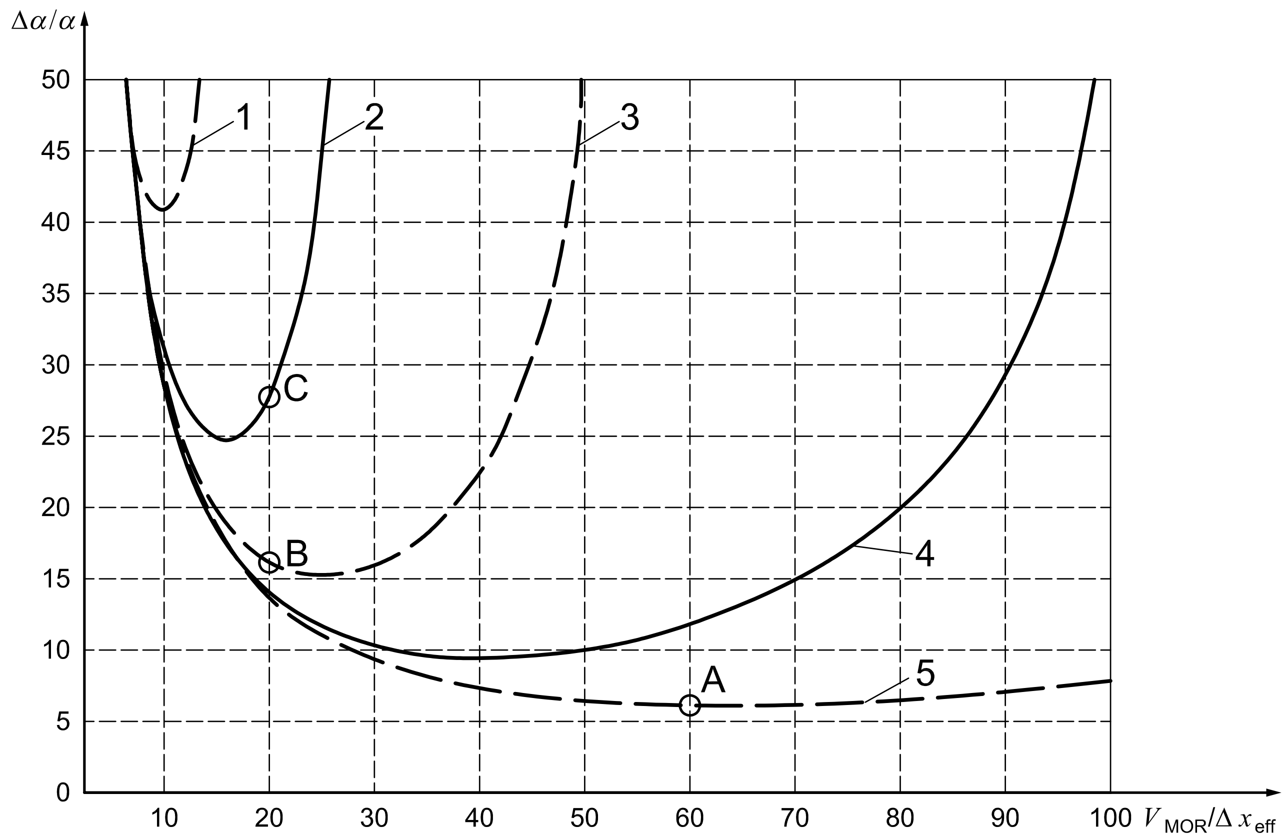
a) Decreasing the effective range resolution reduces the number of data points available for the evaluation according to Equation (11). This increases the relative uncertainty, $\Delta\alpha/\alpha$.

b) If the effective range resolution is increased, the signal values are subject to a larger influence of the reading uncertainty of the signal as fewer averages are possible. This also increases the relative uncertainty, $\Delta\alpha/\alpha$.

The first effect prevails in the left-hand part of the curves in Figure 5; the second effect prevails on the right. A lower resolution is more noticeable with the second effect. Therefore, the minimum of the curve shifts to the right if measurements are made with a higher resolution. The optimum is achieved when the two effects combined gives the minimum of the relative uncertainty of $\Delta\alpha/\alpha$.

Figure 5 shows the relative uncertainty $\Delta\alpha/\alpha$ of the lidar determination of optical range with the Klett algorithm (see 9.1) as a function of $V_{\text{MOR}}/\Delta x_{\text{eff}}$, the ratio of MOR and the selected length of the effective range resolution Δx_{eff}, for different resolutions of the digitization. As suggested in 9.2, the calculation was carried out with

$x_f = V_{MOR}$. The digitization resolution determines the uncertainty of the signal $P(x,\lambda)$. When n laser pulses are averaged, the reading uncertainty shall be multiplied by $1/\sqrt{n}$.



Key

$\Delta\alpha/\alpha$	relative uncertainty of the extinction coefficient, α, in %
$V_{MOR}/\Delta x_{eff}$	ratio of MOR and the selected length of the effective range resolution, Δx_{eff}, in %
1	6 bit
2	8 bit
3	10 bit
4	12 bit
5	14 bit

Figure 5 — Relative uncertainty of a measurement of the extinction coefficient with a visual-range lidar as a function of $V_{MOR}/\Delta x_{eff}$ for different values of the digitization resolution

EXAMPLE With an effective range resolution of 20 m and a digital resolution of 14 bits, V_{MOR} = 1 200 m can be determined with an uncertainty of 6 % (point A) if e.g. 60 000 laser pulses are averaged. At V_{MOR} = 100 m, an effective range resolution of 5 m and 10-bit resolution, one obtains 16 % uncertainty (point B); at an 8-bit resolution, the uncertainty increases to 28 % (point C).

6.3.7 Minimum range and maximum range

Visual-range lidar systems allow a measurement immediately in front of the measuring system, provided the data evaluation algorithm allows the treatment of signals from short distances for which $O(x) < 1$ and considers multiple scattering, e.g. by dense fog. If this condition is not met, the minimum range, x_{min}, shall be set at a distance for which the overlap function $O(x) = 1$ or at which the backscatter signals are maximum. This is necessary to ensure accurate results (see Figure 2). The minimum range of a visual-range lidar depends on the geometry of its optics and usually lies between 3 m and 50 m. Any data evaluation algorithm that depends on signals from distances with overlap function $O(x) < 0{,}8$ is lacking in accuracy, independent of the system design, because of system stability and multiple scattering influences. This is the reason why $O(x)$ at minimum range shall exceed the value of 0,8.

The maximum range is the maximum distance within which a $V_{MOR} \leq 2\,000$ m can be determined. Maximum range, thus, depends on the average extinction coefficient as well as on its homogeneity and on the background luminance which increases noise. Furthermore, the maximum range depends strongly on the measurement duration and the effective range resolution. System parameters such as laser pulse energy, pulse repetition frequency, diameter of the receiving telescope, detector sensitivity and digitization resolution of the analogue-to-digital converter also affect the maximum range. In most practical cases, the maximum range is between 100 m and 1 000 m.

6.3.8 Measuring range and detection limit of extinction coefficients

This part of ISO 28902 is limited to the determination of meteorological optical range $V_{MOR} \leq 2\,000$ m (see the scope and 5.2.5), corresponding to extinction coefficients $\alpha \geq 1{,}5 \cdot 10^{-3}$ m^{-1} [Equation (6)]. There is no fundamental limitation towards high extinction coefficients[4)] but the scope of this part of ISO 28902 is limited to $V_{MOR} > 30$ m.

For optical range determination, the limitation to $V_{MOR} \leq 2\,000$ m implies that the detection limit of the extinction coefficient is also $\alpha = 1{,}5 \cdot 10^{-3}$ m^{-1}. This requirement shall be met for stationary operations of a visual-range lidar. For mobile operations such as the detection of fog banks, a minimum detection limit of $\alpha = 10 \cdot 10^{-3}$ m^{-1} (corresponding to $V_{MOR} = 300$ m) is sufficient.

6.3.9 Definition of the conventional range for visual-range measurement

Two conventional ranges [x_{CR}(200) and x_{CR}(1 000)] are defined by convention for visual-range determination. The purpose of this definition is to ensure that specifications for different measurement systems are based on the same parameter constellations and that their measured data can be compared directly. For this purpose, the conventional ranges shall be measured using the effective temporal resolutions given in Table 1 for different applications ($<$ 1 s for automotive; 30 s to 60 s for traffic safety; 60 s for aviation; 600 s for meteorological applications).

The conventional range x_{CR}(200) is the maximum distance for which a visual-range lidar receives a signal-to noise-ratio of 10 (i.e. a backscatter signal of 10 db) from a standard reflection target[5)] if $V_{MOR} = 200$ m and the measurement takes place under homogenous atmospheric conditions.

The conventional range x_{CR}(1 000) is the corresponding maximum distance for $V_{MOR} = 1\,000$ m. The determination of x_{CR}(1 000) shall be carried out for a background luminance $>$1 000 cd/m^2.

7 Measurement planning and site requirements

The selection of the measurement site is essentially determined by the measurement task. Careful selection of the measurement site is necessary, in particular, for stationary systems or for the quasi-stationary use of mobile systems during long-term measurement campaigns. The following points shall be taken into account when selecting the measurement site:

— unobstructed view: unrestricted visibility can be limited by built up areas, trees, buildings near the installation site of the lidar;

— presence of sources that obstruct visibility (chimney emitting smoke, for example);

— solar altitude at the time of measurement: measurements directly into the sun should be avoided;

— local and seasonal sources which affect the visibility measurements (lake, river or forests, for example).

4) If $V_{MOR} < 30$ m, the influence of multiple scattering has to be considered, as well as technical problems (data resolution, overlap function, etc.) which become more and more critical. Smoke can lead to interferences (Clause 7).

5) Standard reflection target with a reflectivity between 5 % and 10 % within the wavelength range UV to 1,6 µm.

Early inspection of the envisaged measurement site with the participation of experts (e.g. meteorologists) is recommended.

8 Measurement procedure

8.1 General

Accurate and reliable measurement results over years can only be obtained if visual-range lidar systems are carefully tested and calibrated. For this purpose, test tools and special manufacturer certificate(s) may be needed for operation and verification. The range of applications and the measurement procedures are shown in 8.3.

The installation and start-up at the measurement site, operational test, measuring procedure and data processing shall be carried out in accordance with the specifications of the manufacturer. The manufacturer's specifications should specify which procedures, or at what time intervals, the operational test and adjustment procedures are to be repeated. For information, Annex B describes the laboratory test and field tests performed by the manufacturer.

8.2 Maintenance and operational test

8.2.1 General

In order to test the functioning of the system as specified and to rule out deviations and technical errors such as misadjustments[16], the maintenance and the operational test shall be performed in regular intervals.

8.2.2 Maintenance

Maintenance as regular cleaning of the optical components, etc. shall be performed as a basic requirement of quality assurance. The necessity of a maintenance procedure can be done either by an operator or using an automatic software detection of the decrease of the signal due to, e.g. dust deposits. Typical maintenance intervals are 3 months depending on the environmental conditions.

8.2.3 Operational test

Operational tests should be performed every 6 to 12 months. The tests depend on the different systems. The manufacturer shall specify the testing procedure and provide the necessary testing tools.

a) Output power and frequency of the laser source should be measured at the periodicity indicated by the manufacturer.

b) Signal output of the data acquisition system reacting on a defined light pulse or defined target should be measured at the periodicity indicated by the manufacturer.

c) For scanning or steering systems, an alignment test using a calibrated instrument (e.g. compass. inclination meter) should be performed.

8.3 Applications and measurement procedure

8.3.1 General

The following examples illustrate the broad range of potential applications of visual-range lidar systems.

8.3.2 Horizontal optical range

The determination of the horizontal MOR from measurements with a visual-range lidar is described in Equation (5). To realise the measurements, the equipment should usually be operated from a stationary platform. Measurements are possible in various directions. Normally, however, all pulses should be sent out in a horizontal direction. Typical fields of application of this procedure are *in-situ* determinations of visual range at the touchdown point on a runway, and fog alerts for roads and highways as well as waterways and on offshore drilling platforms.

The measurement accuracy of the visual-range lidar is less than that of transmissometers and forward scattering devices, especially at $V_{\mathrm{MOR}} > 1\ 000$ m. Visual-range lidar, however, allows a locally resolved measurement of horizontal optical range and slant optical range (see 8.3.3.) at points inaccessible to other measurement methods.

8.3.3 Slant optical range

The height-dependent slant optical range (SOR), determined according to Equation (8), enables airports to inform approaching pilots of situations such as ground fog or elevated ground fog.

The locally resolved measurement of extinction coefficients allows SOR to be determined for different heights with one measurement. The elevation angle of the measurement should be chosen according to the maximum height for which a SOR value is required. Measurements in several angles improve measurement performance and reduce uncertainty caused by horizontal inhomogeneities of the horizontal distribution of the extinction coefficient.

Measurement angle accuracy is vital for the quality of SOR determination. The uncertainty caused by angle inaccuracies rises with the absolute value of the extinction coefficient gradient.

In compliance with airport operating instructions, a horizontal transmissometer or forward-scatter meter shall be set up close to the touchdown point on the runway. Data from this instrument are used for aviation weather advisory services. With a visual-range lidar, it is possible to make slant-path measurements from the touchdown point into the atmosphere and, thus determine the visual range along the approach path. This case clearly demonstrates the advantages of using lidar slant optical measurements where the installation of a mast is prohibited and, thus, transmissometers cannot be used (airports, platforms, ships).

8.3.4 Runway visual range (RVR) and slant visual range (SVR)

A pilot's visibility immediately after touchdown is described by a quantity called "runway visual range"; this quantity is specified in ICAO, 2007[3].

RVR is the greatest distance to which a pilot with eyes 5 m above the centre line of the runway of an airport can either recognize the lights that indicate the centre line and borders of the runway, or recognize the runway itself with its marking. Here, distance is defined parallel to the runway. RVR is, thus, the length of the projection of the distance between the pilot and the target on the centre line of the runway.

RVR can be calculated from MOR with the luminous intensity of the lamps and the background luminance as the auxiliary variables. At low luminous intensity of the runway lights and high background luminance, RVR = MOR.

In analogy to RVR, a height-dependent quantity called "slant landing runway visual range", or simply "slant visual range" can be defined to characterize visibility conditions for the pilot prior to landing. It is determined from the SOR values.

Following its definition, for the purpose of RVR calculation, the MOR should be measured at a height of 2,5 m or determined from the average extinction coefficient up to 5 m. SVR determination requires the knowledge of the extinction coefficient profile up to the maximum height of interest.

NOTE Subclause 4.2.1.1 of ICAO, 2007[3] recommends that the RVR be calculated from the MOR measured at a height of approximately 2,5 m above the runway and that, if available, the average extinction coefficient up to 5 m should be used. SVR determination requires the knowledge of the extinction coefficient profile up to the maximum height of interest.

RVR and SVR are reported to pilots in steps of 25 m, 50 m or 100 m.

8.3.5 Vertical optical range (VOR)

The determination of the VOR from measurements with a visual-range lidar is described in Equation (7). For aviation safety purposes in haze or fog situations, VOR is reported instead of cloud base height. To realize the measurements, the equipment should be operated from a stationary platform in a nearly vertical direction. The system's maximum range has to exceed VOR.

8.3.6 Fog warning for motor traffic

In motor traffic, visual-range determination by lidar is important for the following fields of application:

— stationary operation parallel to the roadway for speed limitation in areas with a high risk of fog;

— mobile application in vehicles to control the brightness of tail lights and rear fog lamps;

— mobile application in vehicles for fog bank warnings.

The number of accidents in fog has led to the provision of additional information about visual range to motorists. Speed limitations actuated by visibility sensors installed next to the road in areas with high fog risk are presently state-of-the-art[17][18][19]. Visual-range lidar can:

— replace visibility sensors,

— make a larger measurement volume possible,

— be built into vehicles in order to give warnings to fog banks and to determine their density, and

— be built into vehicles in order to control the brightness of rear lights depending on the detected visual range.

9 Signal evaluation

9.1 Klett-Fernald algorithm

It is the aim of the data evaluation process to determine the extinction of light through the atmosphere for every range interval. Only single scattering is taken into account when evaluating the lidar signals. The classical lidar Equation (2) and the lidar signature of Equation (4) contain two unknowns:

β backscattering coefficient;

α extinction coefficient.

To solve Equation (2) or Equation (4), different methods may be applied[20].

The inversion of the lidar equation described below is called the Klett-Fernald algorithm[21][22][23] It has been successful in visibility lidar because no knowledge of the system parameter $B(x)$ in Equation (4) is required. By differentiating the logarithmic signature $S(x)$, one obtains:

$$\frac{\partial \ln\left[S(x)\right]}{\partial x} = \frac{1}{\beta(x)} \frac{\partial \beta(x)}{\partial x} - 2\alpha(x) \tag{9}$$

A linear and range-independent relation of α and β is assumed in this part of ISO 28902 (see 5.2.5). In addition, Rayleigh scattering which contributes relatively little to the high extinction coefficients considered in this part of ISO 28902 is neglected, due to limitation to $V_{\text{MOR}} < 2\ 000$ m. With this simplification and with the assumption of an initial value $\alpha(x_\text{n})$ for the extinction coefficient α, the solution of differential Equation (9) is:

$$\alpha(x) = \frac{S(x)}{\dfrac{S(x_\text{n})}{\alpha(x_\text{n})} - 2\displaystyle\int_{x_\text{n}}^{x} S(\xi)\mathrm{d}\xi} \tag{10}$$

Due to the negative sign in the denominator, omnipresent photon noise, variations of $S(x_\text{n})$, as well as small uncertainties in the choice of $\alpha(x_\text{n})$, result in either absurdly large, oscillating or (meaningless) negative values of α.

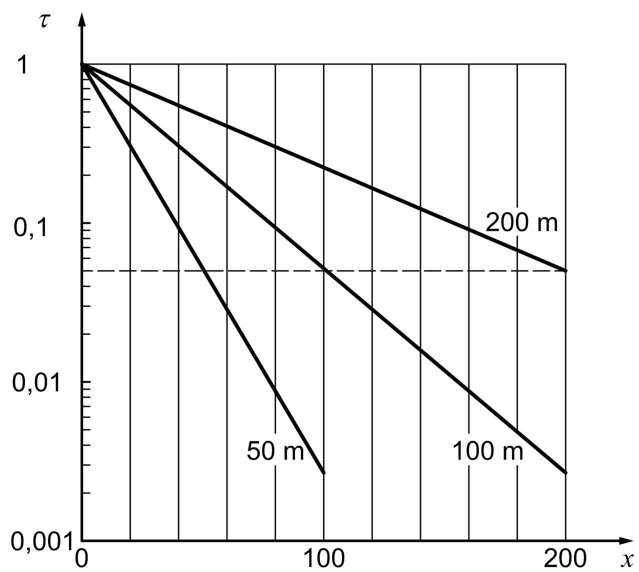
The solution is, thus, unstable and not suited for practical application. If the integration limits are interchanged, the minus sign in the denominator turns into a plus sign, and the difficulty of numerical instability is removed:

$$\alpha(x) = \frac{S(x)}{\dfrac{S(x_\mathrm{f})}{\alpha(x_\mathrm{f})} + 2\displaystyle\int_x^{x_\mathrm{f}} S(\xi)\,\mathrm{d}\xi} \tag{11}$$

Now, the initial value of α shall be determined at the remote end of the range x_f. This value, $\alpha(x_\mathrm{f})$, often can only be estimated. Annex A presents an example for the estimation of the initial value; A.8 shows a calculation example considering the uncertainty of MOR values retrieved by this algorithm.

9.2 Evaluation range

For a homogeneous atmosphere, a linear relation between range and logarithmic transmittance follows from Equation (3). The slope of the corresponding straight line is a measure of the average extinction and, thus, of the meteorological optical range (see Figure 6). With diminishing transparency of the atmosphere for light of the lidar wavelength, the distance up to which measured values are available for signal evaluation decreases and is of the same order as the meteorological optical range. The broken line in Figure 6 corresponds to the transmission for a contrast threshold value of $K' = 5$ %; it intersects the three slant lines at the abscissa $x = V_\mathrm{MOR}$, thus, illustrating this relation. At the same range resolution, fewer measured values are available for the determination of the gradient of the lidar signature of Equation (9) at a shorter visual range. On the other hand, the gradient and, thus, the accuracy with which MOR can be determined increases with decreasing visual range.



NOTE The broken line corresponds to $K' = 5$ %.

Figure 6 — Transmittance as a function of distance, displayed for three homogeneous atmospheres (V_MOR = 50 m, 100 m and 200 m)

9.3 Uncertainty

Table 2 compiles uncertainty contributions to the measurement variables and target variables. The uncertainty contributions of the measurement variables influence the target variables and the additional variables. The dominant uncertainties result from:

— the reference extinction value estimated during the evaluation according to the Klett-Fernald algorithm (see 9.1),

— the initial calibration process of the system by the manufacturer, and

— the prevailing environmental conditions.

Table 2 — Effects leading to uncertainty

Measurement variables	**Effects leading to uncertainty**
Power, P	— noise including photodetector noise
Range and background corrected signal, S	— background radiation estimation
Target variables and additional variables	**Uncertainty contribution**
Particle extinction coefficient, $\alpha(x)$	— far-range calibration value — molecular backscatter coefficient profile (T, P) — system parameter (e.g. receiver sensitivity, laser power) — effective range resolution
Gradient of the particle backscatter coefficient, $\mathrm{d}\beta/\mathrm{d}x$	— particle extinction coefficient $\alpha(x)$ — lidar ratio estimation (external contribution)
Meteorological optical range, V_{MOR}	— particle extinction coefficient $\alpha(x)$
Cloud base height	— particle extinction coefficient $\alpha(x)$ — threshold of the optical density (external contribution)
Boundary layer stratification	— gradient of the particle backscatter coefficient $\mathrm{d}\beta/\mathrm{d}x$ — calculation process, algorithms used, numerical assumption of the starting value

10 Interferences

The determination of visual range can be perturbed by inhomogeneities in atmospheric turbidity. Visual-range lidars cannot distinguish different components that affect visual range. Perturbations can have anthropogenic and natural origins such as:

— precipitation of any type (rain, hail, snow),

— emission from industrial plants and power stations: water either as vapour or condensed as clouds, aerosols or gases that absorb at the wavelength,

— volcanic ash, resuspended mineral dust.

Annex A
(informative)

Alternative data evaluation

A.1 General

Equation (4) allows the determination of range-resolved profiles of the atmospheric extinction coefficient α within the maximum range of a visual-range lidar. According to 6.3.7, the maximum range depends on atmospheric extinction.

The solutions of Equations (10) and (11) require the knowledge of the initial values of $S(x_\mathrm{n})/\alpha(x_\mathrm{n})$ or $S(x_\mathrm{f})/\alpha(x_\mathrm{f})$, respectively. These are generally not known because the extinction coefficients are unknown. Due to the limitations described in 9.2, the use of Equation (10), i.e. forward integration, is restricted to special cases. Backward integration [Equation (11)] offers much better stability and is, therefore, applicable to automated use. An algorithm suitable for such processing of the primary lidar data is described below. It essentially consists of six steps as described in A.2 to A.7.

A.2 Determination of the range of distances over which visual range is to be determined

Whereas the lidar onset distance is normally given by system parameters and does not vary much with meteorological conditions, the maximum distance which will usually coincide with x_f shall be determined from the properties (magnitude, signal-to-noise ratio) of the return signals $P(x, \alpha)$.

A.3 Determination of the initial value $\alpha(x_\mathrm{f})$ to be used in the evaluation of the first measurements of a series

A large value of $\alpha(x_\mathrm{f})$ corresponding to short visual range is used as the starting value to ensure numerical stability of the algorithm. Clearly, $\alpha(x_\mathrm{f})$ shall be within the limits of extinction coefficients that can be measured with the system. The shortest visual range that can be measured is determined by the number of measurement points, the longest by the laser power and size and sensitivity of the receiver and detection system and is a constant of the particular device.

A.4 Calculation of the profile of $\alpha(x)$

With the initial value $\alpha(x_\mathrm{f})$ determined according to A.3, the measured backscatter signal profile is used to calculate the profile of extinction coefficients $\alpha(x)$, or local visual-range values, within the limits (onset distance and maximum distance) determined by A.2.

A.5 Calculating the average visual range

The resulting individual local visual-range data are averaged; data corresponding to α values lower than the minimum detectable threshold of α are excluded.

A.6 Deciding about the quality of the intermediate result

The result is compared with the initial value. If the two differ (typically by ≥ 10 %), then the (new) average is used as the new initial value, and iteration is carried out as described in A.4. The procedure is repeated until either the agreement is sufficiently close (typically $<$ 10 %), or the loop has been called more often than the pre-set number of iterations.

A.7 Defining the final result and the starting value for the next measurement

If the conditions given in A.6 are met, the last profile is considered to be the result of the measurement. Its average visual range, or average extinction coefficient, is taken as the starting value for data evaluation of the following measurement, one measurement typically lasting between 1 s and 30 s. The starting point for the following data evaluation, thus, is again A.2 followed by A.4; A.3 is skipped.

Alternatively, the so-called “slope method” may be used (see Reference [20]). This method is based on the assumption of a series of intervals of homogeneous scattering coefficients β in Equation (9) and directly provides the corresponding profile of $\alpha(x)$. To increase the accuracy of this method, range intervals should be chosen as large as possible in order to be able to average over multiple measurement points (linear fit). The disadvantage of this method is, thus, given by the piece-by-piece homogeneous stratification, i.e. clouds and fog banks limit this method.

A.8 Calculation example

A.8.1 In order to demonstrate the dependency of Equation (11) from the estimated initial values of $\alpha(x_\mathrm{f})$, the following example of a simplified calculation is provided in Table A.1; it skips the steps described in A.5, A.6 and A.7. For this purpose, the following assumptions have been made:

a) the extinction coefficient $\alpha = 0{,}03\ \mathrm{m}^{-1}$ is constant in the atmosphere;

b) the boundary conditions for the integration process [Equation (11)] is set to $\alpha(x_\mathrm{f}) = 0{,}06\ \mathrm{m}^{-1}$ and $x_\mathrm{f} = 150$ m [corresponding to the basic assumption $\alpha(x_\mathrm{f}) > \alpha$, see A.3];

c) the effective range resolution is $\Delta x_\mathrm{eff} = 10$ m and is selected according to Table 1.

A.8.2 Given these assumptions, Table A.1 demonstrates the calculation procedure including the following steps:

a) the theoretical range-corrected lidar backscattering signal $S(x)$ is calculated according to Equation (4);

b) the extinction coefficient α is calculated according to Equation (11);

c) a local $V_\mathrm{MOR} = 3/\alpha$ is calculated from this retrieved extinction coefficient to show the maximum uncertainty of α and V_MOR;

d) the opacity $\int_0^x \alpha(\xi)\mathrm{d}\xi$ is calculated in the last column of Table A.1 and is equal to the left-hand side of Equation (6). It serves for comparison with the value of 3 resulting for $x = V_\mathrm{MOR}$.

The large discrepancy between the assumed extinction coefficient ($\alpha = 0{,}03\ \mathrm{m}^{-1}$) and the boundary condition of the integration process [$\alpha(x_\mathrm{f}) = 0{,}06\ \mathrm{m}^{-1}$] resulting in a minor relative uncertainty of $\Delta V_\mathrm{MOR}/V_\mathrm{MOR}$ after some meters of integration clearly shows the applicability of Equation (11).

Table A.1 — Calculation example for the extinction coefficient and meteorological optical range

x m	Assumed V_{MOR} m	Assumed α m^{-1}	$S(x)$ calculated according to Equation (4) a.u.	$\alpha(x)$ calculated according to Equation (11) m^{-1}	V_{MOR} from retrieved α m	$\Delta V_{MOR}/V_{MOR}$ %	Opacity $\int_0^x \alpha(\xi)d\xi$
10	100	0,030	2,99E-04	0,029	103,0	3	0,29
20	100	0,030	1,64E-04	0,029	103,0	3	0,58
30	100	0,030	9,02E-05	0,029	102,9	3	0,87
40	100	0,030	4,95E-05	0,029	102,9	3	1,17
50	100	0,030	2,72E-05	0,029	102,9	3	1,46
60	100	0,030	1,49E-05	0,029	102,8	3	1,75
70	100	0,030	8,18E-06	0,029	102,6	3	2,04
80	100	0,030	4,49E-06	0,029	102,3	2	2,33
90	100	0,030	2,46E-06	0,029	101,7	2	2,63
100	100	0,030	1,35E-06	0,030	100,7	1	2,93
110	100	0,030	7,42E-07	0,030	98,9	−1	3,23
$x_f = 150$ (boundary condition)	50	$\alpha(x_f) = 0,060$	7,39E-08	0,060	50,0		
a.u. arbitrary units							

Annex B
(informative)

Calibration by the manufacturer

B.1 General

The calibration of the system and the equivalency testing should be done by the manufacturer. The manufacturer should test the lidar systems under laboratory conditions (called “laboratory tests”, see B.2) as well as under field test conditions (called “field tests”, see B.3). The manufacturer should guarantee that tests performed according to B.2 are sufficient to qualify the visual-range lidar.

The manufacturer should make sure that the equipment is subject to an automatic check at regular intervals (at least every 10 min). This check should include laser monitoring to ensure permanent eye-safe operation; this also applies to rotating laser-head devices which possibly require additional safety procedures.

B.2 Laboratory tests

B.2.1 General

These tests are performed once by the manufacturer.

B.2.2 Basic tests

The manufacturer should test the following parameters for each instrument and should deliver a test report with each instrument including these parameters:

a) output power and pulse repetition frequency of the laser source;

b) alignment quality parameters: maximum uncertainty of divergence, deviation of the inclination angle against external reference (e.g. housing), minimum range (see 6.3.7), and maximum range (see 6.3.7);

c) signal output of the data acquisition system reacting on a defined light pulse or defined target resulting in range accuracy and receiver sensitivity.

B.2.3 Advanced tests

Depending on the instrument class, the following additional parameters should be tested:

a) signal output of the system by shooting to standard reflection targets[6] at a given time interval (10 s) and defined distance: the distance depends on the instrument class and can differ between 30 m and several kilometres;

b) signal output from cloud chamber measurements can be necessary for qualification (calibration and quality assurance) of certain types of sensors; in the cloud chamber, a transmissometer has to be integrated as a reference.

B.3 Field tests

Field tests are tests in a natural environment under special weather conditions. For this purpose, a test site with well defined equipment is needed. These tests should be performed by the manufacturer at least for each series. Additionally, it is recommended to perform these field tests once a year. The choice of the suitable

6) Standard reflection target with a reflectivity between 5 % and 10 % within the wavelength range UV to 1,6 μm.

field test method depends on the measurement task (e.g. traffic safety, see also the scope of this document). Especially for large systems, a combination of these field tests should be performed.

A document listing the results of the field tests should be given to the user on request. The contents of that document depend on the measurement task and the kind of tests.

a) *Video camera*: A comparison of a video clip or a photo showing the environmental conditions in a fog event and the calculated MOR of the sensor is sufficient for horizontally measuring systems (e.g. traffic safety market).

b) In-situ *transmissometer and forward scatter meters*: These are ideal instruments to use to compare calculated MOR values of horizontally aligned visual-range lidar.

   In order to compare instruments, only homogenous conditions should be taken into account. This homogeneity can be tested by calculating the ratio of the standard deviation of MOR to the mean value of MOR, over a 10 min period. If the ratio is lower than 0,1, then the conditions are considered to be homogenous[8].

c) *Reference lidar*: This is a good choice for comparing the VOR or SOR values measured by the visual-range lidar if the reference lidar can perform direct extinction measurements. It has to be verified that the reference is using the same wavelength or is using multiple wavelengths to allow an extrapolation to the wavelength of the visual-range lidar. Furthermore, optical parameters like overlap function have to be at least in a fixed relation to allow comparisons.

d) *Tethersondes and/or backscatter sondes on balloons*: These are used to compare the measured VOR of the visual-range lidar with humidity or aerosol parameters in the atmosphere.

Annex C
(informative)

Further applications

The measurement of visual range for $V_{MOR} \leq 2\ 000$ m in fog and mist by the elastic-backscatter lidar technique is described in this document. Other existing types of lidar techniques include the following:

— wind profiling by Doppler lidar[24];

— concentration measurement of water vapour by Raman lidar[25] (other trace components can also be detected);

— specific gas concentration measurements by DIAL (Differential Absorption Lidar)[26];

— extinction and backscatter profile measurement by Raman lidar[25] or HSR lidar[13][14];

— aerosol characterization by multiwavelength lidar[25][27];

— temperature profiling by Raman lidar[25];

An overview of these techniques is given in References [25] and [28]. These techniques are out of the scope of this part of ISO 28902.

In addition to what is described in this document, elastic-backscatter lidars are used for other purposes as well, that also include $V_{MOR} > 2\ 000$ m. They can be used for the detection of the vertical structure of the atmosphere characterized by aerosols or cloud layers. Cloud bases and, in some cases, cloud tops can be detected, e.g. for high-altitude optically thin clouds called cirrus. Most lidars use a threshold criterion in order to identify cloud base(s) and the vertical structure of the boundary layer. Several methods exist as the primary derivative techniques or, more recently, the lidar signal wavelet analysis[29].

For steerable lidars, pollution plumes can be monitored with good accuracy, depending on the aerosol density within the plume and on the angular resolution of the scanning device. Any diffuse or direct source emitted by an industrial plant or transport node, as examples, could be surveyed.

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