White Paper
Visibility Monitoring

Brief explanation of photometry
for the application of visibility monitoring in tunnels

1 General

This document gives a brief explanation of photometry and its application in monitoring the visibility in tunnels.

After an overview of photometry basics, the document discusses photometer technology and practical issues of measuring visibility with photometers in tunnel environments.

2 Photometry

2.1 Lambert-Beer Law

The **Lambert-Beer Law** relates the attenuation of light to the properties of the material through which the light is travelling. It describes a logarithmic dependence between the transmittance *T* of light through a substance and the product of the Attenuation Coefficient of the substance *α* and the distance the light travels through the material (i.e. the path length) *d*.

$$T = \frac{I}{I_0} = e^{-\alpha \cdot d} = e^{-\sigma \cdot n \cdot d}$$

T … Transmittance
I … Intensity of transmitted light
I_0 … Intensity of incident light
α … Attenuation Coefficient
d … Path length
σ … Total Cross Section
n … Number density (here: particle concentration)

2.2 Absorption & Scattering

2.2.1 Absorption, Absorbance & Attenuance

Absorption is the attenuation of light when passing through a **clear medium**. If light is passed through a sample, part of the energy is transmitted to the molecules. As a result, the exiting beam has less intensity *I* than the incident beam I_0. The amount of light absorbed generally follows the Lambert-Beer Law and is therefore proportional to the path length traversed *d*. Absorption highly depends on the wave lengths of the light passing through the medium; the Attenuation Coefficient is a function of the wave length.

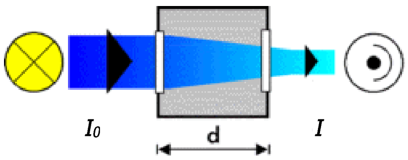

Figure 1 - Absorption by a clear medium

The term Absorption refers to the physical process of absorbing light, while **Absorbance** refers to the mathematical quantity.

If light passes through a **turbid medium**, i.e. a medium containing particles, light is not only attenuated by absorption but also by scattering (see chapter 2.2.4). In such cases it is recommended to use the term **Attenuance** (formerly called **Extinction**) instead of Absorption to indicate that losses due to scattering are also considered.

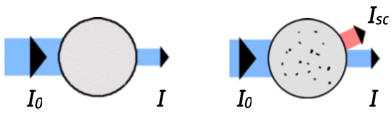

Figure 2 - Absorbance in clear and Attenuance in turbid medium

The **Spectral Attenuance** (also Absorbance or Extinction) *A(λ)* is the fraction of light attenuated at a specific wave length *λ*.

$$A(\lambda) = -\ln\frac{I(\lambda)}{I_0(\lambda)} = -\ln T(\lambda) = \alpha(\lambda) \cdot d = \sigma(\lambda) \cdot n \cdot d$$

λ … wave length

Spectral Attenuance is displayed by most photometers although the photometer actually measures the Transmittance.

2.2.2 Transmission, Spectral Transmittance & Opacity

Transmission is the property of a substance to permit the passage of light, with some or none of the incident light being absorbed. If some light is absorbed by the substance, the transmitted light will be a combination of the wave lengths of the light that was transmitted and not absorbed. For example, a blue light filter appears blue because it absorbs red and green wave lengths. If white light is shone through the filter, the light transmitted also appears blue because of the absorption of the red and green wavelengths.

Spectral Transmittance *T(λ)* describes the fraction of incident light at a given wave length $I_0(\lambda)$ that passes through a sample; losses by absorption and scattering are considered.

$$T(\lambda) = \frac{I(\lambda)}{I_0(\lambda)} = e^{-A(\lambda)} = e^{-\alpha(\lambda)\cdot d}$$

Opacity *O(λ)* is the measure of impenetrability of a substance to light. It describes the absorption and scattering of light by a medium. An opaque object is neither transparent (allowing all light to pass through) nor translucent (allowing some light to pass through).

$$O(\lambda) = \frac{I_0(\lambda)}{I(\lambda)} = \frac{1}{T(\lambda)}$$

2.2.3 Attenuation Coefficient & Cross Section

The **Attenuation Coefficient** (also: **Extinction Coefficient**) describes the extent to which the intensity of a light beam is reduced as it passes through a specific medium. A small Attenuation Coefficient indicates that the medium in question is relatively transparent, while a larger value indicates greater degrees of opacity.

The terms Attenuation Coefficient and **Absorption Coefficient** are generally used interchangeably but differ in the application of measuring the transmittance. When a narrow beam of light passes through a medium, the beam will lose intensity by two processes: The light can be absorbed by the medium, or the light can be scattered (i.e., the photons can change direction) by the medium. Just looking at the narrow beam itself, the two processes cannot be distinguished. However, if a detector is set up to measure light leaving in different directions, one can measure how much of the lost intensity was scattered, and how much was absorbed.

In this context, the Absorption Coefficient measures how quickly the beam would lose intensity due to absorption alone, while Attenuation Coefficient measures the total loss of narrow-beam intensity, including scattering as well. The Attenuation Coefficient is always larger than the Absorption Coefficient, although they are equal in the idealised case of no scattering.

The **Spectral Attenuation Coefficient** *α(λ)* allows to express the attenuation of light through a given medium at a given wave length without the need to specify the path length.

$$\alpha(\lambda) = \frac{A(\lambda)}{d}$$

The **Total Cross Section** *σ(λ)* refers the spectral Attenuation Coefficient to the concentration of a substance along the path *d* with the concentration being expressed as a number density *n*. Cross Sections are hypothetical areas that describe the probability of light being absorbed, or scattered by a particle. The Total Cross Section is the sum of the Cross Sections due to absorption σ_{Ab} and scattering σ_{Sc}, and it is an intrinsic property of a substance.

$$\sigma(\lambda) = \sigma_{Ab}(\lambda) + \sigma_{Sc}(\lambda) = \frac{\alpha(\lambda)}{n} = \frac{A(\lambda)}{n \cdot d}$$

σ_{Ab} … *Absorption Cross Section*
σ_{Sc} … *Scattering Cross Section*

The actual attenuance is determined by the product of the Total Cross Section *σ* and the number of particles present which is again a product of the number density *n* (i.e. the particle concentration) and the path length *d*.

$$A(\lambda) = \alpha(\lambda) \cdot d = \sigma(\lambda) \cdot n \cdot d$$

2.2.4 Light scattering

Light scattering is a form of scattering in which light is the form of propagating energy which is scattered. Light scattering can be thought of as the deflection of a narrow beam from a straight path, for example by irregularities in the propagation medium, particles, or in the interface between two media.

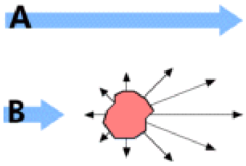

Figure 3 - Light scattered by an obstacle

Only in an optically homogenous medium (with constant refractive index and absorption), the light progresses in a straight line. Actually, this is only the case in vacuum. Any change in the optical properties will deflect the light beam from its path. This physical process, which is referred to as the scattering of light by particles, causes the phenomenon of turbidity.

Most objects that we see are visible due to light scattering from their surfaces. Indeed, this is our primary mechanism of physical observation. Scattering of light depends on the wave length of the light being scattered. Since visible light has a wave length on the order of a micrometre, objects much smaller than this cannot be seen.

One process taking place when light is scattered is diffraction, and another is the excitation of radiation. Diffraction occurs because of the light's wave character: if a wave passes an obstacle in the immediate vicinity, it will be deflected from its path. The deflection angle depends on the relation between the wavelength and the size of the obstacle. The second process occurs because the atoms are excited, i.e. raised to higher energy levels, to radiate off the light that has struck them. This light will be radiated in various directions, depending on the particle characteristics, in accordance with the laws of light refraction, reflection, and dipole radiation.

Figure 4 illustrates the variables affecting the intensity of the scattered light I_{Sc}. The incident light beam I_{inc} of wave length λ impacts a spherical particle with diameter d and refractive index n. The light is scattered in various angles. A certain intensity of light is scattered in direction of the angle Θ.

Explicit formulation of the relations is subject of the scatter theory which shall not be touched here.

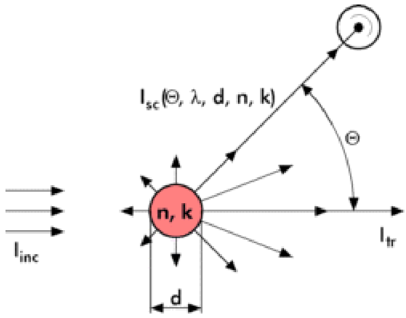

Figure 4 - Intensity of scattered light

2.3 Visibility

Visibility is a measure of the distance at which an object or light can be clearly discerned. Scattering and absorption reduce the contrast of an object against its background. This phenomenon is called light attenuation.

To define visibility, we examine a perfectly black object being viewed against a perfectly white background. The **Visual Contrast** $C_V(x)$ at the distance x from the black object is defined as

$$C_v(x) = \frac{I_b(x) - I(x)}{I_b(x)}$$

C_V … Visual contrast
I … Intensity of transmitted light
I_b … Intensity of background

Because the object is assumed to be perfectly black, it must absorb all of the light incident on it. Thus when $x = 0$ (at the object), $I(0) = 0$ and $C_V(0) = 1$.

Between the object and the observer, $I(x)$ is affected by additional light that is scattered into the observer's line of sight and the absorption of light by gases and particles.

Light scattered by particles outside of a particular beam may ultimately contribute to the irradiance at the target, a phenomenon known as multiple scattering. Unlike absorbed light, scattered light is not lost from a system. Rather, it can change directions and contribute to other directions. It is only lost from the original beam traveling in one particular direction. The multiple scattering's contribution to the irradiance at x is modified by the individual particle scattering coefficient, the number concentration of particles, and the depth of the beam.

The intensity change *dI* is the result of these effects over a distance *dx*. Because *dx* is a measure of the amount of suspended gases and particles, the fraction of *I* that is diminished is assumed to be proportional to the distance, *dx*. The fractional reduction in *I* is

$$dI = -\alpha \cdot Idx$$

α is the Attenuation Coefficient.

The scattering of background light into the observer's line of sight can increase *I* over the distance *dx*. This increase is defined as $\alpha' I_b(x)$ dx, where *α'* is a constant. The overall change in intensity is expressed as

$$dI(x) = [\alpha' I_b(x) - \alpha I(x)]dx$$

I_b represents the background intensity and is independent of *x* by definition. Therefore

$$dI_b(x) = 0 = [\alpha' I_b(x) - \alpha I_b(x)]dx$$

It is clear from this expression that *α'* must be equal to *α*. So the visual contrast obeys the Beer-Lambert law (see chapter 2.1)

$$\frac{dC_v(x)}{dx} = -\alpha \cdot C_v(x)$$

This means that the visual contrast decreases exponentially with the distance from the object.

$$C_v(x) = e^{-\alpha \cdot x}$$

Lab experiments have determined that contrast ratios between 0,018 and 0,03 are perceptible under typical daylight viewing conditions. A contrast ratio of 2 % (C_v = 0,02) is usually used to calculate visual range.

Plugging this value into the above equation and solving for x produces the following visual range expression (the Koschmieder equation):

$$x_v = \frac{3{,}912}{\alpha}$$

2.4 Summary

Light passing through a medium is attenuated by the effects of absorption and scattering. Both effects influence the visibility and can be used to measure the degree of this influence which for the application of measuring visibility in a tunnel is usually expressed by the Attenuation Coefficient (also known as: Extinction Coefficient).

3 Photometers

In the broadest sense, a photometer is an instrument used to measure the intensity of light or optical properties of solutions or surfaces.

This covers the measurement of

- Luminance
- Illuminance
- Irradiance
- Light absorption
- Scattering of light
- Reflection of light
- Fluorescence
- Phosphorescence
- Luminescence

Light absorption and scattering are the principles used to measure the turbidity of gases like air and derived therefrom the visibility. The objective is always to expose the medium in question – in the tunnel that is usually the air – to light and then to measure the intensity of the light produced by the respective phenomenon.

This chapter describes the different methods practically used, their characteristics, advantages and disadvantages.

3.1 Single vs. dual beam methods

3.1.1 Single beam method

The light source (L) transmits a light beam through the medium in the flow cell (M) and the photo receiver (Ph) measures the intensity of the remaining light. After being amplified in the amplifier (V), an electrical signal is delivered as the attenuance reading.

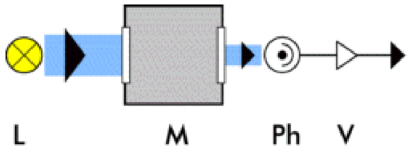

Figure 5 - Single beam method

The purpose of the measurement is to detect how much the light intensity is attenuated by the substance in the flow cell. Besides this sought variable, however, the reading will also be affected by the luminosity of the light source (L) and the sensitivity of the photo receiver (Ph). Because the properties of these components vary as a result of aging and fluctuations of the supply voltage and the ambient temperature, single-beam photometers are inherently unstable and require frequent recalibration.

This may be feasible for intermittent measurements in the laboratory, but it is clearly unacceptable for industrial duty and continuous measurement. One way to eliminate the effect of light source fluctuations is to use the dual-beam method.

3.1.2 Dual beam method with 2 photo detectors

With this configuration, a semi-transparent mirror produces two beams: a measurement beam (M), which passes through the sample and strikes the first photo detector, and a reference beam (V) that goes straight to the second receiver.

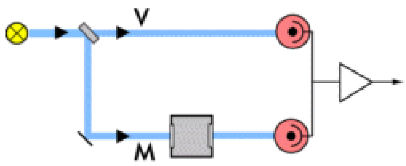

Figure 6 - Dual beam method with 2 photo detectors

Because the reading represents the ratio of the two, fluctuations of the light source's luminosity have no effect on the results. But the changing sensitivity of the two photo detectors remains as source of error. It makes these dual-beam photometers, too, unstable over the long term and necessitates frequent recalibration.

3.1.3 Alternating light, dual beam method

The optimal solution is to use two beams and just one photo detector.

Here again the reading is arrived by forming the ratio between the measurement and reference beams. This method can be illustrated by a rotating disk, or "chopper", that lets the two beams alternately pass to the same photo detector. As a result, both the luminosity fluctuations of the light source and any changes in photo detector's sensitivity are eliminated as sources of error. Alternating light, dual beam photometers are stable over their entire service lives and generally require no recalibration.

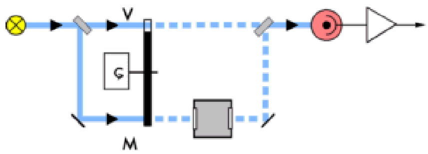

Figure 7 - Alternating light dual beam method

3.2 Transmission vs. scattered light

The objective of measuring the visibility is to obtain information on the concentration of scattering particles in a medium. This can be done by either of two fundamentally different methods:

- determination of the light loss of the transmitted beam or
- determination of the intensity of the light scattered sideways.

The methods mainly differ in their applicability at various concentration levels. Measurement of the scatter intensity permits the detection of lower concentrations, while transmission measurement is used for higher concentrations.

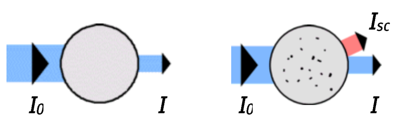

Figure 8 – Transmission vs. scattered light

Devices using either method are available on the market to monitor the visibility in tunnels.

3.2.1 Transmissiometers

Transmissiometers detect the spectral transmittance T_λ for the wave length λ used by the built-in light source over the measuring path *d*.

$$T_\lambda = \frac{I}{I_0} = e^{-\alpha(\lambda)\cdot d}$$

Figure 9 - DURAG DR-220 T Transmissiometer

From the spectral transmittance measured the Attenuation Coefficient $\alpha(\lambda)$ is calculated.

Given that the light loss through concentration of particles in the air to be measured is relatively low such devices need a substantial path length of at least 15 to 30 m to achieve a sufficient precision.

Transmissiometers usually consist of a pair of devices, one of which being the light source and detector (transceiver), the other just being a reflector to double the path length. This setup requires a precise installation and alignment in the tunnel. Besides a direct line of sight is required that must not be interfered by traffic.

By their nature such transmissiometers can only implement the single beam method (see chapter 3.1.1) as the beam can only be sent through the medium to be measured.

Popular devices for tunnel applications are:

- DURAG D-R 220T
- SICK Vicotec 410 Series
- TunnelSensors VICONOX and VIPA-L
- CODEL TunnelTech 100 and 200 series

3.2.2 Scattered light photometers

Figure 10 - SIGRIST VisGuard in-situ scattered light photometer

Instead of measuring the transmittance over a certain distance scattered light photometers measure the intensity of the light scattered sideways by the illuminated dust particles. This method does not need a long measuring distance, measurement can take place right inside the instrument.

The instrument can be installed directly in the tunnel (in-situ setup), or using an intake system it can be located at an easily accessible spot outside the tunnel's driving area (extractive setup) like a niche, crosscut or operating room. In an extractive setup an intake switch unit can be installed to analyse air from several intake points with one photometer.

Pre-heating the air before it is analysed allows to eliminate influences of fog and moisture on the reading.

Scattered light photometers can implement every method described in chapter 3.1.

Popular devices for tunnel applications are:

- SIGRIST VisGuard
- SICK VISIC 100 SF
- SICK Vicotec 450 Series

3.3 Practical issues

3.3.1 Calibration & reading of scattered light photometers

Detection of the scattered light intensity permits the measurement of low dust concentrations in air. Scattered light photometers do not detect the attenuation of light directly and such cannot directly display the Attenuation Coefficient. The quantity measured by the photometer is an equivalent concentration of a defined substance the attenuation of which is known.

In case of the SIGRIST VisGuard the instrument displays an equivalent concentration of PLA. PLA stands for polystyrene-latex aerosol which is used for the calibration of the instrument. It contains spheroidal particles with a diameter of 1 µm. The photometer measures the intensity of light scattered by a sample and expresses the equivalent concentration of the PLA aerosol that would have caused the same intensity of scattered light (0 … 100 PLA). The measured PLA equivalent concentration together with the Total Cross Section of PLA (see chapter 2.2.3) for the wave length of the light used for measuring allows the calculation of the spectral Attenuation Coefficient (see chapter 3.3.4).

Generally the relation between the attenuation of light and the particle concentration in a medium is influenced perceptibly by the light-scattering properties of the solid particles. The quantity of scattered light depends not only on the concentration, but also on the particle size and the ratio of the refractive indices of the particles and the medium. The more the particles differ from the medium (i.e. the more their refractive indices differ), the more light will be scattered by the particles.

3.3.2 Contamination, ageing & recalibration

Whenever optics are exposed to polluted air they are over the time contaminated by particles which adhere to their surfaces. This **contamination** substantially influences the measuring result of photometers described here.

Manufacturers of photometers deal with contamination in three ways:

- Constructive measures (usually mechanical) to avoid contamination
- Measures to compensate the measuring results for contamination
- Recalibration

Examples for constructive measures to avoid contamination are dust protection tubes usually employed by transmissiometers or flow concepts in scattered light photometers where a part of the inducted air is filtered and then used to envelope the sample air in a protective shroud of clean air such that the optics do not get in contact with the sample air itself.

However none of the constructive measures can totally avoid contamination. So the measuring results have to be compensated for contamination. This can be done by measuring the effects of contamination on a clean sample. A clean sample, i.e. unpolluted air, should indicate a defined attenuation or scattering.

For transmissiometers – which by their nature can only employ a single beam method – a compensation is implemented by determining a reference Attenuation Coefficient at times without traffic present in the tunnel and consider this value as “clean air”.

Dual beam methods are modified such that the optics in the reference beam (V) suffer from the same contamination as in the measurement beam (M). This is achieved by passing the sample air through a compensation cell in the reference beam. This cell needs to be shorter than the flow cell. The effective photometric path length *d* is then the difference between the two path lengths.

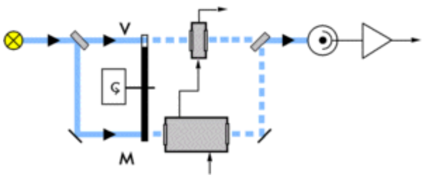

Figure 11 - Dual beam method with compensation of contamination

The term **Ageing** covers several effects that influence measuring results over the time, e.g. light sources losing their original luminosity, photo receivers losing sensitivity, etc.

Some of the ageing can be compensated in operation by using dual beam methods as described before. The SIGRIST VisGuard photometer for example employs a variation of the alternating light, dual beam measuring method. It determines the relation between the light scattered at a 30° angle and the directly transmitted light and so elegantly eliminates the effects of any light source fluctuations as well as ageing or temperature effects of the electronics.

However from time to time every instrument used in a tunnel environment needs recalibration and maintenance to achieve reliable measuring results in the long term. **Recalibration** is the adjustment of the reading on a measurement instrument to agree with the value of an applied standard, within a specified accuracy. For photometers usually a medium with a defined attenuation is inserted in the measurement path and the reading is adjusted to match this defined attenuation.


Figure 12 - VisGuard recalibration plug

The VisGuard photometer is provided with a recalibration plug with a glass of certain refractive index the PLA equivalent of which is measured with the just factory calibrated photometer. This plug can later be used to recalibrate this photometer to the plug's PLA value. By manufacturing tolerances of the port the plug is inserted the PLA value of the plug is different for every single photometer. However the PLA value of one recalibration plug can be measured for several photometers during factory calibration. In such case on the recalibration plug one PLA value is stated per photometer serial number.

Manufacturers of transmissiometers usually also use a glass of defined attenuation that is inserted into the measurement path. Given that the measurement path is around 20 m long recalibration by inserting a glass in the measurement path also requires "clean air" in the tunnel which can only be achieved without any traffic present.

3.3.3 Accuracy and precision of visibility measurement

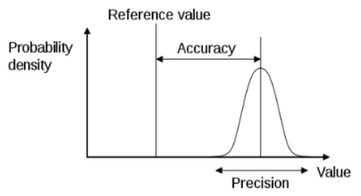

Figure 13 - Accuracy and precision

The **accuracy** of a measurement system is the degree of closeness of measurements of a quantity to that quantity's actual (true) value. The **precision** of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results. Although the two words precision and accuracy can be synonymous in colloquial use, they are deliberately contrasted in the context of the scientific method. A measurement system can be accurate but not precise, precise but not accurate, neither, or both.

Generally an instrument is calibrated in the factory and its manufacturer may specify a certain accuracy against the reference values used during the calibration process. However contamination and ageing have an impact on the accuracy. Accuracy is best retained over the time by measures to compensate these effects. However it is clear that the accuracy of an instrument in the field will always suffer over the time. Accuracy can only be restored by recalibration and maintenance, though not always to its initial level.

Precision indicates how reliable the applied measuring method delivers equal results under the same conditions. In the context of visibility monitoring in tunnels – more than the accuracy – it is a measure for the quality of the measurement system used.

3.3.4 Relation between instrument reading and the Attenuation Coefficient

For tunnel applications the Attenuation Coefficient has established as the measure for visibility with a typical measuring range of 0 to 0,015 m^{-1}. None of the applied measurement methods is able to directly measure this coefficient, so it needs to be calculated from the actual reading of the instrument.

Transmissiometers measure the Transmittance along a measuring path using a light source of known wave length. Thus, applying the formulas from chapter 2.2.1 and 2.2.3 the Attenuation Coefficient is calculated by

$$\alpha = \frac{A}{d} = \frac{-\ln T}{d}$$

α	T (d = 1 m)	T (d = 10 m)	T (d = 20 m)
0,000	100,000%	100,000%	100,000%
0,001	99,900%	99,005%	98,020%
0,002	99,800%	98,020%	96,079%
0,003	99,700%	97,045%	94,176%
0,004	99,601%	96,079%	92,312%
0,005	99,501%	95,123%	90,484%
0,006	99,402%	94,176%	88,692%
0,007	99,302%	93,239%	86,936%
0,008	99,203%	92,312%	85,214%
0,009	99,104%	91,393%	83,527%
0,010	99,005%	90,484%	81,873%
0,011	98,906%	89,583%	80,252%
0,012	98,807%	88,692%	78,663%
0,013	98,708%	87,810%	77,105%
0,014	98,610%	86,936%	75,578%
0,015	98,511%	86,071%	74,082%

Figure 14 - Influence of path length on Transmittance

Figure 14 shows the values of Transmittances for different path lengths corresponding to Attenuation Coefficients within the typical measuring range. It is clear that an Attenuation Coefficient of zero (i.e. for "clean air") always converts into a Transmittance of 100 %. However, the path length highly influences the Transmittance of polluted air. So, path length needs to be chosen in a way that the transmittance difference versus clean air is scaled sufficiently for a precise reading of the instrument.

Some manufacturers specify the **accuracy** and **precision** of their instruments in percent of the Transmittance or Opacity as these are the immediate readings of the measuring method. Because of the logarithmic relation between the Attenuation Coefficient and the Transmittance these specifications need to be converted.

Example: *Accuracy ± 1,35 % Transmission*

At the end of the measuring range with an attenuation coefficient α = 0,015 m^{-1} using a path length of 20 m the transmittance T = 74,082 %. Considering an error of 1,35 % this means T' = 72,731 % and T'' = 75,431 %. The corresponding Attenuation Coefficients being α' = 0,0159 m^{-1} and α'' = 0,0141 m^{-1}.

$$f_\alpha = \frac{\alpha' - \alpha}{\alpha} = \frac{0{,}0159 - 0{,}0150}{0{,}0150} = 6\%$$

So the accuracy with regard to the Attenuation Coefficient is only ± 6 %.

Scattered light photometers measure the scattered light intensity of a sample and read the equivalent concentration of a reference substance that would cause the same intensity of scattered light. Together with the Total Cross Section of the reference substance (see chapter 2.2.3), which is a constant for this substance and the wave length used for measuring, the Attenuation Coefficient can be calculated by

$$\alpha = \sigma \cdot n$$

The relation between the concentration (number density) and the Attenuation Coefficient is linear; thus accuracy and precision of the instrument reading are identical to accuracy and precision of the Attenuation Coefficient.

4 Summary

The task of monitoring the visibility in tunnels involves photometers utilising different measuring methods that generally either

- determine the loss of light of a narrow beam (Transmissiometers) or
- determine the intensity of light scattered at a certain angle (Scattered light photometers).

Whereas the application of Transmissiometers is the classical approach to visibility measurement Scattered light photometers show advantages in the tunnel environment including:

- One device vs. transceiver and reflector that have to be precisely aligned
- Effective compensation of contamination and ageing by employing dual beam method
- Easy compensation of fog by pre-heating of sample air (where indicated)
- Linear relation between instrument reading and visibility measure