# SICK AG
# WHITE PAPER

## VISIBILITY MEASUREMENT IN TUNNELS –
## ADJUSTMENT OF VISUAL RANGE MEASUREMENT VALUES

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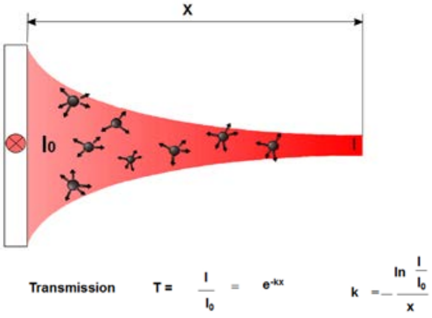
## Introduction

In modern tunnels, the switch from sodium-vapor lamps to halogen or LED lamps as light sources have changed the prevailing light spectra from a more long-wavelength range (red or orange) to a more short-wavelength range with high proportions of blue light. For tunnel users, this has improved their subjective perception of visibility. However, the change in the type of lighting has also changed their perception of obscuration. Particles cause obscuration in tunnels. The measuring devices used to detect the k coefficient in tunnels usually measure in the long-wavelength or infrared range. This leads to a difference between the visibility perceived by tunnel users and the k coefficients detected by the measuring devices. In this white paper, SICK AG presents correction factors for adjusting the wavelength for visibility measuring devices. Moreover, it aims to fuel a discussion with regard to defining a measurement for visibility in the wavelength range around 520 nm.

## Actual visual range in contrast to the k coefficient



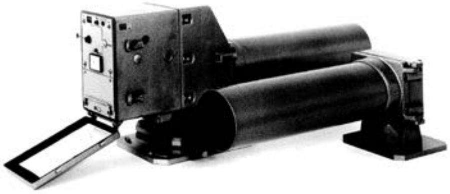
When determining the visual range, there are many influencing factors, such as tunnel lighting, vehicle lighting, and of course the people themselves. These influencing factors are not constant, but rather often result in deviations between the visibility detected by measurement technology and the visual range actually perceived in tunnels. Calculation of the standard visual range can produce more or less usable results in measurements performed in the open (outside the tunnel), according to Koschmieder or in daylight in foggy conditions. This is however not the case in a tunnel.

This is one of the main reasons why the standard visual range in a tunnel is not calculated using transmissometer data, but the so-called k coefficient is determined instead. The absorption coefficient or k coefficient denotes an optical characteristic of the air in a tunnel.

Another reason to output the k coefficient and not the standard visual range is the significantly more linear allocation of air pollution. This allows the fresh air required for tunnel ventilation to be calculated easily. The dust pollution, which is of paramount importance when it comes to visibility in a tunnel, gives a good overall idea of the total pollution level in the tunnel. For these reasons, the k coefficient is also considered to be more of a pollutant concentration indicator. It has an indirect connection to the actual visual range in a tunnel.

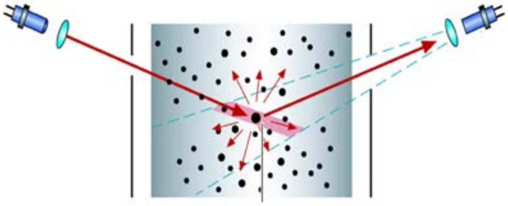
## Wavelength dependence of the k coefficient

Tunnel sensors such as the VICOTEC410 from SICK AG detect transmission expressed as T. This can be directly converted to the k coefficient using the Beer–Lambert law.

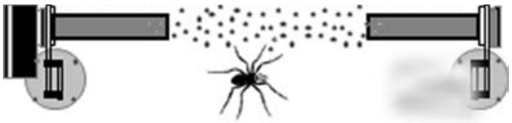


Measurement of the k coefficient in tunnels using LED technology in the near-infrared range caught on in the 1990s. Thanks to their reliability, LED lamps were quickly favored over the incandescent lamps used up until that point. Measurement in the near-infrared range produced slightly lower k coefficients. Tunnel operators therefore adjusted the switching thresholds to local conditions during trial operations.

## Correlation between scattered light and transmission



The use of transmission-based measuring devices for measurement of the k coefficient in tunnels comes with some disadvantages. Such devices require a long measuring distance to work effectively. Due to the length of the measuring distance, it is not possible to filter out influencing factors such as fog or spiders from the measuring path. Furthermore, mounting and correctly aligning a sender unit and a reflector unit in a tunnel are not easy.



It is for this reason that scattered-light-based measuring devices are favored for use in tunnels. Scattered-light-based measuring devices work with very small measuring volumes. Suitable covers can protect the measuring volume from interference through objects and living things (insects, birds, etc.). Cross sensitivity to fog can also be eliminated by heating the measuring device. These measuring devices do not measure the visual range or transmission directly, but rather detect the light scattered by particles. When measuring scattered light, Mie scattering plays a key role. This is dependent on the wavelength used, the size distribution of particles, and the type of particles. Strictly speaking, the values measured by scattered light measuring devices only apply to a certain type of dust. For determining a calibration function for a scattered light measuring device for use in a tunnel, it is therefore important to carry out the measurements with a stream composition found in tunnels. This can only really be done in a reference tunnel. Industrial “standard dust” can differ considerably from dust distributions present in tunnels and is therefore not suitable.

## Adjustment of measuring devices to detect the k coefficient

At SICK AG, transmissometers are adjusted using gray lenses. These weaken the emitted light in a defined manner. The weakening factor of each gray lens is applied for a specific wavelength by means of a laboratory spectrometer.

Scattered light measuring devices are synchronized with transmission-based measuring devices in a real tunnel with real tunnel dust. Here, the scattered light intensity of particles in the tunnel air is correlated with the k coefficient determined using the transmission-based measurement.

This synchronization step produces a device-specific calibration function. The adjustment of scattered light measuring devices is then based on synchronized diffusers. The scattering values of these diffusers also correlate with a k coefficient detected by a transmissometer.

## Lack of standardization in terms of the wavelength for detecting the k coefficient

There is no stipulation as to the wavelength to be used for detecting the k coefficient in a tunnel.

Manufacturers of visibility measuring devices therefore use different approaches, meaning that measuring devices from different manufacturers produce different results under the same conditions in a tunnel.

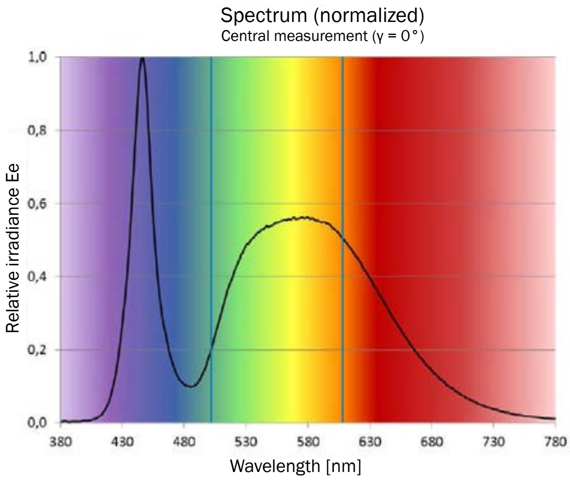
It is common for users to adjust the thresholds to the actual conditions of the respective tunnel, but this is not an easy task. With this experiment, SICK AG would like to provide users with information regarding this adjustment.

For SICK AG, this experiment is also explicitly intended to fuel the current discussion in terms of a uniform definition of device requirements.

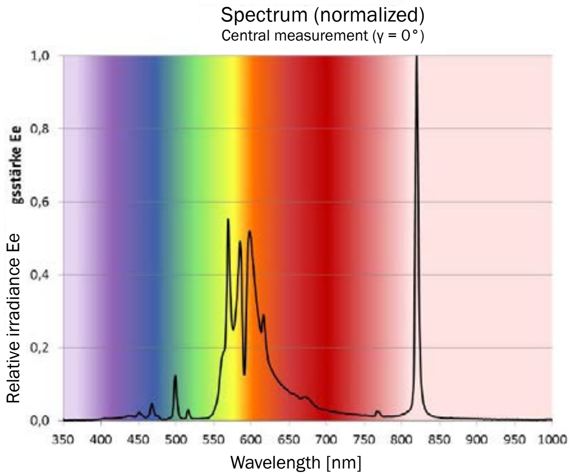
## Experiment at different wavelengths

When it comes to how conditions are perceived in a tunnel, human perception on the one hand and the tunnel's lighting on the other are decisive factors.

A reference wavelength should lie within a range in which the human eye has a good spectral sensitivity. In this respect, it is rather the range of photopic vision that is relevant for lighting in tunnels. The spectral sensitivity of the human eye is discussed in DIN 5031-3. The 50% range of the maximum spectral sensitivity is between 510 nm and 610 nm. It is therefore appropriate to conduct the experiment in this range.



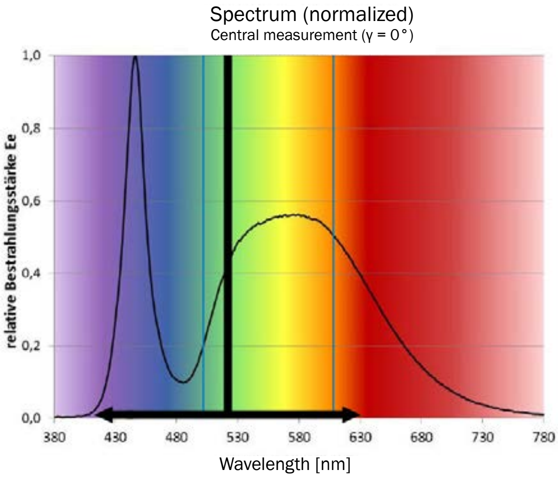
In recent years, lighting in tunnels has changed considerably. In the past, typical tunnel lighting was in the form of sodium-vapor lamps. While low-pressure sodium-vapor lamps emit an almost monochromatic light at a wavelength of approximately 590 nm, high-pressure sodium-vapor lamps emit light over a larger spectrum. However, sodium-vapor lamps have a relatively high proportion of longer wavelengths in the yellow or red range overall.



In tunnel projects of today, sodium-vapor lamps are rarely used. Either halogen lamps or increasingly LED lamps are implemented when equipping modern tunnels. It would be reasonable to assume that the changed light radiation from tunnel lighting further increases the difference between the measurement of transmission in the infrared range and the perceived visibility. This is why an experiment relating to the k coefficient should be conducted in a range that reflects the light sources currently found in tunnels.

During an experiment conducted on modern tunnel lighting systems of ASFINAG, the spectra emitted by the light sources in a tunnel were examined. It was observed that the light spectra have a significantly larger proportion in the green and blue area of the visible light spectrum as the sodium-based lighting used previously (Figs. 6 and 7).

In addition to the measured spectra, the 50% spectral sensitivity range is also shown by the two blue lines.



With this experiment, SICK wanted to cover the spectral ranges present in a tunnel as much as possible. The wavelength was therefore to be approximately in the middle of the relevant spectral range.

The wavelength range of approximately 520 nm lies both in the range of the 50% spectral sensitivity of the human eye and in the middle of the significant spectral range emitted by LED lamps (Fig. 8, vertical black line). On this basis, SICK chose a light source with a target wavelength of approximately 520 nm for the experiment.

## Test procedure

The test was conducted in Kirchberg Tunnel on the outskirts of Schiltach, Germany. The Kirchberg Tunnel has a length of 1,830 m and is a bidirectional tunnel with around 17,000 vehicles passing through it every day. The tunnel is used by a high proportion of heavy-load vehicles.

A reference transmissometer with a light source at 520 nm was set up for the experiment. An LED lamp of type LT H9GP from OSRAM was used as the light source.

Gray lens filters specially produced for this test were used to adjust the reference transmissometer. Using a laboratory spectrometer adjustable across a wavelength range of 487 nm to 553 nm, the transmission values of the gray lens filters were measured for the wavelength range of around 520 nm. These filters served to calibrate the reference transmissometer over a measuring distance of 10 m corresponding to the installation conditions in the tunnel.

During field tests each taking place for at least two weeks, a VICOTEC414, VISIC100SF and VICOTEC320 of the latest generation were operated in the tunnel at the same time as the aforementioned reference transmissometer.

The measurement data was correlated with one another to empirically calculate a sensitivity difference.

The measurement of visibility using a transmissometer is extremely sensitive to contamination on the optical interfaces. For this reason, all transmission-based devices have a function that temporally filters out contamination on the interfaces. This function is different for every measuring device and prevents constant synchronous operation when comparing measuring devices. A slight measuring device drift will always be observable because drift correction takes place at different times. As a result, the two devices used for the test produced different zero points (zero-point drift). For the reference transmissometer, it was decided not to adjust the contamination compensation.

## Comparison of the VICOTEC410 with a reference spectrometer at 520 nm

In the first test, the air quality tunnel sensor VICOTEC410 and the reference transmissometer were compared with one another.

In the following figure, the simultaneous measured values of the VICOTEC410 are shown on the y axis and those of the reference transmissometer are shown on the x axis using a point coordinate.

The red dotted line through the origin is produced when both devices depict the same value.

The blue point cluster shows the measured values of both devices.

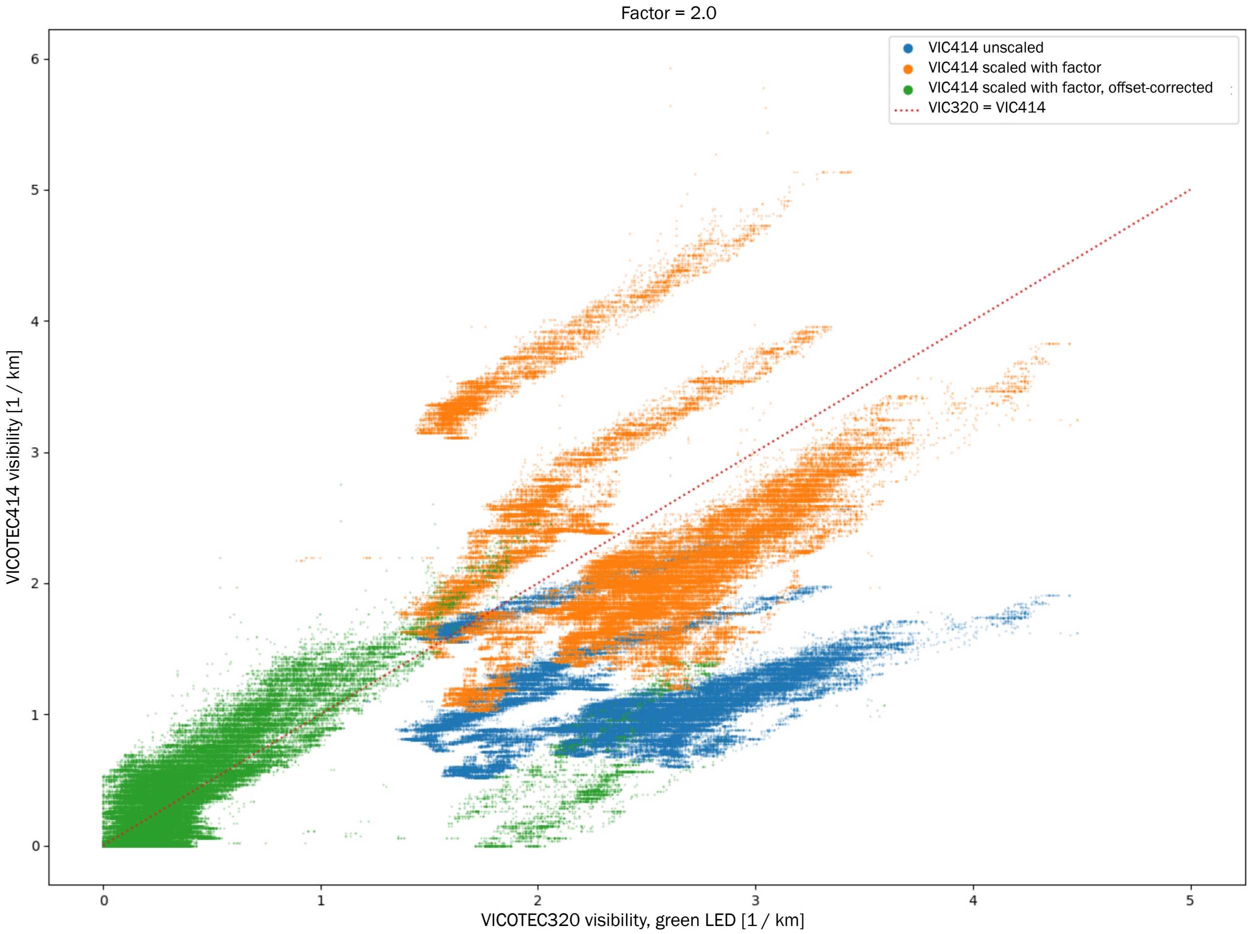
It is to be noted that the blue point cluster does not lie parallel to the red line through the origin.

A factor now needed to be determined with which the gradient of the blue point clusters could be changed so that they run parallel to the line through the origin.

The measured values of the VICOTEC410 could be adjusted to the wavelength of the reference transmissometer using the factor 2.00. This produces the orange point clusters.

To cancel out the effect of the different drift corrections, the high-pass filter was placed over the orange measured values. The green point cluster can be seen as a result of this. The following figure therefore shows the measured values after the described high-pass filtering and scaling with the factor 2.00.

The empirically calculated factor for wavelength correction of the VICOTEC410 is therefore 2.00.



## Comparison of the VISIC100SF with a reference spectrometer at 520 nm

In the second test, the air quality sensor VISIC100SF and the reference transmissometer were compared with one another.

In the following figure, the simultaneous measured values of the VISIC100SF are shown on the y axis and those of the reference transmissometer are shown on the x axis using a point coordinate.

The red dotted line through the origin is produced when both devices depict the same value.

The blue point cluster shows the measured values of both devices.

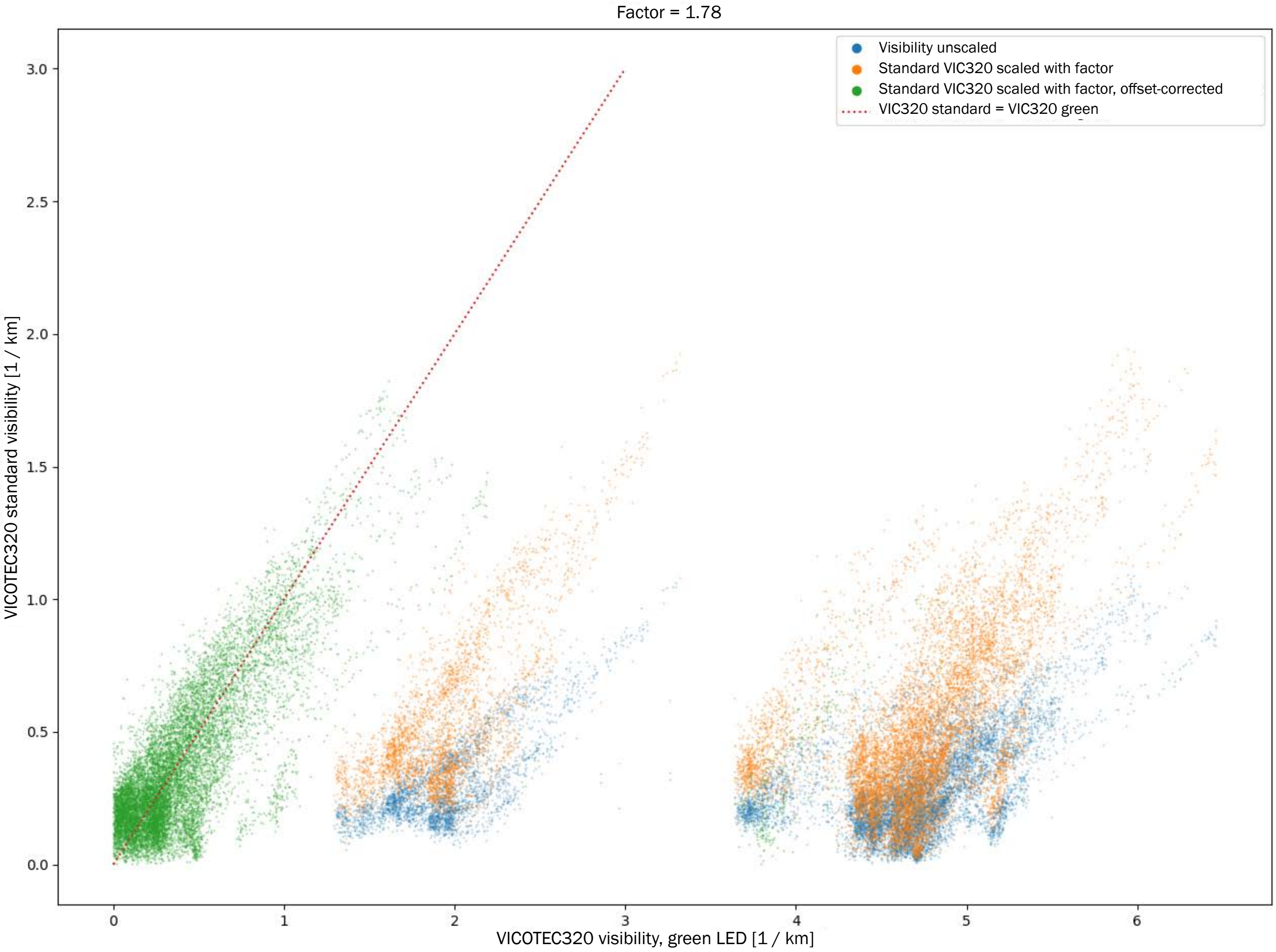
It is to be noted that the blue point cluster does not lie parallel to the red line through the origin.

A factor now needed to be determined with which the gradient of the blue point clusters could be changed so that they run parallel to the line through the origin.

The measured values of the VISIC100SF could be adjusted to the wavelength of the reference transmissometer using the factor 2.25. This produces the orange point clusters.

To cancel out the effect of the different drift corrections, the high-pass filter is placed over the orange measured values. The green point cluster can be seen as a result of this. The following figure therefore shows the measured values after the described high-pass filtering and scaling with the factor 2.25.

The empirically calculated factor for wavelength correction of the VISIC100SF is therefore 2.25.



## Comparison of the VICOTEC320 with a reference spectrometer at 520 nm

In the third test, the air quality tunnel sensor VICOTEC320 and the reference transmissometer were compared with one another.

In the following figure, the simultaneous measured values of the VICOTEC320 are shown on the y axis and those of the reference transmissometer are shown on the x axis using a point coordinate.

The red dotted line through the origin is produced when both devices depict the same value.

The blue point cluster shows the measured values of both devices.

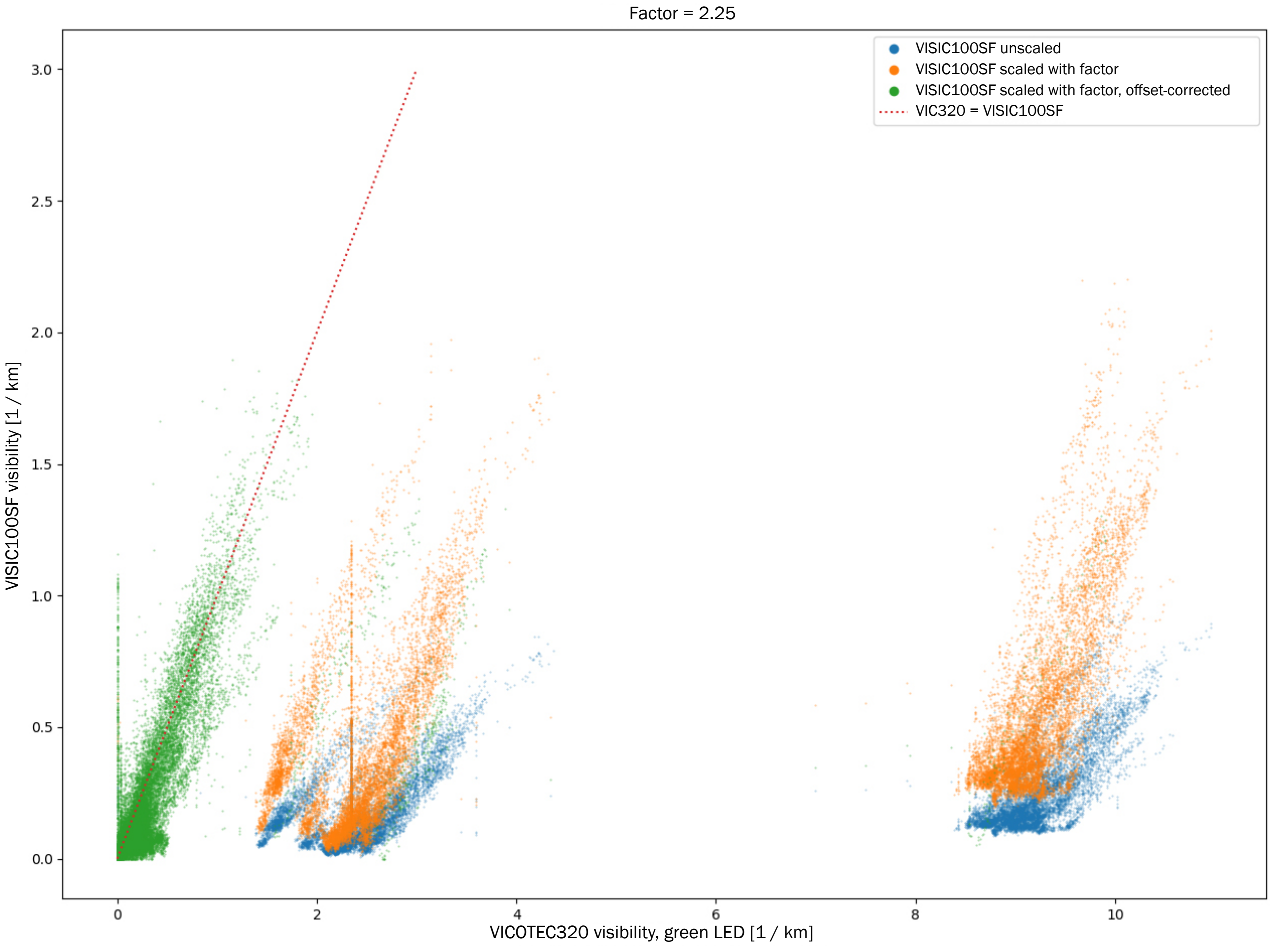
It is to be noted that the blue point cluster does not lie parallel to the red line through the origin.

A factor now needed to be determined with which the gradient of the blue point clusters could be changed so that they run parallel to the line through the origin.

The measured values of the VICOTEC320 could be adjusted to the wavelength of the reference transmissometer using the factor 1.78. This produced the orange point clusters.

To cancel out the effect of the different drift corrections, the high-pass filter was placed over the orange measured values. The green point cluster can be seen as a result of this. The following figure therefore shows the measured values after the described high-pass filtering and scaling with the factor 1.78.

The empirically calculated factor for wavelength correction of the VICOTEC320 is therefore 1.78.



## Comparison of the VICOTEC450 with a reference spectrometer at 520 nm

In the last test, the extractive scattered light measuring device VICOTEC450 and the reference transmissometer are compared with one another.

For this, the simultaneous measured values of the VICOTEC450 are shown on the y axis and those of the reference transmissometer are shown on the x axis using a point coordinate.

The red dotted line through the origin is produced when both devices depict the same value.

The blue point cluster shows the measured values of both devices.

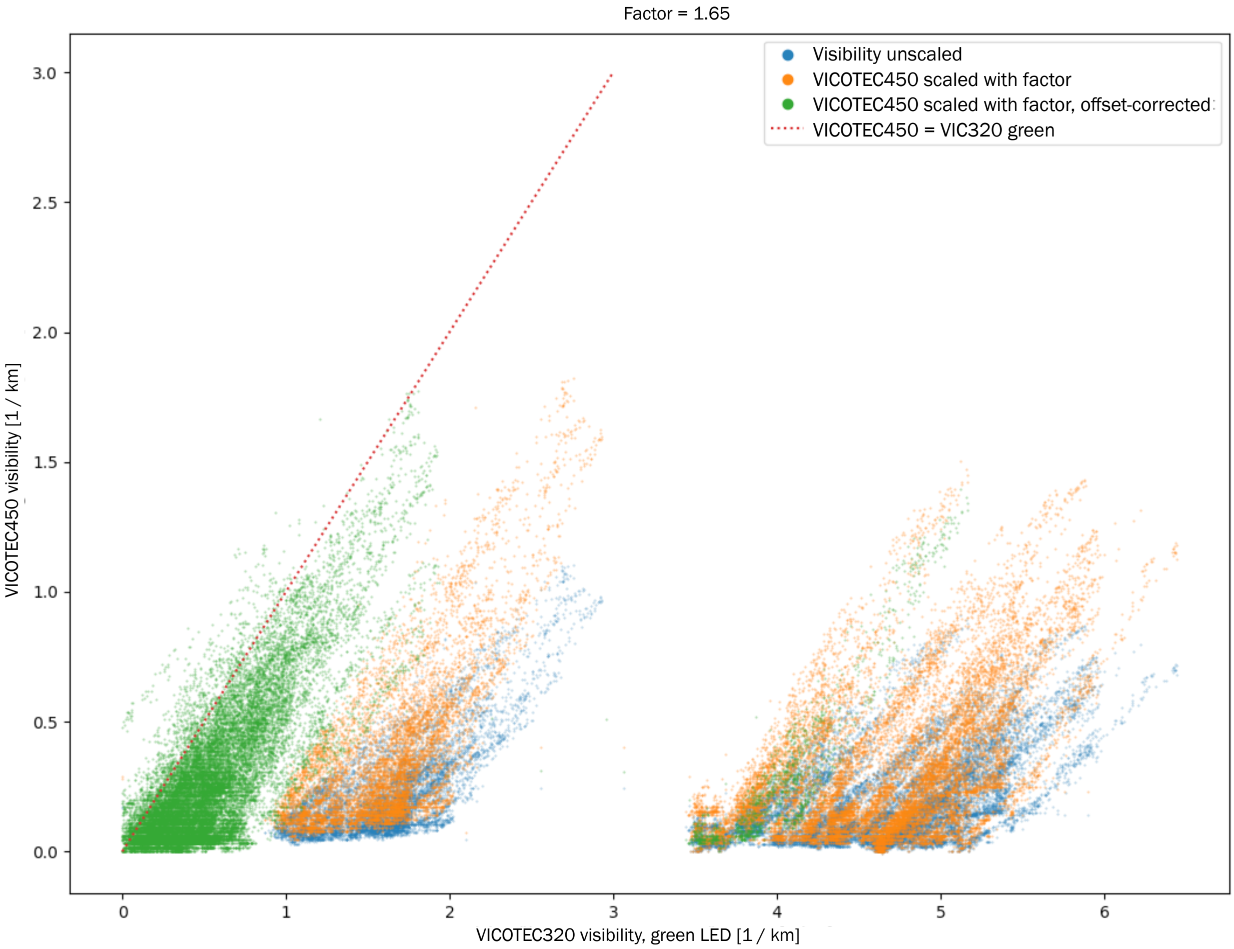
It is to be noted that the blue point cluster does not lie parallel to the red line through the origin.

A factor now needs to be determined with which the gradient of the blue point clusters can be changed so that they run parallel to the line through the origin.

The measured values of the VICOTEC450 can be adjusted to the wavelength of the reference transmissometer using a factor of 1.65. This produces the orange point clusters.

To cancel out the effect of the different offset corrections, the high-pass filter is placed over the orange measured values. We can see the green point cluster as a result of this. Here, the measured values after the described high-pass filtering and scaling with factor = 1.65 are therefore shown.

The empirically calculated factor for wavelength correction of the VICOTEC450 is therefore 1.65.



## Plausibility test: Comparison of the VICOTEC410 and VISIC100SF

To check the consistency of the measured values, the measured values of the transmission-based VICOTEC410 were then compared with the measured values of the VISIC100SF.

To this end, the measured values of the VISIC100SF were first multiplied by 2.25 (the factor determined for the VISIC100SF in relation to the reference device) and then divided by 2 (the factor determined for the VICOTEC410 in relation to the reference measuring device).

After this consistency check, the measurement points of both devices ran parallel to the line through the origin. Consequently, SICK was able to show that the conversion factors between the individual devices and the reference spectrometer are consistent. SICK decided not to use a high-pass filter in this case.

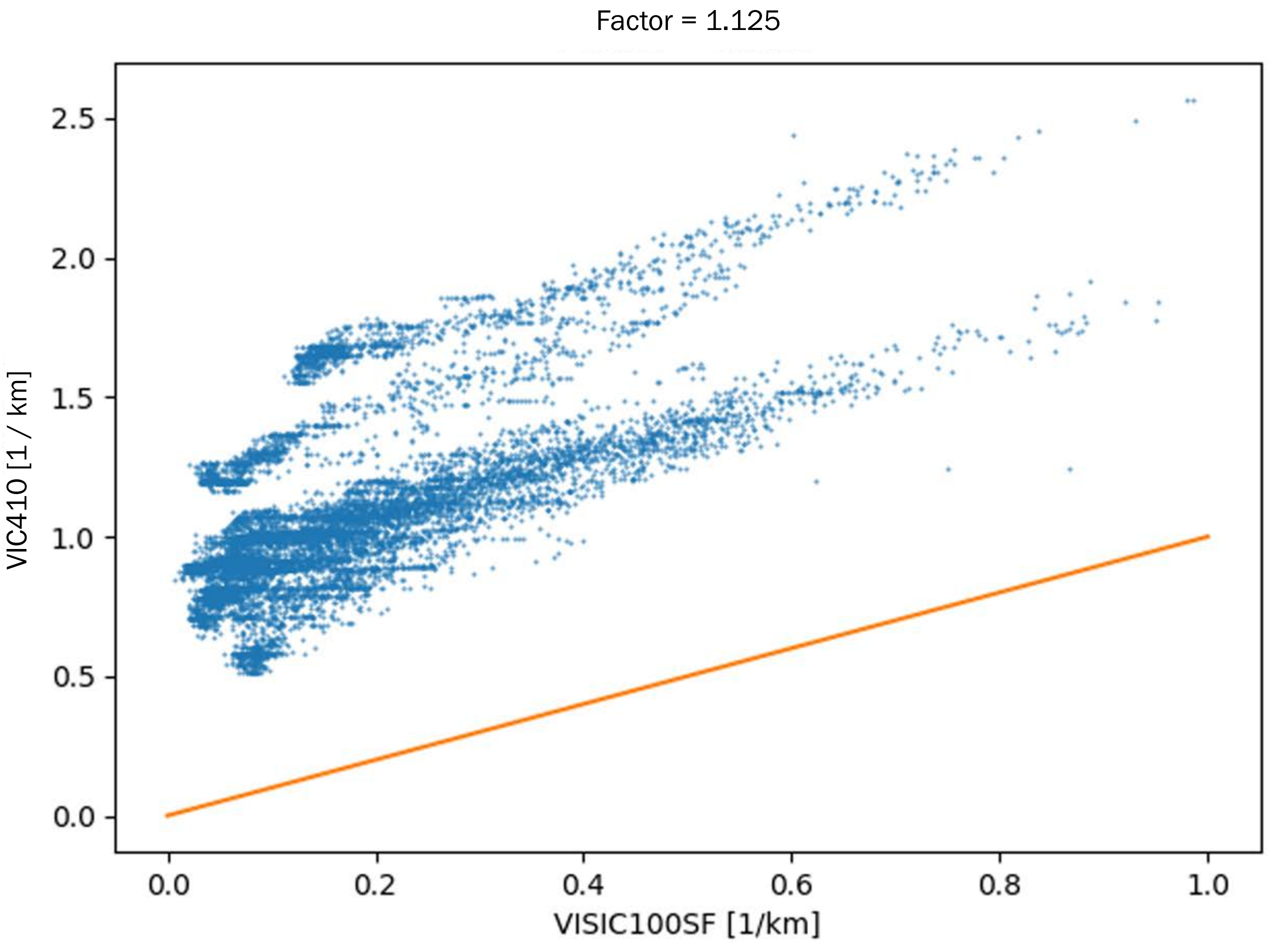
## Summary and result

The experiment allowed correction factors for the air quality tunnel sensors of SICK AG to be empirically calculated for a wavelength range that lies in the 50% range of the maximum spectral sensitivity and that is also adapted to tunnel lighting used today.

The following wavelength correction factors were determined for the three product families examined:

| Product family | VICOTEC410 | VISIC100SF | VICOTEC320 | VICOTEC450 |
|---|---|---|---|---|
| Factor | 2.00 | 2.25 | 1.78 | 1.65 |

These factors can be used to convert the measurement results of the visibility measuring devices of SICK AG to a wavelength of 520 nm.



## Conclusion and recommendation

The experiment shows that the measurement results of measuring devices for determining the k coefficient in a tunnel can be adjusted to the changed lighting conditions in tunnels using adjustment factors.

The factors cannot replace the adjustment of switching points to the actual tunnel conditions. The influencing factors such as the individual tunnel design and the actual stream composition in the respective tunnels are too different for this.

SICK AG recommends using the factors stated in this experiment to adjust the switching points more quickly.

To make it possible for tunnel operators to compare products for measuring the visibility in tunnels, SICK AG suggests a reference wavelength of approximately 520 nm. This wavelength range lies both in the range of the 50% spectral sensitivity of the human eye and in the middle of the significant spectral range emitted by LED lamps.

It is not of importance here whether the measurement is actually carried out at this wavelength, but rather manufacturers of measuring devices should be encouraged to state the adjustment of the measured values of the respective products in relation to this wavelength range.

# NOTES

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