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Improvement of Field Calibration of a Transmissometer for Visibility Measurement

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Abstract

A long-path transmissometer is one of the optical instruments widely used to measure atmospheric light extinction coefficient without enclosing a light beam and perturbing aerosols. Over the past two decades, a number of measurements have been carried out using the long-path transmissometer manufactured by OPTEC, Inc. Calibration of the transmissometer should be performed when any component of the transmissometer system is interchanged or installation condition is changed. For a better calibration of the transmissometer, application of a modified calibration method for the existing neutral density (ND)-filter method was recommended for the computation of the atmospheric transmittance using model MODTRAN 4 in this study. It was revealed that the measured light extinction coefficient from the transmissometer which was calibrated using the existing ND-filter method could be overestimated due to the assumption of the atmospheric transmittance suggested by OPTEC, Inc. The uncertainty of the measured light extinction coefficient from the transmissometer calibrated based on the modified ND-filter method was calculated to be approximately 13 Mm^{-1}.

Key words : Visibility, Transmissometer, Light extinction, Calibration

1. INTRODUCTION

Visibility is not only a primary and highly obvious indicator of general air quality but also relatively easy to understand by public. Visual range has been widely used to quantify visibility. The range has been performed by measuring a known distance by well-trained human eyes at the Meteorological Office in Korea (Ghim *et al.*, 2005). Visual range may, however, not be sufficient to understand the impact of visibility degradation. In U.S.A. the range has been usually derived by measuring the atmospheric light extinction coefficient by various optical means (Kim *et al.*, 2001; Malm and Persha, 1991; Molenar *et al.*, 1989; Ruby, 1985; Malm and Molenar, 1984; Tombach and Allard, 1983). The light extinction coefficient that is the sum of light scattering and light absorption coefficient by various particulate and gaseous species is a quantifiable factor that can be used to monitor visibility. Effective visibility monitoring programs involve taking photographs of an appearance of a scene under various levels of visibility. However, instruments to record

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optical characteristics of the atmosphere and chemical compositions of visibility-impairing aerosols are used because it is difficult to extract quantitative information from photographs. Optically measured light extinction coefficient is a usual measure of visibility.

A long-path transmissometer is one of the optical instruments widely used to measure atmospheric light extinction coefficient without enclosing a light beam and perturbing aerosols. Over the past two decades, a number of measurements have been carried out using the long-path transmissometer manufactured by OPTEC, Inc., Lowell Mich (Kim *et al.*, 2004; Gebhart *et al.*, 2001; Baik *et al.*, 1996; Mathai, 1995; Dzubay *et al.*, 1982). The transmissometer consists of a constant output-light transmitter and a computer-controlled receiver. The irradiance from the transmitter can be detected to the photometer of the receiver over a path length of up to 15 km (Air Resource Specialists Inc., 1988). The transmissometer must be calibrated as a unit. Theoretically, calibration must be conducted by determining the output signal of the transmitter that is measured by the receiver when the optical sight path between the two units allowed in 100% atmospheric transmittance, near-Rayleigh atmospheric condition. However, it is difficult to perform the calibration method. It is suggested from OPTEC, Inc. that the transmissometer can be calibrated using the two methods, neutral density (ND)-filter method and differential path method. They are performed by placing indirectly neutral density filter on the receiver or moving directly the transmitter and receiver for allowing longer path length, respectively. It is assumed that the effect of atmospheric extinction is negligible at the path length of less than 0.5 km in the ND-filter method. Thus specific atmospheric transmittances for various calibration path lengths are suggested (Air Resource Specialists Inc., 1988). For better calibration of the transmissometer, application of a modified calibration method for the existing ND-filter method was suggested to calculate the atmospheric transmittance using MODTRAN 4 (Moderate Resolution Transmittance) model in this study.

The type of visual degradation is perceived to be an indicator of serious human health impacts. The community may judge the effectiveness of environmental control policies to improve air quality by visibility. As a result, the accuracy of measurement from the transmissometer should be required to estimate visibility change.

2. CALIBRATION CONSIDERATIONS

It is known that the instrumentation and calibration mechanism of the transmissometer are well designed (Molenar *et al.*, 1989). The transmissometer has two optical and computational control units, a transmitter and a receiver. To minimize the effect of background or ambient illumination, the transmitted light beam is modulated at 78.125 Hz from lamp-on to lamp-off using a four blade chopper, while the receiver electronics are designed to measure the difference between background radiance (transmitter off) and background plus transmitter radiance (transmitter on) (Malm and Persha, 1991). A 63 mm refractor lens with a focal length of 350 mm is used to amplify optically the light from the transmitter and provide smoothing of the signal noise caused by atmospheric turbulence as shown in Fig. 1. Light from the transmitter is directed to the detector of the receiver. A narrow band filter with a center wavelength of 550 nm, a bandwidth of 10 nm, and a peak transmission of 60% is placed in front of the detector in the receiver unit. The detector is a sensitive silicon photodiode operating in a current-to-voltage amplifier configuration. The output voltage from the photometer head is dependent on detector response, filter/telescope transmission, electrometer gain, and output from the transmitter, path length and atmospheric transmittance. As a result, the calibration should be performed when any component of the transmissometer system including ambient atmospheric condition is interchanged or installed.

There are two calibration methods suggested by OPTEC, Inc., ND-filter method and differential path method. The former can be conducted by only one site calibration but the latter needs short and

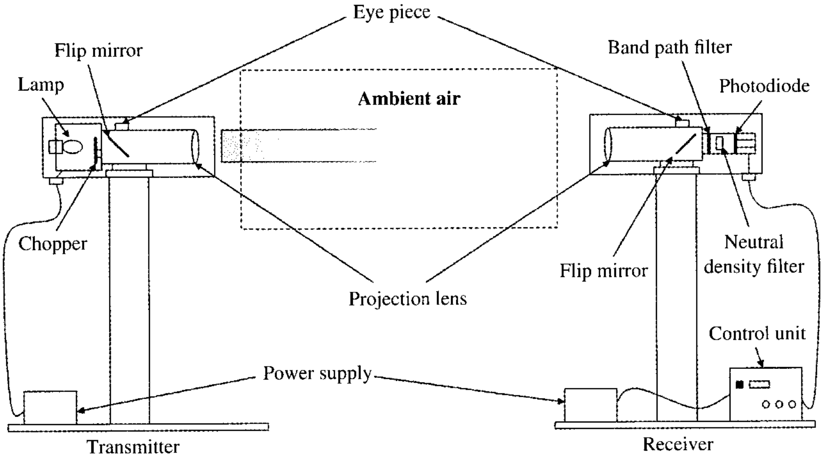

Fig. 1. Function diagram of a transmissometer.

Table 1. Atmospheric transmittances for various calibration path lengths and light extinction coefficients suggested by OPTEC, Inc. (Air Resource Specialists Inc., 1988).

Path length (m)	Atmospheric light extinction coefficient (Mm^{-1})						
	10	20	30	40	50	60	100
100	0.999	0.998	0.997	0.996	0.995	0.994	0.990
200	0.998	0.996	0.994	0.992	0.990	0.988	0.980
300	0.997	0.994	0.991	0.988	0.985	0.982	0.970
400	0.996	0.992	0.988	0.984	0.980	0.976	0.961
500	0.995	0.990	0.985	0.980	0.975	0.970	0.951
600	0.994	0.988	0.982	0.976	0.970	0.965	0.942

long distance sites. The ND-filter method is performed by moving the transmitter and receiver to a site which allows for a calibration path length between 0.25 and 0.50 km. This method assumes that the atmosphere is very clean with average light extinction coefficients of 10～60 Mm^{-1} and the ambient air in the site path is homogenously mixed (OPTEC, Inc., 2004). The atmospheric transmittance at these distances is very close to 100% and can be ignored for the calculation of the calibration constant that represents a raw reading value of the transmissometer at the near-Rayleigh atmospheric condition. Atmospheric transmittances for various calibration path lengths and light extinction coefficients suggested by OPTEC, Inc. are summarized in Table 1. This ideal calibration condition has been recommended for the transmissometer used at the western United States (Air Resource Specialists Inc., 1988). For sites where the atmospheric light extinction exceeds 100 Mm^{-1}, OPTEC, Inc. recommends the differential path method to take into account the atmospheric transmittance over the short calibration path length. This method is performed by measuring the two atmospheric light extinction coefficients at the calibration path and the installation site path. It is assumed that atmospheric condition is homogeneous throughout the sites during the calibration. This method has been recommended for the transmissometer installed at the eastern United States (OPTEC, Inc., 2004).

However, the both calibration methods require the assumption of atmospheric condition during the calibration. The atmospheric transmittance summarized in Table 1 is an assumed value and the near-Rayleigh atmospheric condition for the ideal calibration is rare in Korea. An instrument requires precision and accuracy. The atmospheric transmittance is used to determine the uncertainty of light extinction coefficient measured by the transmissometer. The modified ND-filter method was, therefore, introduced to calculate atmospheric transmittance under the clean atmosphere in this study.

Fig. 2. Calibration sites and scenic data for the atmospheric condition during the transmissometer calibration.

3. EXPERIMENTS

Atmospheric extinction coefficient was made by the OPTEC, Inc. model LPV-2 transmissometer for visibility measurement in Gwangju, Korea. Calibration of the transmissometer was conducted before it was installed at the visibility monitoring stations, Gwangju regional meteorological office and Hyundae department store in the downtown of Gwangju. A calibration site was chosen to be high off the ground to avoid thermal effects and away from stacks, roads or other sources of airborne particles and gases. The calibration was conducted within two hours after noon on clear day to avoid the artifact effects by doing an hour or two after sunrise or before sunset or cloudy days. Atmospheric temperature, wind speed, and relative humidity were 4°C, less than 1 m/sec, and 32%, respectively. Fig. 2 shows calibration sites and scenic data for the atmospheric condition during the transmissometer calibration.

In this study, a modified ND-filter method was considered to calculate the atmospheric transmittance at the calibration site. The accurate atmospheric transmittance should be considered in determining the calibration constant when it is performed using the ND-filter method. The modified ND-filter method was introduced to perform better accuracy of measured atmospheric light extinction coefficient. The calibration was performed at the site that allowed for calibration path length of 0.366 ±0.008 km at the top of buildings (52 m above sea level) in Gwangju Institute of Science of Technology (GIST). In order to prevent from saturating the photometer electronics at the short distance, an optical filter with transmission of 1.193±0.36% was inserted into the photometer head of the receiver telescope. Calibration gain was set to be 200± 0.0025 and total shelter window transmission was determined to be 0.831±0.0012 in the transmissometer system. An additional neutral density filter with transmission of 0.792±0.001 was inserted to avoid an over-voltage-error. Ten tungsten lamps were randomly sampled to measure the raw reading

Table 2. Calibration condition and optical parameters for the transmissometer calibration.

Parameters	Specifications	Measurements
CP	Calibration path length (km)	0.366±0.008
WP	[a]Working path length (km)	1.91±0.008
CG	Calibration gain	200±0.0025*
WG	[b]Working gain	100±0.0025*
FT	Calibration filter transmission	0.01193±0.0036*
WT	Total shelter window transmission	0.831±0.0012*
NFT	Neutral density filter transmission	0.792±0.001
CR	[c]Average raw reading value	107±0.07

[a] The site path length between the visibility monitoring stations.

[b] The gain value set from the transmissometer system during the field measurement at the visibility monitoring stations.

[c] The mean raw reading value converted from the output voltage from the photometer head in receiver unit.

*(OPTEC, inc., 2004)

value that was voltage output from the silicon photodiode of the receiver. Working path length between the visibility monitoring stations was measured to be 1.91±0.008 km using a GPS (geophysical position system) based instrument. The gain value (working gain) set from the transmissometer system during the field measurement at the visibility monitoring stations was determined to be 100±0.0025. Calibration condition and optical parameters for the transmissometer calibration are summarized in Table 2.

MODTRAN 4 was used to calculate the atmospheric transmittance in this study. MODTRAN developed over the past 35 years at the US Air Force Phillips Laboratory contains the complete LOWTRAN (Low Resolution Transmittance) model (Kneizys *et al.*, 1988). This model consists of various standard models based on common geographic locations defined an atmospheric profile with the specified set of parameters (Berk *et al.*, 1989). Aerosol models are also used to simulate the effects of dust, clouds, or other particulate matters in the study path range (Clough *et al.*, 1992; Soberman and Hemenway, 1965). Molecular continuum absorption, molecular scattering, and aerosol absorption and scattering are considered to calculate the atmospheric transmittance (Shettle *et al.*, 1983). MODTRAN is valid for the wavelengths longer than 0.2 μm and its maximum spectral resolution is 2 cm^{-1}. The atmosphere is treated from 0 to 100 km altitude.

4. RESULTS AND DISCUSSIONS

The purpose of the transmissometer calibration is to determine the calibration constant (CAL) from the specified equation which is a function of path length, transmissions of the optics, electrical amplification, and lamp intensity. The equation suggested by OPTEC, Inc. is

$$CAL=(CP/WP)^2\times(WG/CG)\times(1/FT)\times WT \times(1/T)\times CR \qquad (1)$$

where CP and WP are the calibration and working path length, CG and WG are the calibration and working gain, FT, WT, and T are the filter transmission, the window transmission, and the atmospheric transmittance, and CR is a mean raw reading value from the detector. In this study, the additional neutral density filter was inserted to avoid over-voltage-error. CAL is, therefore, calculated using Equation 2.

$$CAL=(CP/WP)^2\times(WG/CG)\times(1/FT)\times WT \times(1/T)\times(1/NFT)\times CR \qquad (2)$$

Where NFT is the transmission of the neutral density filter.

Atmospheric transmittance used to calculate CAL for the transmissometer was obtained using atmospheric transmittance model MODTRAN 4. There are several types of available aerosol profiles which are based on common aerosol mixtures such as rural, urban, and marine condition (Hidas *et al.*, 2000). During the calibration, atmospheric condition was almost optimal to apply an atmospheric profile of middle latitude Asian rural type. Rural aerosol profile was introduced to calculate the atmospheric transmittance in this study. The profiles for atmospheric trace constituents (O_3, O_2, HNO_3, H_2O, CO_2, CO, CH_4, N_2O, NH_3, NO, NO_2, SO_2, CFCs, CCL_4, and N_2O_5) were set from measured value at the calibration site and MODTRAN's standard model. Atmospheric profiles for calculating the atmospheric transmittance using MODTRAN 4 in this study are summarized in Table 3. Frequency ranges were considered to be from 10,000 cm^{-1} (1.00 μm) to 50,000 cm^{-1} (0.20 μm). From the results, atmospheric transmittance at the calibration site was calculated to be 0.9423 at the wavelength of 550 nm as shown in Fig. 3.

CR was recorded at least 10 consecutive 1 minute integration of lamp-on during the calibration. From Table 2, the standard deviation of the CRs did not exceed ±0.007 at the gain of 200. Consequently, CAL from the modified ND-filter method was calculated to be approximately 183 from Equation 2. In order to compare CAL from the existing ND-filter method, the atmospheric transmittance was selected to be from 0.9640 to 0.9780 with an interpolative method assuming atmospheric light extinc-

Table 3. Atmospheric profiles for calculating the atmospheric transmittance using MODTRAN model in this study.

Height (km)	P^a (mb)	T^b (K)	RH (%)	CLD^c (g/m^3)	Rain rate (mm/h)
0.05	1013.25	277	32	0	0
O_3 (UV) (atm cm/km)	O_2 (UV) (atm cm/km)	HNO_3 (atm cm/km)	H_2O (atm cm/km)	O_3 (atm cm/km)	CO_2 (atm cm/km)
2.79E-03	3.82E + 04	5.19E-06	4.11E + 02	2.79E-03	3.50E + 01
CO (atm cm/km)	CH_4 (atm cm/km)	N_2O (atm cm/km)	O_2 (atm cm/km)	NH_3 (atm cm/km)	NO (atm cm/km)
0	0	0	2.09E + 04	5.02E-05	3.00E-05
NO_2 (atm cm/km)	SO_2 (atm cm/km)	CFCs (atm cm/km)	CCL_4 (atm cm/km)	N_2O_5 (atm cm/km)	Aerosol Type
2.30E-06	2.96E-05	1.40E-05	1.30E-05	3.84E-11	Rural

[a]Atmospheric pressure, [b]Atmospheric temperature, [c]Cloud density profile

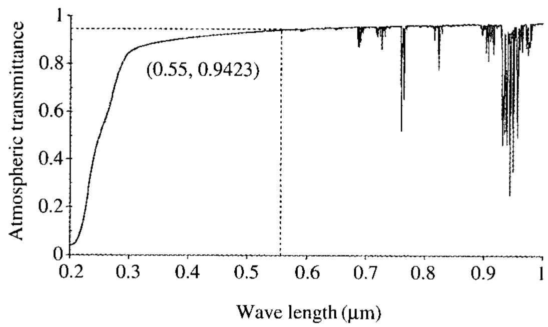

Fig. 3. Calculated atmospheric transmittance at the wavelength of 550nm using MOTRAN 4.

tion coefficient of 60 ~ 100 Mm^{-1} from Table 1. The CAL from the existing ND-filter method was calculated to be from 176 to 179. As a result, it was revealed that CAL suggested by OPTEC, Inc. was underestimated in comparison to the one from the study. This result indicates that measured light extinction coefficient from the transmissometer calibrated using the existing ND-filter method can be overestimated due to assumption of the atmospheric transmittance suggested by OPTEC, Inc.

The calibration operating procedure for the transmissometer was to take 10 one-minute measurements of transmitter irradiance and report the average and standard deviation of the ten values. A mean light extinction coefficient and associated uncertainty were then calculated from the measurements. The atmospheric condition at the calibration site varied quite slowly with time constant about a few hours. This condition enables to measure the irradiance of transmitter constantly during 10-minute detection time. The total uncertainty (U_T) of the measurement can be calculated with the sum of three optical instrument uncertainties including intensity of light detected at distance r, calibration value of the transmissometer, and lamp intensity. The total uncertainty can be calculated using Equation 3 (IMPROVE, 1998).

$$U_T=(U_{Ir}^2+U_{Ical}^2+U_{lamp}^2)^{1/2} \qquad (3)$$

Where U_{Ir} is due to in tensity of light measured at distance (r) of 366 m, U_{Ical} is due to calibration value of the transmissometer, and U_{lamp} is due to lamp intensity. It was reported that U_{Ir} was 0.006 when no meteorological and optical interferences (e.g., fog, mist, precipitation, optical turbulence, and beam wander) were considered (IMPROVE, 1998). U_{lamp} is determined to be 1.5% from the information of lamp regulation (OPTEC, Inc., 2004). I_{cal} was the value that was measured by the transmissometer detector using Equation 2 when atmospheric transmittance was calculated using MODTRAN 4. U_{Ical} can be then described Equation 4 (IMPROVE, 1998).

$$U_{Ical}=(2U_{CP}^2+2U_{WP}^2+U_{WG}^2+U_{CG}^2 \\ +U_{WT}^2+U_{FT}^2+U_{NFT}^2+U_{CR}^2)^{1/2} \qquad (4)$$

The uncertainties of the parameters abbreviated as U_{CP}, U_{WP}, U_{WG}, U_{CG}, U_{WT}, U_{FT}, U_{NFT}, and U_{CR} represent the standard deviations of them given in

Table 2. From the above equations, U_T was calculated to be approximately 0.023. This value accounts for the uncertainty in the photometer response of the transmissometer without consideration of the distance between the transmitter and the receiver at the work site. The uncertainty of measured light extinction coefficient (σ_{bext}) from the transmissometer calibrated using the modified ND-filter method can be calculated using Equation 5 (IMPROVE, 1998).

$$\sigma_{bext} = U_T / r \qquad (5)$$

Consequently, σ_{bext} at the working distance of 1.91 km was calculated to be approximately 13 Mm^{-1}.

5. CONCLUSION

Field calibration of an optical instrument is significantly important if it is required. Calibration of the transmissometer should be performed when any component of the transmissometer system is interchanged or installation condition is changed. ND-filter method and differential path method were suggested by OPTEC, Inc. In this study, a modified ND-filter method was considered to calculate the atmospheric transmittance at the calibration site. Improvement of this method was to obtain the accurate atmospheric transmittance from the calculation using MODTRAN 4 but from its assumption suggested by OPTEC, Inc. Consequently, calibration constants from the modified ND-filter method and the existing ND-filter method were calculated to be approximately 183 and 176～179, respectively. This result indicates that measured light extinction coefficient from the transmissometer calibrated using the existing ND-filter method can be overestimated due to assumption of the atmospheric transmittance sug-gested by OPTEC, Inc. The modified ND-filter method was introduced to perform better accuracy of measured atmospheric light extinction coefficient. The uncertainty of measured light extinction coefficient from the transmissometer calibrated using the modified ND-filter method was calculated to be approximately 13 Mm^{-1} at the working dis-tance of 1.91 km.

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