Comparative Calibration Method Between Two Different Wavelengths With Aureole Observations at Relatively Long Wavelength

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Abstract

A multi-stage method for calibration of sunphotometer is proposed by combining comparison calibration method between two different wavelengths with aureole observation method for long wavelength calibration. Its effectiveness in reducing the influences for calibration due to molecular and aerosol's extinction in the unstable turbidity conditions is clarified. By comparing the calculated results with the proposed method and the existing individually calibration method, it is found that the proposed method is superior to the existing method in terms of calibration accuracy. Namely, Through a comparison between ILM and the proposed method using band 0.87um as reference, the largest calibration errors are 0.0014, 0.0428 by PM are lower than that by ILM (0.011,0.0489) for sky radiances with no error and -3~+3%, -5~+5% errors. By analyzing the observation data of 15 days with POM-1 Skyradiometer, the largest standard deviation of calibration constants by PM is 0.02016, and is lower than that by ILM (0.03858).

Keywords: Sunphotometer, Calibration, Langley Method, Modified Langley Method, Aureole, Solar Direct Irradiance, Solar Diffuse Irradiance.

1. INTRODUCTION

Sunphotometer have been applied widely to measure aerosol optical properties for analyzing local and global climate, such as Aerosol Robotic Network (AERONET)[1]. There are about 500 institutions of ground based aerosol monitoring by sunphotometers or skyradiometers in the AERONET. Thus, the maintenance of the calibration constants of sunphotometers is essential in such works, especially for monitoring of long-term variations of atmospheric turbidity [1]-[9].

It is well known that the common Langley method (CLM) is inability to assure to obtain accurate calibration constant for sunphotometer due to the influence by unstable atmospheric extinction [10]-[13]. In the CLM, the calibration constant is obtained by extrapolation of the plot of the logarithm of the sunphotometer reading against atmospheric air mass to air mass 0. Large error of calibration constant, however, it will occur as the optical depth of atmosphere changes during the calibration period because of the unstable atmospheric turbidity. For this reason, many previous works which focus on reducing the influence due to the unstable atmospheric turbidity in the instrument calibration have been studied. One of the typical representatives is Improved Langley method proposed by T. Nakajima [13]. They introduced an analysis of volume spectrum to firstly estimate the aerosol optical depth in order to avoid the error due to the change of aerosol optical depth in accordance with the unsteady turbidity conditions. In consequence, it made a greater improvement for sunphotometer calibration than the common Langley method.

[1] **aeronet**.**gsfc**.nasa.gov/Operational/pictures/.../Cimel_set_up.PDF

Some factors, however, such as observation errors in circumsolar radiances, the scattering of atmospheric molecular, the estimate errors of volume spectrum and the other assumptions of atmospheric conditions, result in insufficiency to reduce the contribution of multiple scattering by analysis of volume spectrum. Sometime estimation errors of aerosol optical depth are also significant. Thus the estimation accuracy of the calibration constants also becomes small by ILM, especially for the short wavelength. On the other hand, ratio Langley method (RLM), proposed by B.W. Forgan (1994) [12], is the method which is depend on a known calibration for a reference wavelength to permit calibration at the others. Using this method, it is possible to improve calibration accuracies by selecting the long wavelength with being calibrated well by ILM as a reference to perform calibration at the others.

In the following section, a multi-stage calibration method by combining ILM with RLM to perform calibration for sunphotometer is proposed. Results from a numerical simulation and an analysis for the actual data measurement by skyradiometer are followed by in order to validate the proposed method. Then conclusions and some discussions are followed.

2. ANALYSIS OF VOLUME SPECTRUM AND IMPROVED LANGLEY METHOD

The CLM is based on the Beer-Lambert law as follows,

$$\ln F = \ln F_0 - m\tau \tag{1}$$

where F and F_0 are solar downward irradiances at surface and extra-atmosphere, respectively. τ is total optical depth of atmosphere. m is atmospheric air-mass, is approximately equal to $1/\cos(\theta_0)$ as θ_0 (solar zenith angle) is less than 75□. Invariance of the aerosol optical depth in accordance with stable atmospheric condition at different solar zenith angles is necessary to estimate high accurate solar constant in CLM. But, it is difficult to satisfy the temporal stability of atmosphere in usual locations, except for some special region, such as high elevation of mountain. A sensitivity analysis for calibration in different aerosol models have been performed by M.Tanaka (1986) [11], and there were about 2.6~10% retrieval errors of the calibration constants by means of CLM as the aerosol optical depth varies based on a parabolic variation corresponding changes with the extent of ±10%.

To remove the influence due to variant optical depth of aerosol in accordance with the unsteady turbidity conditions during calibration period, T.Nakajima (1996) proposed an improved Langley method in which the calibration are performed by simultaneous measurements combining the direct-solar and circumsolar radiation [13]. The aerosol optical depth is estimated firstly by an analysis of volume spectrum (AVS). In this analysis, the circumsolar radiances are replaced by a relative intensity as equation (2).

$$R(\theta) = \frac{F(\theta)}{Fm\Delta\Omega} = \omega\tau P(\theta) + q(\theta) \tag{2}$$

where, $R(\theta)$ is the relative intensity of circumsolar radiance, $F(\theta)$, and normalized by direct irradiance(F), approximate air mass (m) and the solid angle($\Delta\Omega$). ω is the single scattering albedo. $q(\theta)$ indicates the multiple scattering contribution. $P(\theta)$ is the total phase function of aerosols and molecules at scattering angle is θ and given by.

$$P(\theta) = (\omega_a \tau_a P_a(\theta) + \omega_m \tau_m P_m(\theta)) / \omega\tau \tag{3}$$

where ω_a, τ_a and $P_a(\theta)$ are the single scattering albedo, the optical depth, and the phase function of aerosol, respectively; and ω_m, τ_m and $P_m(\theta)$ are corresponding quantities of air molecule. Assume the aerosol particle is sphere and homogeneous, by Mie theory, $\omega_a \tau_a P_a(\theta)$ and the aerosol optical depth can be defined as,

$$\omega_a \tau_a P_a(\theta) = \int_{r1}^{r2} K(\theta, kr, \tilde{m}) v(r) d \ln r \quad (4)$$

$$\tau_a = \int_{r1}^{r2} K_{ext}(kr, \tilde{m}) v(r) d \ln r \quad (5)$$

where $v(r) = (4\pi/3) r^4 n(r)$, $n(r)$ is columnar radius distribution of aerosol. $k = 2\pi/\lambda$, $\tilde{m} = n - i\xi$ is refractive index, $K_{ext}(kr, \tilde{m})$, $K(\theta, kr, \tilde{m})$ are kernel functions and can be calculated by Mie theory. Using an inversion scheme of solving radiative transfer equation to correct repeatedly the multiple scattering contribution, $q(\theta)$ [4], an approximate solutions of volume spectrum, $v(r)$, can be estimated by circumsolar radiances. Then the aerosol optical depth also can be estimated by equation (5). Thus, equation (1) can be rewritten by

$$\ln F + m(\tau_m + \tau_o) = \ln F_0 - m\tau_a \quad (6)$$

where τ_o is ozone optical depth, and the calibration constants can be obtained by extrapolation of the plot of the left item against $m\tau_a$ to $m\tau_a$=0. This method is referred to Improved Langley Method (ILM). Because most of influence due to variant optical depth of aerosol in accordance with the turbidity atmosphere can be estimated by circumsolar radiances, the estimation accuracies of calibration constants will be improved conspicuously comparing with the CLM, with the plot of $\ln F$ against m.

On the other hand, the influences due to the small extent (θ<30°) of the circumsolar radiation, the scattering of atmospheric molecule, the observation errors of circumsolar radiances, the estimate errors of the volume spectrum and the other assumptions of atmospheric conditions, result in insufficiency to reduce the contribution of multiple scattering in solving radiative transfer equation by inversion scheme (T. Nakajima, 1996) [13]. Some errors will occur in estimation of the aerosol optical depth by AVS. Thus it is hardly assured to estimate the aerosol optical depth accurately for every wavelength of sunphotometer. Figure 1 shows the difference of the aerosol optical depth estimated by the AVS and by reanalysis of volume spectrum from skyradiometer measurement in several days.

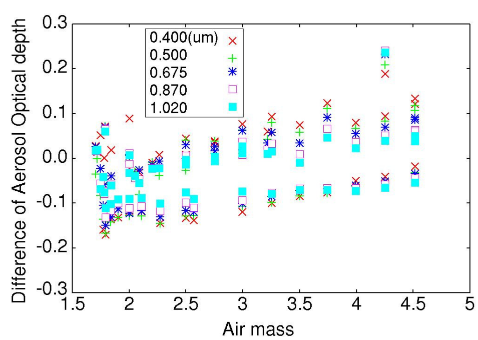


FIGURE 1: The Differences of aerosol optical depth by means of AVS and reanalysis of volume spectrum from air-mass 1.5 to 4.5. Data are observed by POM-1 of Skyradiometer[2] in 11/26/2003, 12/03/2003 and 12/04/2003 at Saga, Japan

It is found that the differences of aerosol optical depth between the estimation by AVS and by reanalysis sometime are larger than 10%. It means that the estimate accuracies of calibration constants can become low by ILM.

3. THE PROPOSED METHOD

From Figure 1, it is also found that the differences of aerosol optical depth in long wavelength are small than that in the shorts. This is because the influences due to the multiple scattering in the long wavelength are smaller, and the optical depth can be estimated accurately. This also means that the estimate accuracies of the calibration constants are higher in long wavelengths than that in the shorts. On the other hand, Ratio Langley method, proposed by B.W. Forgan (1994) [12], is the method which is depend on a known calibration for a reference wavelength to permit calibration at the others by assuming the relative size distribution of aerosol to remain constant as equation (7), so that the ratio of aerosol optical depth between the different wavelengths are assure to be constant as equation (8).

$$\tau_a(\lambda,t) = \pi A(t)\int K_{ext}(r,\lambda) f(r) d\ln r \qquad (7)$$

$$\tau_a(\lambda_1,t)/\tau_a(\lambda_2,t) = \tau_a(\lambda_1,t_0)/\tau_a(\lambda_2,t_0) = \psi \qquad (8)$$

where $f(r)$ is the relative size distribution that is dependent only on particle radius *r*, and $A(t)$ is the multiplier necessary to produce the correct size distribution at some time *t*. Thus the calibrations at the other wavelengths can be performed by using the reference wavelength as equation (9).

$$\ln F(\lambda_1) + m(\tau_m(\lambda_1) + \tau_o(\lambda_1)) = \ln F_0(\lambda_1) - \psi m \tau_a(\lambda_0) \qquad (9)$$

where λ_0, λ_1 are the reference wavelength and the calibrated wavelength, respectively. ψ is a constant. Because $m\tau_a(\lambda_0)$ has been calibrated well, it is calculated accurately $\ln F_0(\lambda_1)$ by least square regression for equation (9) between the left item and $m\tau_a(\lambda_0)$. It is possible to improve calibration accuracies by selecting the long wavelength with being calibrated well by ILM as reference to perform calibration at the others.

Therefore, a multi-stage calibration method is proposed. In the proposed method, accurate calibration constants in the long wavelength which are estimated by ILM are used. Also it is used as a reference to that at the other wavelengths. Because the ILM does work well in the code of Skyrad.pack, developed by T.Nakajima (1996) [4], this code will be used in our algorithm. The proposed process flow is shown in Figure 2.

[2] It is similar to the Aureolemeter for AERONET which is manufactured by Prede Co. Ltd.

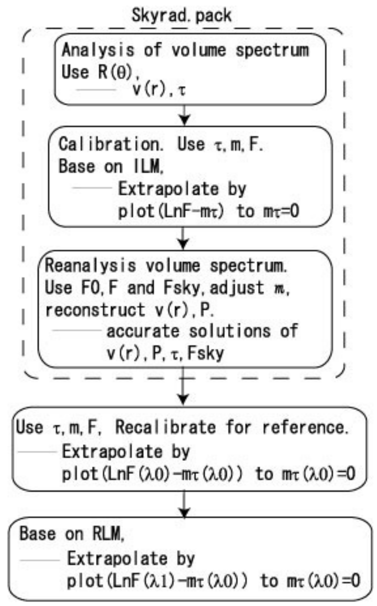


FIGURE 2: The algorithm of multi stage calibration method.

Firstly, the code Skyrad.pack.v42 is introduced in our algorithm. It includes three processes, level 0, calibration and level 1. In the level 0, based on AVS, the aerosol optical depth and the volume spectrum are approximately estimated by the circumsolar radiation. In the calibration, the calibrations are performed by ILM. In the level 1, on the other hand, it is used as the calibration constants estimated by ILM, and then it is combined with the direct and sky radiances. Thus, more accurate solution of aerosol optical depth, aerosol volume spectrum, refractive index of aerosol can be estimated by reanalysis of volume spectrum. Consequently, it is used the aerosol optical depth which is estimated from the level 1, i.e. reanalysis of volume spectrum, instead of that from the level 0. Then it is performed a calibration for the reference wavelength selected to obtain more accurate calibration constants. Finally, based on RLM, the well-calibrated at the reference wavelength can be used for that at the other wavelengths.

4. NUMERICAL SIMULATIONS

A numerical simulation is conducted to check a validity of the proposed method by comparing to the ILM method. The wavelengths are selected 0.4, 0.5, 0.675, 0.87 and 1.02um in accordance with the POM-1 of Skyradiometer manufactured by Prede Co. Ltd. The reference wavelength is set at 0.87um. The simulated data is generated by the Skyrad.pack.v42. The aerosol size distributions are defined two modes of log-normal distributions (bi-modal) as follows

$$n(\ln r) = \sum_{i=1}^{2} \frac{C_i}{\sqrt{2\pi}\log\sigma_i} \exp\left(-\frac{(\log r - \log \overline{r_i})^2}{2\log^2\sigma_i}\right) \quad (10)$$

where *n(lnr)dlnr* is the number density of particles between radii *r* and *r+dlnr*. The values of C_i is set as 1, and σ_i, $\overline{r_i}$ are set as same as the aerosol type observed at Saga, Japan in 2003. The set of parameters are shown in Table 1.

No mode	Ci	ri(um)	σi
1	1.0	0.37	1.95
2	1.0	3.06	2.36

TABLE 1: The parameters for log-normal distribution.

The refractive index of aerosol is set *m=1.50-0.01i.* Solar irradiance of extra-atmosphere is set 1.0. The variation of the optical depth of aerosol with time is given as follows (Shaw, 1976) [14].

$$\tau_a = \tau_{a0}(1+\alpha t^2) \qquad (11)$$

where τ_{a0} is aerosol optical depth at noon, and are set 0.1 and 0.2. α is assumed to be 0.011. So that the aerosol optical depth changes in the extent of 0~20% of τ_{a0} as the air-mass vary from 1.5 to 4.5. We set 0,-3~3%,-5~5% random errors for the sky radiances to evaluate the calibration accuracies by ILM and the proposed method (PM). Figure 3 (a) and (b) shows the estimate errors of aerosol optical depth by AVS and reanalysis of volume spectrum for the wavelengths 0.4, 0.5 and 0.87μm with no error in sky radiances.

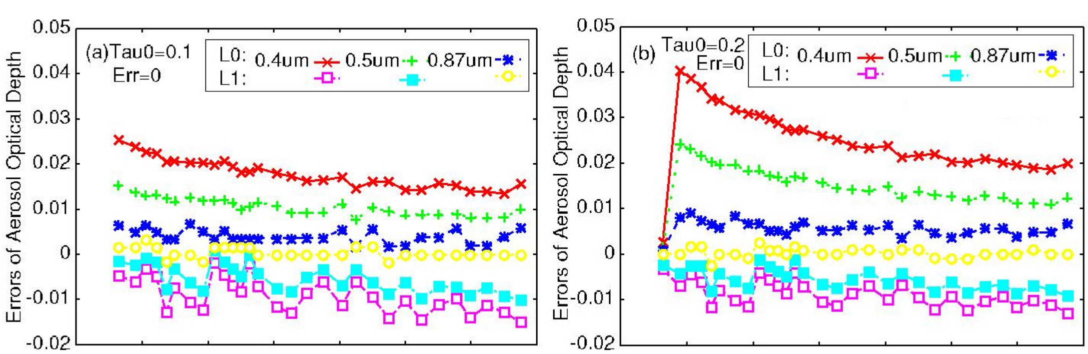
From this Figure, it may be concluded that,
(1) Estimate accuracies of the aerosol optical depth by reanalysis of volume spectrum are almost better than that by AVS,
(2) Estimate errors of aerosol optical depth in band 0.87μm are smaller than that in 0.4 and 0.5μm. Similarly, the cases with -3~3% and -5~5% errors in sky radiances, also can be concluded the same points as above.

Table 2(a), (b), (c) show that the comparisons of estimate accuracies of calibration constants by ILM and PM for the aforementioned five wavelengths. From the table, it is found that the calibration accuracies are higher by PM, especially in short wavelength 0.4μm.

To evaluate the influence of calibration accuracies due to changing of the relative size distribution, it is set σ_i and $\overline{r_i}$ ±3% and ±5% change in equation (10). The calibration results are shown in Table 3. From the table it may say that the calibration accuracies of the proposed method are higher than that of PM in ±3% change.

5. VALIDATION THROUGH OBSERVATIONS

It is also validated the proposed method by analysis of observation data from POM-1 of Skyradiomater. The POM-01 Skyradiometer can measure the direct, diffuse solar irradiance as well as aureole in solar almucantar and in the principal plane. It consists of the seven filters which the central wavelengths are at 0.315, 0.40, 0.50, 0.675, 0.870, 0.94 and 1.02μm. The filters of the wavelength center at 0.315μm and 0.94μm are used for estimation of O_3 concentration and precipitable water, respectively. The other filters are used for aerosol optical depth measurements. The instrument is acquired with a 0.5□half angle field of view. The instrument is located at Saga University, and observations were performed from September 2003 to May 2004. Data of 15 days are selected; these days are cloud-free.



(a) (b)

FIGURE 3: The estimation errors of aerosol optical depth by the method of AVS and the method through reanalysis of volume spectrum at the wavelength of 0.4, 0.5, and 0.87μm without any error in sky radiance measurement.

The Figure 4 shows the calibration constants at the reference wavelength estimated by ILM in the 15 days. It is found that the accuracies are high enough with the standard deviation of only 1%.

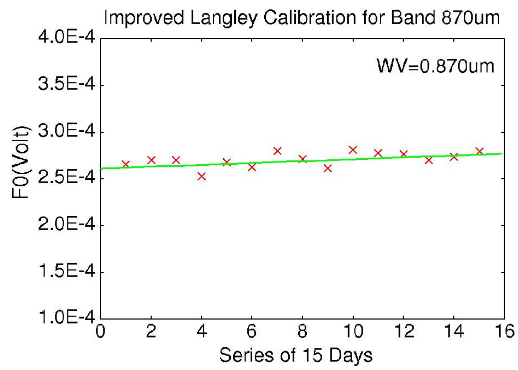


FIGURE 4: Calibration for the reference wavelength by ILM

The calibration results of ILM and PM methods are shown in Figure 5 (a) and (b) and Table 5. Figure 5 (a) shows calibration coefficient for the wavelength of 0.4μm and 0.5μm, while Figure 5 (b) also shows calibration coefficient for 0.675μm and 1.02μm. Table 5 indicates the standard deviations for each band in 15 days. Consequently, it is found that the standard deviation of PM method is smaller than that of ILM method, especially at the wavelength of 0.4μm. This also means that the number of times of calibration required for PM is less than that for ILM to attain the same accuracies.

	0.1		0.2		0.3	
WV(um)	ILM	PM	ILM	PM	ILM	PM
0.4	0.0008	0.0006	0.0029	0.0009	0.013	0.0014
0.5	0.0003	0.0006	0.0015	0.0006	0.01	0.0009
0.675	0.0012	0.0005	0.0006	0.0006	0.005	0.0005
0.87	0.0002	0.0002	0.0001	0.0001	0.003	0.0004
1.02	0.0002	0.0002	0.0001	0.0001	0.002	0.0004

(a) No error in circumsolar radiances

	0.1		0.2		0.3	
WV(um)	ILM	PM	ILM	PM	ILM	PM
0.4	0.011	0.004	0.017	0.009	0.023	0.011
0.5	0.008	0.003	0.009	0.006	0.012	0.009
0.675	0.003	0.002	0.003	0.002	0.015	0.007
0.87	0.006	0.002	0.001	0.001	0.002	0.001
1.02	0.002	0.001	0.001	0.002	0.001	0.001

(b)-3%~3% random errors in circumsolar radiances

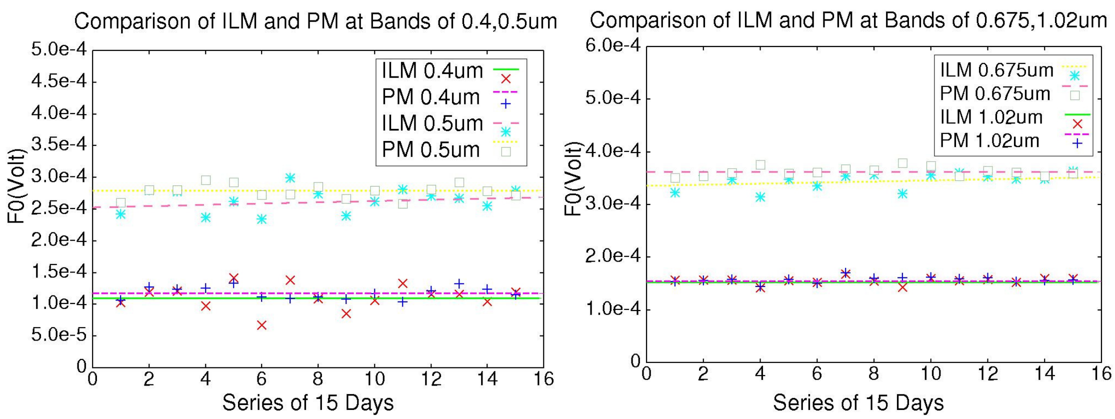
	0.1		0.2		0.3	
WV(um)	ILM	PM	ILM	PM	ILM	PM
0.4	0.013	0.007	0.015	0.005	0.027	0.014
0.5	0.006	0.006	0.005	0.004	0.011	0.01
0.675	0.003	0.003	0.003	0.003	0.007	0.005
0.87	0.001	0.001	0.002	0.001	0.001	0.001
1.02	0.001	0.001	0.002	0.001	0.001	0.002

(c)-5%~5% random errors in circumsolar radiances.

TABLE 2: Comparison of estimation error for calibration from ILM and the proposed method as the optical depth are 0.1, 0.2 and 0.3.

WV (um)	standard deviation	
	ILM	PM
0.4	0.03858	0.02016
0.5	0.02219	0.01691
0.675	0.01837	0.01295
1.02	0.01022	0.00938

TABLE 3: Comparison of the Standard deviations between ILM and PM.



(a) 0.4 and 0.5μm **(b) 0.675 and 1.02μm**

FIGURE 5: Calibration for 0.4μm and 0.5μm by ILM and PM.

6. CONCLUSIONS

A multi stage calibration method combining Improved Langley Method with Ratio Langley Method is proposed in this paper. From the numerical simulation, the estimation errors of aerosol optical depth result in calibration precision decrease by ILM. Through a comparison between ILM and the proposed method using band 0.87μm as reference, the largest calibration errors are 0.0014, 0.0428 by PM are smaller than that by ILM (0.011,0.0489) for sky radiances without any error and -3~+3%, -5~+5% errors. By analyzing the observation data of 15 days with POM-1 of Skyradiometer, the largest standard deviation of calibration constants by PM is 0.02016, and is smaller than that by ILM (0.03858). Thus it may say that the proposed calibration method is superior to the other conventional methods.

7. ACKNOWLEDGEMENTS

The authors thank Prof, T.Nakajima and Engineer, M.Yamano of Center for Climate System Research, The University of Tokyo for their constructive comments.

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