# Transfer method to calibrate the normalized radiance for a CE318 Sun/sky radiometer

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A transfer method is introduced to derive the normalized radiance for CE318 Sun/sky radiometer using viewing solid angles and extraterrestrial calibration constants. The new transfer method has a good consistency at different parts of the sky scanning. Error analysis suggests that the uncertainty of the transferred method is about 2.0%–2.4%. The normalized radiances are used as input of the aerosol inversion to test the performance of the new transfer method. The residuals of the inversion (e.g., difference between fitted and measured radiance) are chosen as the index of the radiance calibration accuracy. Analyses of one year's measurements in Beijing suggest an average sky residual of 3.3% for almucantar scanning (while 3.7% for the AERONET method), which suggest a better accuracy of the transfer method when used in aerosol retrieval.

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Ground-based radiometer observation has the highest accuracy among aerosol remote sensing approaches and can provide more inverted aerosol parameters than satellite observations. The CIMEL CE318 Sun/sky radiometer is the standard instrument[1] used in the AERONET[2], which consists of more than 500 observation sites all over the world. The aerosol properties provided by AERONET play an important role not only in climate change studies[3] and environment monitoring[4], but also in the validation of satellite aerosol products[5]. The CE318 usually contains two kinds of measurements: spectral data of direct Sun radiation extinction and the angular distribution of sky radiances[6]. The scattering sky radiance is the principal information used in the aerosol inversion based on remote sensing measurements[7,8]. It can be used to retrieve aerosol properties, such as phase function, single scattering albedo, particle size distribution, and complex refractive index. The accuracies of these retrievals depend greatly on the accuracy of the sky radiance calibration[9,10].

An integrating sphere is the primary light source for radiance calibration. However, due to limits in obtaining highly absolute accuracy of the sphere light source, at present, the radiance calibration with an uncertainty of 3%–5%[2] is less accurate than that of the extraterrestrial radiometer constant $V_0$. In terms of aerosol inversion, the sky radiance $L$ needs to be normalized by the extraterrestrial solar irradiance $E_0$. The uncertainty in $E_0$ can be also as large as that of $L$[11].

In order to characterize the atmospheric radiation field, CE318 measures the angular sky radiance in two parts of the sky, aureole ($a$) and dark-sky ($k$), in the almucantar (ALM) and the solar principal plane (SPP). Usually, the angular sky radiance, for the aureole part $L_a$, is obtained from the CE318 output digital number (DN) $V_a$ and the radiance calibration coefficient $C_a$ (in the units of $\mathrm{W/m^2/sr/nm/DN}$),

$$L_a(\lambda;\Theta) = C_a \cdot V_a(\lambda;\Theta), \tag{1}$$

where $\lambda$ is the central wavelength and $\Theta$ is the scattering angle. Meanwhile, according to Li *et al.*[12], one can derive the radiance calibration coefficient as follows:

$$C_a = \frac{E_0}{\Omega_v \cdot V_0} \cdot \frac{G_s}{G_a} \cdot \frac{\mathrm{LG}}{\mathrm{HG}_a}, \tag{2}$$

where the solid angle $\Omega_v$ is related to the field of view (FOV) of the radiometer; $V_0$ denotes the radiometer signal measured at the top of the atmosphere; the subscript $s$ refers to the instrument function using the Sun optical path; $G_s$ and $G_a$ are adjustable user gains for Sun and aureole measurements, respectively; LG and $\mathrm{HG}_a$, respectively, represent the instrument internal gain of Sun and aureole measurements. The instrument internal gains are assumed to be independent of wavelength, when aiming at the same light source (e.g., an integrating sphere), the internal gains ratio can be expressed as

 

$$\frac{\mathrm{LG}}{\mathrm{HG}_a} = \frac{V_s(\lambda)}{V_a(\lambda)} \cdot \frac{G_a(\lambda)}{G_s(\lambda)}. \tag{3}$$

Then, applying Eqs. (2) to the angular sky radiance [Eq. (1)], we obtain,

$$L_a(\lambda;\Theta) = \frac{\mathrm{LG} \cdot G_s(\lambda) \cdot E_0(\lambda)}{\Omega_v \cdot \mathrm{HG}_a \cdot G_a(\lambda) \cdot V_0(\lambda)} \cdot V_a(\lambda;\Theta). \tag{4}$$

The downward normalized sky radiance $L'$ is defined as follows:

$$L'(\lambda;\Theta) = \frac{\pi \cdot L(\lambda;\Theta)}{E_0(\lambda) \cdot f_{\mathrm{es}}}, \tag{5}$$

where $f_{\mathrm{es}}$ means the Earth-Sun distance correction factor corresponding to the sky radiance acquisition time. Combining Eqs. (4) and (5), the normalized sky radiance can be yielded as

$$L'_a(\lambda;\Theta) = \frac{\pi \cdot \mathrm{LG} \cdot G_s(\lambda)}{\Omega_v \cdot \mathrm{HG}_a \cdot G_a(\lambda) \cdot V_0(\lambda) \cdot f_{\mathrm{es}}} \cdot V_a(\lambda;\Theta). \tag{6}$$

Based on the double 6° sky measurement (D6sky), part of the CE318 observation protocol that consists of sequential aureole and dark-sky radiance measurements at a fixed scanning angle (6°) within a very short time period (<1 s)[12], when aiming at the same light source, the relationship between the aureole and dark-sky measurements can be described as

$$C_k(\lambda) = C_a(\lambda)\, V_a^{@6}(\lambda) / V_k^{@6}(\lambda), \tag{7}$$

where $C_k$ is the dark-sky radiance calibration coefficient $V_a^{@6}$ and $V_k^{@6}$ are output DNs of the aureole and dark-sky measurements at the scanning angle of 6°. Then the dark-sky normalized radiance $L_k$ can be expressed as

$$L'_k(\lambda;\Theta) = \frac{\pi \cdot \mathrm{LG} \cdot G_s(\lambda)}{\Omega_v \cdot \mathrm{HG}_a \cdot G_a(\lambda) \cdot V_0(\lambda) \cdot f_{\mathrm{es}}} \cdot \frac{V_a^{@6}}{V_k^{@6}} \cdot V_k(\lambda;\Theta). \tag{8}$$

Equations (6) and (8) provide a method to transfer the instrument extraterrestrial constant $V_0$ and the viewing solid angle $\Omega_v$ to the normalized sky radiance $L'$ by measuring radiometer output signals in the field.

A CIMEL CE318 Sun/sky radiometer, number 350 in AERONET[2], located on the roof of the Institute of Remote Sensing and Digital Earth (RADI), was used in this research work. The type of the radiometer #350 is dual Polar (DP), which has ten channels centered at 340, 380, 440, 500, 675, 870, 936, 1020, 1020i, and 1640 nm. The spectral channel 1020i is the second 1020 nm band using an independent optical path shared with the 1640 nm band[2,13], thus radiometer #350 is characterized by two viewing solid angles and two FOVs (one is covering the spectral range 340–1020 nm, and the other is covering the channels of 1020i and 1640 nm. In this Letter, the normalized radiances of six SKY measurement channels for two geometries are considered, while the bands used in the inversion procedures are only four common channels for the ALM measurement geometry.

The extraterrestrial constant $V_0$ of radiometer #350 is obtained by comparing with a master radiometer at Carpentras, a field calibration site located in southeastern France, on November 2, 2009, and the radiance calibration coefficients are obtained with an integrating sphere in Lille, France on October 28, 2009. The calibration coefficients are listed in Table 1.

The viewing solid angle $\Omega_v$ (units of sr) is a function of the FOV,

$$\Omega_v = 2\pi(1 - \cos(\mathrm{FOV}/2)). \tag{9}$$

The FOV is a basic parameter of an optical instrument, usually fixed in the design and manufacture (nominally 1.2° for the new CE318 radiometer types, e.g., NE, DP). However, this angle may change with instruments produced in different periods and especially with different types of instruments. According to Torres *et al.*[14], the maximum discrepancy of the FOV with respect to the CIMEL specification (1.2°) was 10%.

There are two ways to derive this solid angle. One is the so-called vicarious method by which one can directly compute this solid angle from historical calibration coefficients by using Eq. (2); the specific calculation steps have been presented by Li *et al.*[12], and the solid angle calculated from Eq. (2) is $4.0268 \times 10^{-4}$ sr for 340–1020 nm channels and $4.0114 \times 10^{-4}$ sr for 1640 and 1020i nm bands, and the FOVs are 1.297° and 1.295°, respectively, following Eq. (9).

Alternatively, by geometrically measuring the FOV of the radiometer, one can compute the solid angle by using

**Table 1.** Calibration Coefficients of Radiometer #350 on November 2, 2009 and October 28, 2009

| WV (nm) | 1020 | 1640 | 870 | 675 | 440 | 500 |
|---|---|---|---|---|---|---|
| $V_0$ | 9885.2 | 11303.8 | 26820.2 | 18751.1 | 10868.4 | 14905.4 |
| $C_a$ (W/m$^2$/sr/nm/DN) | 0.01802 | 0.00247 | 0.01708 | 0.01954 | 0.03956 | 0.03104 |
| $C_k$ (W/m$^2$/sr/nm/DN) | 0.00225 | 0.00031 | 0.00427 | 0.00488 | 0.00988 | 0.00776 |
| $E_0$ (W/m$^2$/nm) | 0.70776 | 0.23273 | 0.95432 | 1.51577 | 1.84143 | 1.92228 |

Eq. (9). A matrix measurement method[14,15] (the program to control the radiometer to do matrix measurements is provided by Cimel Electronique) was used to compute the FOV of the radiometer. The calculation of the $\Omega_v$ is given in[14]

$$\Omega_v = \sum_{x,y} \frac{V(x,y)\Delta S}{V(x_c, y_c)}, \tag{10}$$

where $x$ and $y$ are the orthogonal coordinates, $V(x,y)$ represents the DN measured at coordinate $(x,y)$, $x_c$ and $y_c$ are the estimated pointing errors; $\Delta S$ is the differential area, same as $\mathrm{d}x\mathrm{d}y$.

In this Letter, the matrix measurement in the lab by using laser as light source was chosen to obtain the FOVs of radiometer #350 on August 20, 2014 at 03:00:00 (UTC). The subfigure on the left in Fig. 1 displays the 3D surface map of the raw measurements. The right subfigure shows the plane map of the measurements. The average FOV calculated from five matrix measurements is 1.300°(±0.004°) for 340–1020 nm, which is close to the results of the vicarious method.

In this Letter, the FOV obtained with matrix measurements of the laser was adopted to calculate the normalized radiance.

The extraterrestrial solar irradiance at each wavelength is calculated from the convolution of the solar spectral irradiance and the filter transmittance (the response function of the sensor is flat within the narrow band according to the manufacture), as follows:

$$E_0(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) \cdot R(\lambda) \cdot \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda) \cdot \mathrm{d}\lambda}, \tag{11}$$

where $E_s(\lambda)$ is the spectral irradiance of the Sun, $R(\lambda)$ is the spectral transmittance profile of the filter from the instrument manufacturer, and $\lambda_1$ and $\lambda_2$ denote the boundaries of the filter profile. In this work, we consider using the ASTM2000 spectra[16], which has been commonly used in the community. The spectral irradiance of #350, $E_0(\lambda)$, can be found in Table 1.

According to the D6sky measurement protocol of the CE318 radiometer, the aureole and dark-sky measurements at the fixed scanning angle, 6°, should be the same, ignoring the time shift of the two measurements and the errors during the optical signal to electrical signal conversion of the radiometer. However, there is always some discrepancy of radiances at 6° due to the uncertainties of the radiance calibration coefficients following traditional AERONET's calibration approach. In order to explain this discrepancy, we first employ one year's (2010) measurements to calculate the normalized radiance with AERONET calibration coefficients $C_a$ and $C_k$, and then we compare the radiances of the D6sky measurements. Two examples, measured in SPP and ALM measurement geometries, have been chosen to illustrate the jump between aureole and dark-sky measurements at the scanning angle of 6°. Table 2 shows the differences in the normalized radiance based on AERONET calibration between D6sky measurements for SPP and ALM geometries, while the radiance calculated with the new transfer method is exactly the same.

AERONET's inversion code[9] was chosen to test the performance of the aerosol retrievals. The normalized radiances calculated with AERONET calibration coefficients $C_a$, $C_k$ and the transfer method are chosen as the input. Meanwhile, the AOD and other initial guesses are kept the same for the two inversion procedures. Therefore, differences can only originate from the two calibration approaches to investigate the performance of the transfer method.

One year's measurements by radiometer #350 at the Beijing RADI in 2010 were analyzed in this Letter. The average radiance difference at the scanning angle of 6° is 0.79% for ALM measurement geometry with the AERONET calibration. During the inversion procedure, the total residuals are 3.7% and 4.1% (the sky part residuals are 3.3% and 3.7%) by using the transfer method and the AERONET calibrations, respectively, according

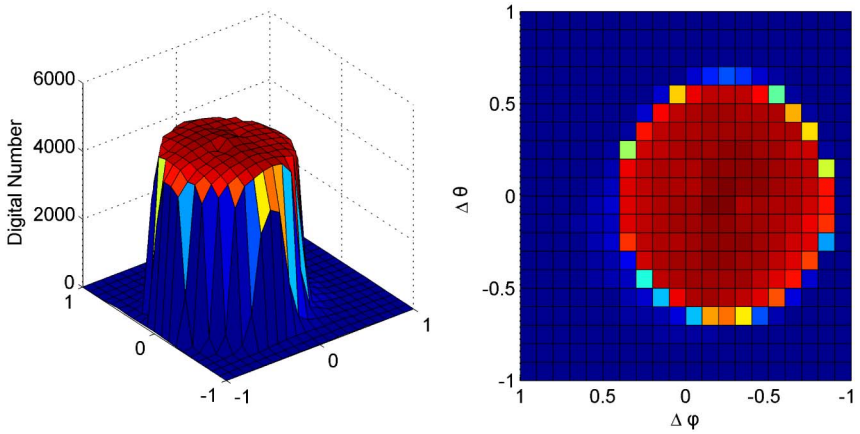


Fig. 1. Matrix measurements of radiometer #350. The left one shows the 3D surface map of the raw measurements taken in Beijing on August 20, 2014 at 03:00:00 (UTC), while the right one shows the plane map of the measurements.

**Table 2.** Average Differences in Normalized Radiance $L'$ Based on AERONET Calibration Between Double 6° Sky Measurements for Radiometer #350 in the Year 2010

| WV (nm) | 1020 | 1640 | 870 | 675 | 440 | 500 |
|---|---|---|---|---|---|---|
| Diff. in SPP $L'$ (%) | 0.32 | 0.28 | 0.19 | 0.27 | 0.15 | 0.18 |
| Diff. in ALM $L'$ (%) | 0.52 | 0.50 | 0.54 | 0.57 | 0.21 | 0.55 |

to residual definitions in AERONET's quality assurance criteria[17].

Figure 2 shows one year of average residuals of normalized sky radiances based on fitted and measured normalized radiance corresponding to the AERONET calibrations and the transfer method in ALM geometry. The residuals of the transfer method is generally smaller than that of the AERONET. Figure 3 shows an example of retrievals based on the AERONET calibrations and the transfer method. The total residuals (consisting of Sun and sky parts) of the inversion are 2.6% and 2.8% for the transfer method and the AERONET calibrations, respectively. There are differences in these two retrievals. From the previous description, the better retrievals come from the more accurate normalized radiances, thus the retrievals from the transfer method seem better than the AERONET method although there are no true values of the retrievals.

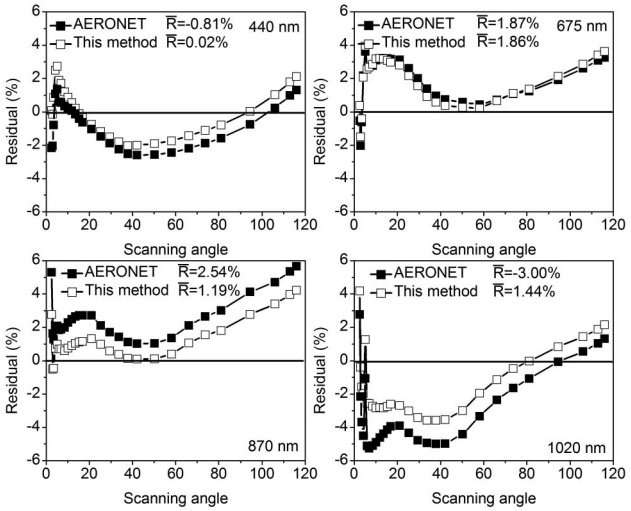


Fig. 2. Comparison of one year's averaged inversion residuals (difference between the fitted and measured normalized radiance) corresponding to the AERONET calibrations and the transfer method in ALM geometry; $\bar{R}$ denotes the averaged residual of the inversion.

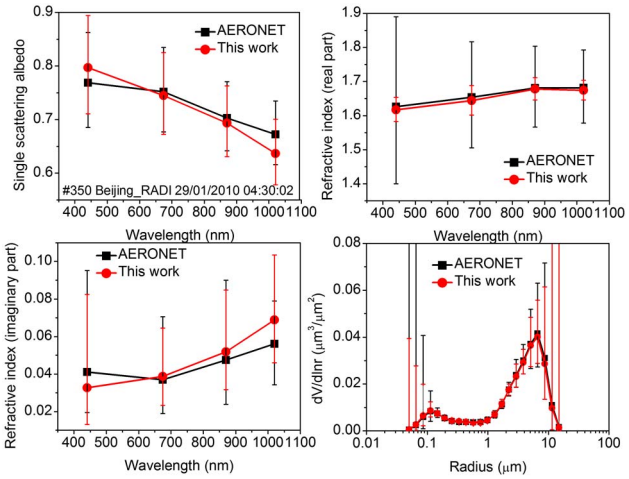


Fig. 3. Comparison of retrievals corresponding to the AERONET calibrations and the transfer method in ALM geometry. The vertical lines mean the min and max values of the retrievals.

The uncertainties in normalized radiance $L'$ can be estimated by the error propagation following Eq. (6); considering the independent error sources, one can obtain

$$\frac{\Delta L'_a}{L'_a} = \sqrt{\left(\frac{\Delta\Omega_v}{\Omega_v}\right)^2 + \left(\frac{\Delta(f_{\rm es})}{f_{\rm es}}\right)^2 + \left(\frac{\Delta\left(\frac{\rm LG}{\rm HG_a}\right)}{\frac{\rm LG}{\rm HG_a}}\right)^2 + \left(\frac{\Delta\left(\frac{G_s}{G_a}\right)}{\frac{G_s}{G_a}}\right)^2 + \left(\frac{\Delta V_0}{V_0}\right)^2 + \left(\frac{\Delta V_a}{V_a}\right)^2}. \tag{12}$$

On the right hand side of Eq. (12), four items are important: (i) the instrument viewing solid angle $\Omega_v$; (ii) the internal gain ratios $\mathrm{LG/HG}_a$; (iii) the instrument calibration coefficient $V_0$; (iv) the instrument measurement $V_a$. The uncertainty of the Sun-Earth distance correction factor is $10^{-4}$[18], which can be ignored considering it is minor compared with other error sources. The uncertainties from user gain ratios, the $G$ items, can also be neglected considering the gain techniques employed by the modern radiometers are sufficiently precise[13]. The estimated uncertainties are listed in Table 3.

**Table 3.** Uncertainties Estimated on the Normalized Radiance Based on the Transfer Method

| Error sources | Uncertainties (%) |
|---|---|
| $\Delta\Omega_v/\Omega_v$ | 1.5 |
| $\Delta\left(\frac{\rm LG}{\rm HG_a}\right)/\frac{\rm LG}{\rm HG_a}$ | 0.5 |
| $\Delta V_0/V_0$ (master, field) | 0.5, 1.5 |
| $\Delta V_a/V_a$ | 0.5 |
| Others | 0.5 |
| Total | 2.0 (master)/2.4(field) |

The most important error sources are from the viewing solid angle $\mathbf{\Omega}_v$ and $V_0$. The uncertainty in $\mathbf{\Omega}_v$ obtained by using the vicarious method is ~1.5% according to Li *et al.*[13], while the estimated error in $\mathbf{\Omega}_v$ obtained from the matrix measurement is also ~1.5% and can be decreased in the future. The uncertainty in $V_0$ for the Langley calibration instrument is ~0.5%[2] and, for the field calibration, one must consider an extra ~1% error in $V_0$[2]. The error in LG/HG$_a$ is from electronic circuit resistances, which have an order of magnitude of ~0.5% compared to theoretical values[12]. The error on the output DNs has an uncertainty of ~0.5%. The uncertainty in "others" covers all possible remaining error sources, e. g., errors in the user gain ratio items, the dark signal correction, and the spectral variation of the $\mathbf{\Omega}_v$ due to the optical dispersion effect. According to Eq. (12), the final uncertainty of $L'$ is ~2.0% for the Langley calibrated instruments, ~2.4% for the field calibrated instruments depending on $V_0$.

In conclusion, we propose a new transfer method to derive the normalized radiance for the ground-based CE318 Sun/sky radiometer. We present two methods to obtain the viewing solid angle $\mathbf{\Omega}_v$, which is then combined with the radiometer extraterrestrial constant $V_0$ to calculate the normalized radiance. The matrix measurement is done in the lab on August 20, 2014, which has a FOV of 1.300° for 340–1020 nm. The accuracy of the normalized radiance is assessed based on the error propagation method, which are ~2.0% for the Langley calibrated instruments and ~2.4% for the field calibrated instruments, depending on $V_0$. The consistency of the double 6° sky measurements is inspected, and the residuals of the aerosol inversion are compared. The new transfer method possesses the following features: (i) it avoids using $E_0(\lambda)$, which has considerable uncertainty; (ii) the transfer method uses high precision $V_0$ instead of $C_a$ and $C_k$. At the same time, considering the joint constraint of the AOD and radiance during the inversion, this transfer method guarantees the consistency of the input information and inversion process, hence can improve the accuracy of retrievals; (iii) the transfer method is easy to use and it does not need to do any integrating sphere calibration in the lab. Moreover, this method can be further improved by considering $\mathbf{\Omega}_v$ wavelength dependence, and more accurate $\mathbf{\Omega}_v$ characterization approaches.

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