Error Budget Analysis of the Proposed Vicarious Calibration Method with an On-Site Calibration

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Abstract

A method of vicarious calibration for visible to short wave infrared wavelength region of mission instruments onboard satellites based on the reflectance based method is proposed. The method allows to improve vicarious calibration accuracy utilizing spectral radiometer which allows to measure the downwelling radiance at the surface with a certain calibration accuracy by using a portable calibration source. At the same time, the stability of the spectral radiometer for surface reflectance and BRDF measurement is also improved by using the portable calibration source results in improvement of surface reflectance measurement. Through error budget analysis, it is found that 9.7% of vicarious calibration accuracy improvement can achieved by the proposed method compared to the typical vicarious calibration methods based on the reflectance based method results in 3.16% of vicarious calibration accuracy can be achieved by the proposed method.

Introduction

The reflectance based method of vicarious calibration of the mission instruments onboard satellites is now widely used [l]. In the method, optical depth is measured with sun-photometer. Since Rayleigh optical depth due to atmospheric molecular is calculated precisely with atmospheric pressure, aerosol optical depth can be estimated by subtracting the Rayleigh optical depth from the measured optical depth in total. Assuming an aerosol model, aerosol type (refractive index) and size distribution, the Top of the Atmosphere (TOA) radiance can be estimated with a radiative transfer equation (RTE). According to the error budget analysis, the most influencing factor to the TOA radiance estimation accuracy is refractive index followed by size distribution, BRDF measurement (surface and plaque as a reference panel for the surface reflectance measurement), optical depth measurement [2]. Other than these, the vicarious calibration based on the solar irradiance [3], the vicarious calibration with a well-characterized scene [4], the vicarious calibration with an optical depth due to water vapor estimation based on down welling radiance measurement data at the surface [5], the vicarious calibration based on radiative transfer calculation by means of inversion with the measured optical depth and aureole [6], the vicarious calibration with an integration of the aforementioned methods [7], the vicarious calibration taking into account the BRDF of the plaque for surface reflectance measurement [8], etc. were proposed. In terms of BRDF measurement of plaques, Spectralon was carefully measured [9] while a comparison between the Spectralon and Barium Sulfide was reported [10]. Furthermore, stability and contamination of Spectralon in the wavelength region of ultra-violet was reported [11].

In this paper, a method for improving estimation accuracy of refractive index by measuring a down welling radiance at the surface with a precise calibration based on an on site calibration source. In the radiation transfer process, down welling radiance is estimated with all the parameters required including refractive index of aerosol. The refractive index is estimated by minimizing the difference between the estimated and the measured down welling radiance at the surface. The proposed method also intends to improve the estimation accuracy of the surface BRDF through a monitoring the stability of a ground based spectral radiometer with the on site calibration source.

Firstly, the method is proposed followed by experimental results showing a validity of the proposed method. Finally, results from an error budget analysis is discussed in comparison between the proposed method and the typical reflectance based method.

Proposed Method

A typical reflectance based method is illustrated in Figure 1.

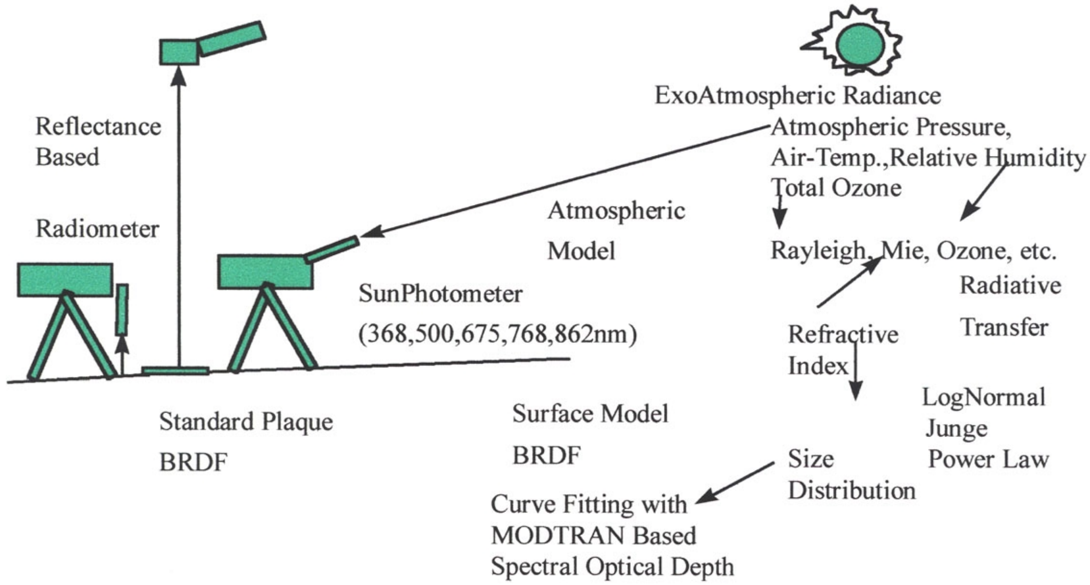

Figure 1. Illustrative view of a typical reflectance based vicarious calibration method

In order to estimate TOA radiance, plane parallel multi-layered atmospheric model, in general, is used. In the wavelength of visible to near infrared, molecular absorption and scattering can be estimated precisely with MODTRAN 4.0 of atmospheric model. It is hard to estimate Mie scattering component, in particular, aerosol type (as well as estimation of refractive index) identification and size distribution. An error budget analysis for the Gauss-Seidel iterative method of multiple scattering calculation with a typical atmospheric condition (Solar Zenith=45 degrees, observation angle=10 degrees, Junge parameter=3.0, optical depth of molecular=0.12, optical depth of aerosol=0.2, surface reflectance=0.5, real part of refractive index=1.14, imaginary part of refractive index=0.005±50% at the wavelength of 550 nm) shows that changes of the TOA radiance are 1.6, 1.8, and 2.1% when the imaginary part of refractive index=0.0025, 0.005, and 0.0075, respectively as is shown in Figure 2. It can be a great contribution to determine the imaginary part of refractive index of aerosol more precisely. An iterative method for estimation of imaginary part based on the measured down welling radiance with an absolute certain calibration accuracy better than 1% is proposed here. The estimated down welling radiance at the surface with a set of atmospheric parameters including imaginary part of refractive index of aerosol can be compared to the measured radiance. By minimizing the square of the difference between the estimated and the measured radiance, more precise imaginary part of refractive index of aerosol can be estimated.

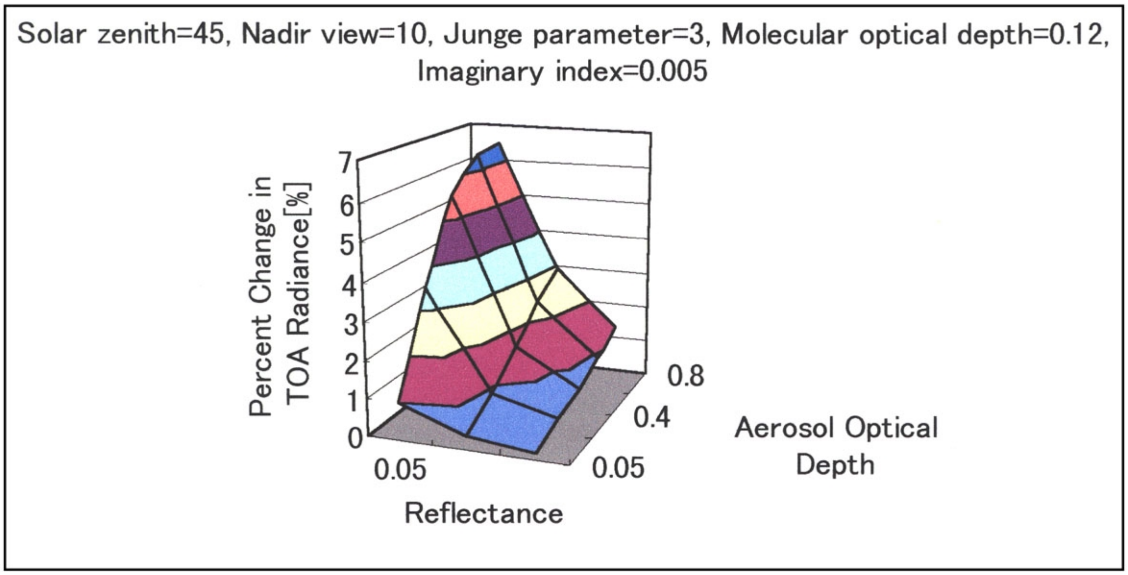

Figure 2. Sensitivity of the imaginary part of refractive index of aerosol to the estimated TOA radiance

Downwelling radiance at the surface, $I^{-}(\tau,\omega)$ can be expressed as follows,

$$I^{-}(\tau,\omega) = I(0,\omega)\exp\{-(\tau/|\mu|)\} + \int_0^{\tau} \exp\{-(\tau-\tau')/|\mu|\} J^{-}(\tau',\omega) d\tau'/\mu \tag{1}$$

where $\omega=(\mu,\phi)$ denotes incident angle, $I(0,\omega)$ is solar irradiance, $J^{-}(\tau',\omega)$ is down welling radiance at the layer of the optical depth of τ' so that the first term of the equation (1) expresses the down welling radiance of the direct solar irradiance while the second term represents the down welling sky light or diffuse irradiance. Assuming the atmosphere composed with n layers and the optical depth of each layer is same and is expressed τ_I where i= 1,2,...,n with the step of $\Delta\tau$ ($0=\tau_0<\tau_I<...<\tau_n=\tau$), down welling radiance at the surface can be estimated by means of Gauss-Seidel iteration. The down welling radiance at the layer between (τ_I, τ_{I+2}) can be approximated as follows,

$$\begin{aligned} I^{-}(\tau_{I+2},\omega) &= I(\tau_I,\omega)\exp\{-(2\Delta\tau/|\mu|)\} + \int_0^{\tau} \exp\{-(\tau_{I+2}-\tau')/|\mu|\} J^{-}(\tau',\omega) d\tau'/\mu \\ &= I(\tau_I,\omega)\exp\{-(2\Delta\tau/|\mu|)\} + (1-\exp\{-(2\Delta\tau/|\mu|)\}) J^{-}(\tau_{I+1},\omega) \end{aligned} \tag{2}$$

where the optical depth can be estimated with precisely calculated Rayleigh optical depth and aerosol optical depth assuming refractive index and size distribution. Minimizing the difference between the calculated and the measured down welling radiance at the surface, a best fit refractive index (imaginary) can be obtained. In conjunction with this procedure, absolute calibration accuracy of the measuring instrument is important. In order to ensure the accuracy, on site calibration source is required.

On-Site Calibration Source

In terms of on site calibration source, B. C. Johnson et al. proposed FEL lamp as well as semi-standard lamps with diffuse glass [12], etc. It is not easy to get a stable enough and a contamination free calibration source. In this paper, a portable box type of calibration source of a semi-standard lamp with silicon photomonitor is proposed. Figure 3 and 4 show the outlook of the calibration source and the configuration.

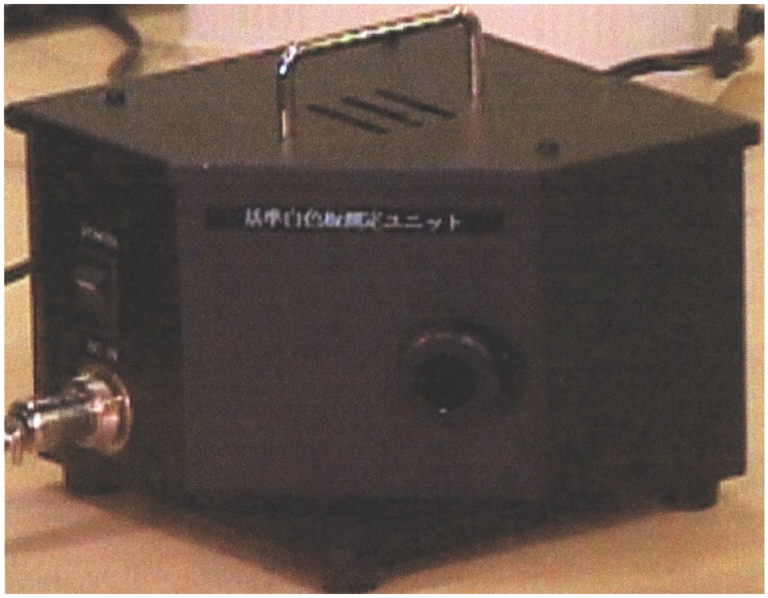

Figure 3. Outlook of the proposed portable calibration source

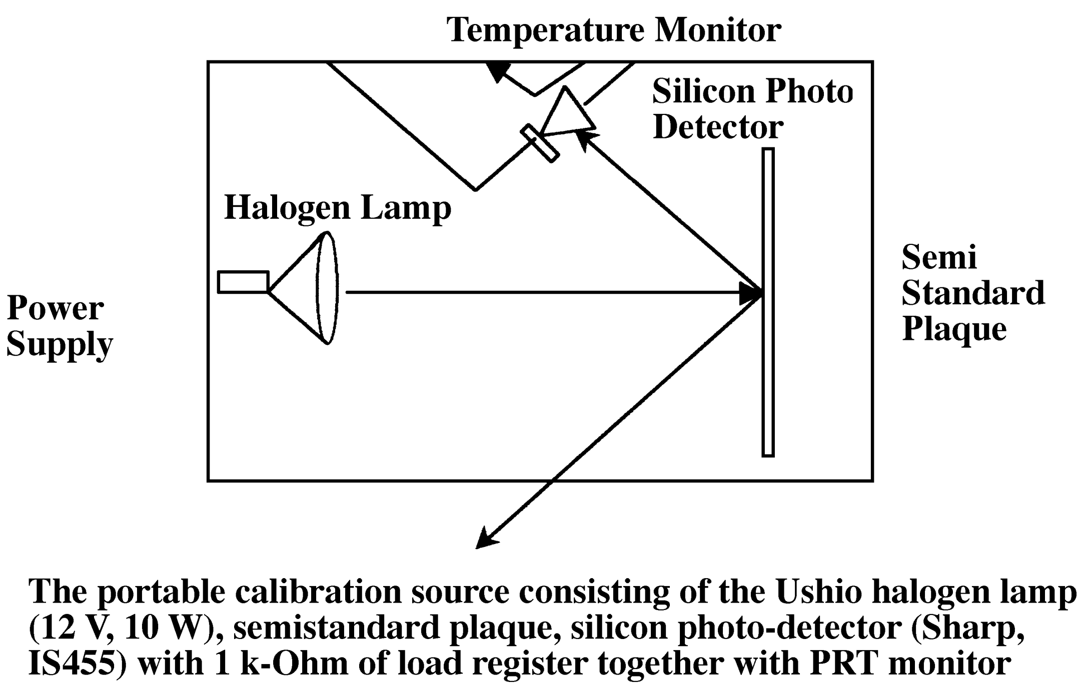

Figure 4. Configuration of the portable calibration source

Usually, field campaign is take place at a dusty areas such as playas, deserts so that contamination free is mandatory. The calibration source proposed here is the box type so that it essentially is a contamination free. Furthermore, it has stability monitor, silicon photodiode so that the output radiance from the calibration source can be corrected after the field campaign. It also is useful to check the stability of the spectral radiometer for the surface reflectance measurement.

The calibration source consists of semi-standard lamp of halogen lamp (12 V, 10 W) manufactured by Ushio Co. Ltd. with semi-standard plaque of barium sulfide produced by Opt-research Co. Ltd., silicon photodiode of Sharp IS455 of Shotkey Barrier type of linear output scale of diode with 1 kΩof loard register, temperature monitor (PRT) of Satoh Model-PC-3500 with 0.01 K of accuracy. This is a totally battery drive source of which the supply voltage is monitored by data logger with 0.05 V of accuracy. The stability and the absolute calibration accuracy of the silicon photodiode is a key. By referencing the output radiance from the integrating sphere installed at Nasu factory of Fujitsu Ltd., the stability and the absolute calibration accuracy is measured. Figure 5 shows how to measure the absolute calibration accuracy of the portable calibration source.

Figure 5. Test configuration of absolute calibration accuracy of the portable calibration source (right)

On left hand side, there is the exit port (30 cm in diameter) of 1 m of the Labsphere integrating sphere of Fujitsu Ltd. while on the right hand side, there is the proposed portable calibration source. In the middle, there is the Ocean Optics fiber spectral radiometer with the wavelength coverage from around 410-820 nm.

Figures 6, 7, 8 and 9 show percent changes of the silicon photodiode output against supply voltage (4.5-7.5 V) and room temperature changes (293-303 K), dark output changes against room temperature changes(293-303 K) and the changes of the output radiance from the portable calibration source for the time duration (4 hours and 23 minutes), respectively. From these measured data, it is concluded that the absolute calibration accuracy of the portable calibration source is around 1% while the stability of the source is better than 1%.

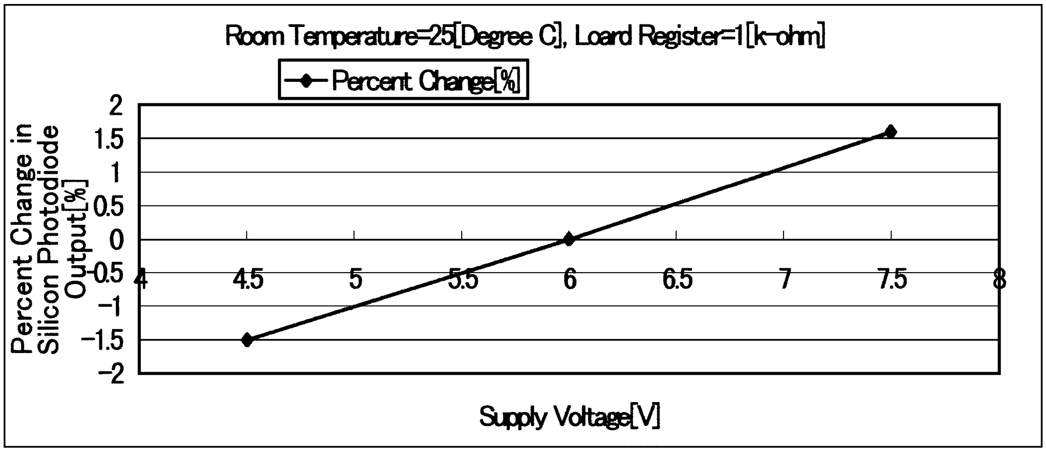

Figure 6. Percent change of photodiode output against supply voltage change from 4.5 to 7.5 V

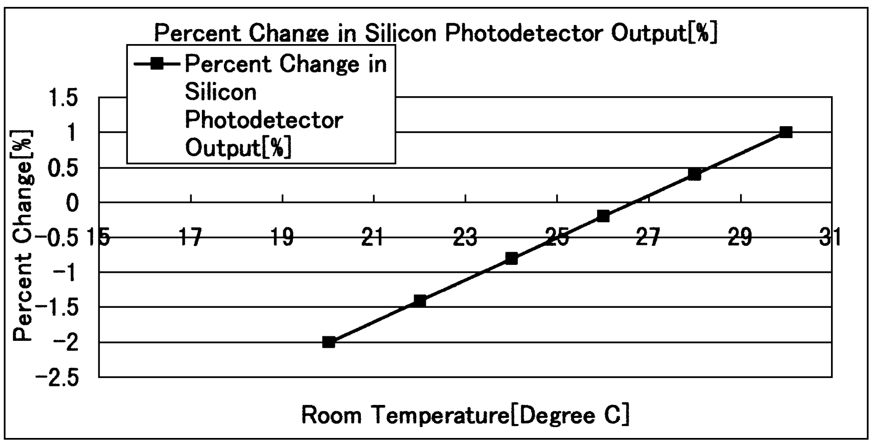

Figure 7. Percent changes of photodiode output against room temperature change from 20 to 30 degrees C

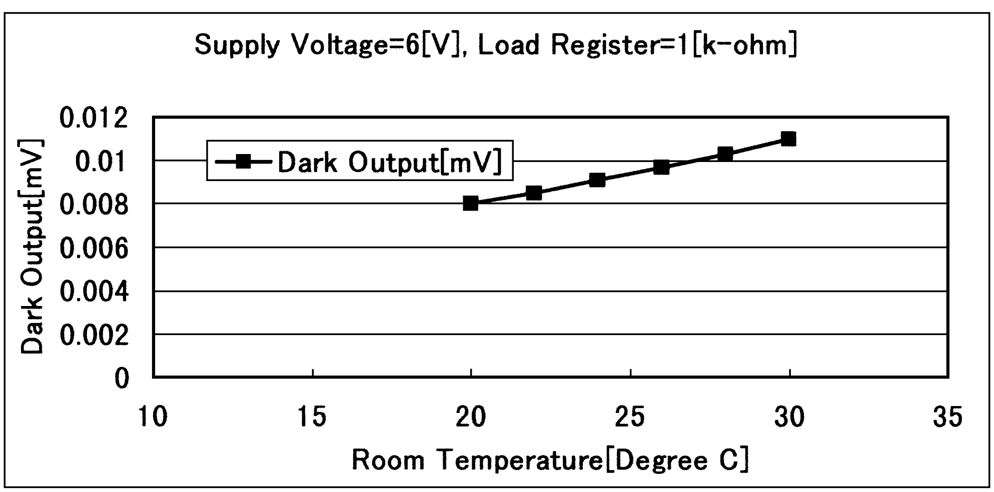

Figure 8. Dark output changes against room temperature change from 20 to 30 degrees C

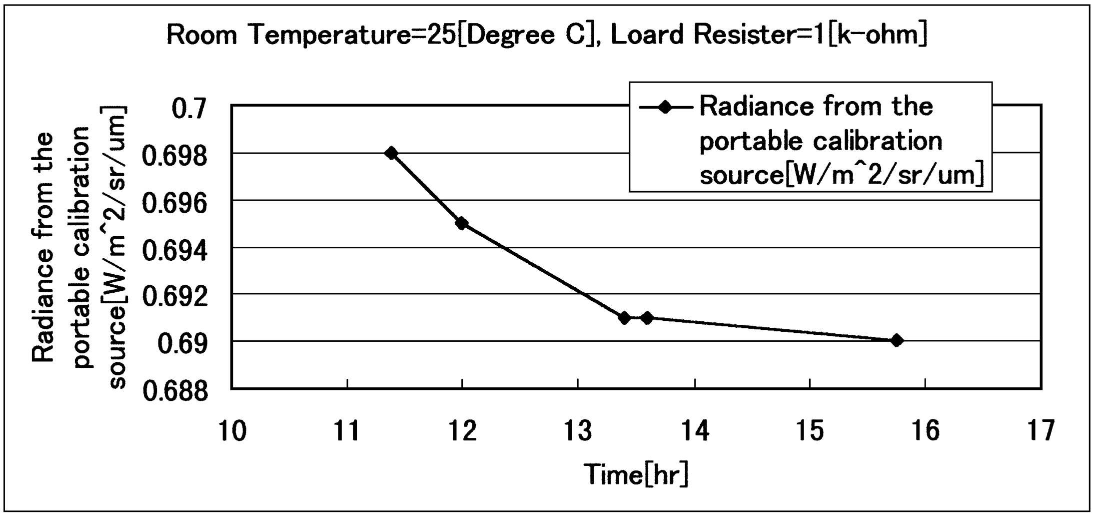

Figure 9. Radiance change for the time duration from 11:23 to 15:46 on August 24, 1998

Error Budget Analysis

The error sources for the typical reflectance based vicarious calibration are as follows,
1.Optical depth measurement (Sun photometer calibration accuracy, etc.)
2.Surface reflectance measurement (Stability of the spectral radiometer, BRDF of the plaque, averaging error, etc.)
3.Radiative transfer calculation (Refractive index and size distribution of aerosol, code error, etc.)
4.Mis-registration (Identification error of the test site location in the satellite imagery data, etc.)

With the portable on site calibration source, estimation accuracy of the imaginary part of the refractive index of aerosol is improved by ensuring absolute calibration accuracy of the spectral radiometer for optical depth measurement as well as down welling radiance at the surface. The stability of the spectral radiometer is improved by referring the sensitivity of the spectral radiometer for surface reflectance measurement as well as BRDF measurement. As the results, the Root Sum Square Error (RSSE) of Table 1 is concluded.

Table 1. Error budget for the typical and the proposed method

	% Error	
Error Sources	Typical	Proposed
Optical depth measurement	1.0	1.0
Surface reflectance measurement as well as surface BRDF	1.0	1.0
BRDF of the plaque	1.0	1.0
Others in the surfaced measurement (Including averaging)	0.0	0.0
Aerosol refractive index	1.8	1.0
Aerosol size distribution	2.0	2.0
Radiative transfer code	1.0	1.0
Mis-identification of the test site location in satellite images	1.0	1.0
Root Sum Square Error (RSSE)	3.50	3.16

It is assumed that imaginary part of the refractive index of aerosol can be estimated with 1% of accuracy by using a well calibrated down welling radiance at the surface. The other errors were justified in the reference [13].

Concluding Remarks

It is concluded that the proposed method of reflectance based vicarious calibration method achieve around 3.2% of calibration accuracy which corresponds to 9.7% of improvement compared to the typical reflectance based vicarious calibration method.

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