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Evaluation of BAER surface model for aerosol optical thickness retrieval over land surface

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Abstract

Estimation of surface reflectance is essential for an accurate retrieval of aerosol optical thickness (AOT) by satellite remote sensing approach. Due to the variability of surface reflectance over land surfaces, a surface model is required to take into account the crucial factor controlling this variability. In the present study, we attempted to simulate surface reflectance in the short-wave channels with two methods, namely the land cover type dependent method and a two-source linear model. In the two-source linear model, we assumed that the spectral property can be described by a mixture of vegetated and non-vegetated area, and both the normalized difference vegetation index (NDVI), and the vegetation continuous field (VCF) was applied to summarize this surface characteristic. By comparing our estimation with surface reflectance data derived from Moderate Resolution Imaging Spectroradiometer (MODIS), it indicated that the land cover type approach did not provide a better estimation because of inhomogeneous land cover pattern and the mixing pixel properties. For the two-source linear method, the study suggested that the use of NDVI as parameterization for vegetation fraction can reflect the spectral behavior of shortwave surface reflectance, despite of some deviation due to the averaging characteristics in our linear combination process. A channel-dependent offset and scalar factor could enhance reflectance estimation and further improve AOT retrieval by the current Bremen AErosol Retrieval (BAER) approach.

1 Introduction

Atmospheric aerosols play an important role in regulating the global climate with their direct radiative forcing and indirect effect on cloud microphysics and cloud albedo. With time-series routine observation, satellite remote sensing of aerosols provides an unprecedented capability for understanding global aerosol budgets and their spatial/temporal variability. The large uncertainties of radiative forcing and radiant flux

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could be minimized with enhanced scientific understanding of different aerosol loadings. Terrestrial and ocean remote sensing, which requires accurate absolute atmospheric correction, can also benefit from a priori knowledge about the composition of atmospheric constituents (gases, molecules, and aerosol loading) and their potential contribution to the top-of-atmosphere (TOA) satellite signals. Meanwhile, potential environmental control also requires precise estimates about anthropogenic contribution to ambient aerosol budget and the corresponding transport of these pollutants.

Such an effort has been fulfilled by a mounting contribution from geostationary and polar-orbiting satellite platforms with corresponding measuring techniques. Based on the spectral, angular, and polarization properties of solar radiation which interacts with atmospheric aerosol, AOT and columnar mass concentration can be retrieved and further validated with ground-based AErosol Robotic NETwork (AERONET) (Holben et al., 2001).

The retrieval of optical aerosol properties from spaceborne measurements requires an estimation procedure to separate surface and atmospheric contribution from the TOA radiance. In contrary to ocean surface, which benefits from its distinct low surface reflectance in the NIR channel, land surface is characterized by inhomogeneous cover pattern and variant surface reflectance, and presents lower surface reflectance in the shortwave channels. Therefore, a priori knowledge of surface contribution for the shortwave regions is essential for accurate aerosol retrieval over land surface. A dark surface approach (Kaufman et al., 1997; Levy, 2009), which takes advantage of empirical inter-correlated spectrum between 2.1 µm and shortwave channels at 0.465 or 0.645 µm, has been developed by MODIS science team for AOT retrieval in the vegetated and dark soil areas. Since other ocean color instruments, like SeaWiFS (Sea viewing Wide Field Spectrometer) or MERIS (MEdium Resolution Imaging Spectrometer), do not have observations at 2.1 µm channel like MODIS, the inter-correlation approach cannot be applied. Therefore, the Bremen AErosol Retrieval (BAER) approach uses a two-source linear model (von Hoyningen-Huene et al., 2003, 2011) to estimate shortwave surface reflectance, with an assumption that surface spectral properties can

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be properly described by a linear mixture of spectra between green vegetation and bare soil. This linear mixture, an acronym of vegetation cover fraction, is tuned by the normalized difference vegetation index (NDVI). Therefore, this technique can even be applied to multi-spectral sensors without observations in the mid-infrared range. Over land, however, the application is limited to the shortwave spectral regions (e.g. 0.412–0.665 µm for MERIS), since high surface reflectance accompanied by high uncertainties in the infrared regions will produce a larger error for AOT retrieval. With a series of calibration and improvements, BAER approach has been applied to multi-spectral radiometers such as SeaWiFS, MERIS (Hoyningen-Huene et al., 2006, 2011), and MODIS over a wide variety of land cover patterns (Dinter et al., 2006).

MERIS is one of the principal sensor onboard ESA's environmental satellite (ENVISAT), which is designed in a sun-synchronous orbit with equator crossing time around 10:00 a.m. The total field of view is 68.5°, which corresponds to a footprint swath of 1150 km at a platform reference altitude of 800 km. A global coverage of earth can be acquired in every 3 days with a spatial resolution of 300 m (full resolution at nadir) and 1200 m (reduced resolution). The primary objective of MERIS is to investigate the ocean color, both in the costal zones and open ocean. However, with its 15 programmable spectral bands between 0.390 and 1.040 µm, MERIS is also ideal for atmospheric and terrestrial remote sensing. The characterization of atmospheric constituent is also essential for a reliable retrieval of underlying surface phenomena (Bezy et al., 2000).

Since estimation of terrestrial surface reflectance is critical for accurate measurements of aerosol properties, this study aims to evaluating current BAER surface model for AOT retrieval over land surfaces. Specifically, a description of the BAER surface treatment will be summarized, followed by an attempt to evaluate current two-source linear model with either NDVI or vegetation continuous field (VCF) as parameterization for vegetation fraction. Reference data for the evaluation of BAER surface model were MODIS reflectance data product, which were also used to derive correction for the present BAER surface model. We further investigated an alternative land cover dependent approach, which requires a priori knowledge of surface pattern. Finally, the AOT results based on the modified surface model were demonstrated for south-east Asia region.

2 Methodology and retrieved AOT

2.1 Bremen AErosol Retrieval (BAER)

BAER is used for AOT retrieval over both land and ocean surfaces. The theoretical basis is the focus on spectral property of solar radiation which interacts with atmospheric aerosols. The spectral AOT is assumed to have a smooth nonlinear property defined by Angström power law, from which the surface and aerosol reflectance components can be critically distinguished. To retrieve a first estimate of AOT, the relation between aerosol reflectance and AOT must be defined. This is described in the lookup table (LUT) built by radiative transfer model (RTM) calculation with input data from Lindenberg Aerosol Characterization Experiment (LACE-98), where a closure between radiance and flux has been achieved amongst ground-based, aircraft, and satellite measurements (von Hoyningen-Huene et al., 2003). Meanwhile, the retrieval of aerosol reflectance must take into account all factors contributing to TOA signal. These include Rayleigh path reflectance, gases absorption, and surface reflectance, with an assumption that each component is independently coexisted. While the influence of gas absorption can be minimized by carefully avoiding the gas absorption bands, Rayleigh scattering and surface reflectance needs to be considered in the shortwave channel. A brief description of BAER algorithm will be as follows. A more detailed explanation and improvement can be found in von Hoyningen-Huene et al. (2003, 2007, 2009, 2011) and Dinter et al. (2006).

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The main part of BAER algorithm is the retrieval of aerosol reflectance, which is formulated as Eq. (1)

$$\rho_{\mathrm{Aer}}(\lambda, z_o, z_s) = \rho_{\mathrm{TOA}}(\lambda, z_o, z_s) - \rho_{\mathrm{Ray}}(\lambda, z_o, z_s, P_{\mathrm{Surf}}(z)) - \frac{T(\lambda, M(z_s)) \cdot T(\lambda, M(z_o)) \cdot A_{\mathrm{Surf}}(\lambda, z_o, z_s)}{1 - A_{\mathrm{Surf}}(\lambda, z_o, z_s) \cdot \rho_{\mathrm{Hem}}(\lambda, z_o)} \tag{1}$$

where ρ_{Aer}, ρ_{TOA}, ρ_{Ray} represent aerosol reflectance, TOA reflectance, and path reflectance of Rayleigh scattering, respectively. They are wavelength-dependent (λ) and affected by zenith distance for illumination geometry z_o and viewing geometry z_s. $P_{\mathrm{Surf}}(z)$ is the surface pressure at ground elevation z(km) for determination of atmospheric Rayleigh scattering. ρ_{TOA} can be derived from the normalization of MERIS TOA radiance $L(\lambda)$ to extraterrestrial irradiance $E_0(\lambda)$ with consideration of airmass factor for solar elevation M_0, as Eq. (2)

$$\rho_{\mathrm{TOA}}(\lambda) = \frac{\pi L(\lambda)}{E_0(\lambda)} \cdot M_0. \tag{2}$$

The part of surface contribution observed on satellite sensor is presented in the last term of Eq. (1), where $T(\lambda, M(z_0))$ and $T(\lambda, M(z_s))$ are the total atmospheric transmission that includes both direct and diffuse transmission for incoming and outgoing radiation. Together with hemispherical atmospheric reflectance ρ_{Hem}, these three factors are determined by the parameterization from radiative transfer calculations.

For the application of AOT retrieval over land surface, due to heterogeneous cover patterns and the corresponding mixing spectral behavior, a surface model is required to account for the crucial factors determining this variability. This is expressed as the surface reflectance term A_{Surf} in Eq. (3)

$$A_{\mathrm{Surf}}(\lambda) = \frac{F}{\mathrm{BRDF}} \cdot \left(C_{\mathrm{veg}} \cdot \rho_{\mathrm{veg}}(\lambda) + \left(1 - C_{\mathrm{veg}}\right) \cdot \rho_{\mathrm{soil}}(\lambda)\right). \tag{3}$$

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where spectral surface property is described by a two-source mixture of reference reflectance between green vegetation ρ_{veg} and bare soil ρ_{soil}. This linear mixing is defined by the fraction of vegetation cover C_{veg}, with atmospherically corrected NDVI for parameterization. BRDF stands for bidirectional reflectance distribution function and consider the anisotropy effects of land surfaces. Details can be found in Dinter et al. (2007). F is the scaling factor used to normalize estimated surface spectra to each satellite scenes, as Eq. (4)

$$f = \frac{\rho_{TOA}(0.665) - \rho_{Ray}(0.665) - \rho_{Aer}(0.665)}{\left(C_{veg} \cdot \rho_{veg}(0.665) + \left(1 - C_{veg}\right) \cdot \rho_{soil}(0.665)\right)}. \quad (4)$$

MERIS channel 7 at 0.665 µm is used as the reference channel, since the influence of Rayleigh and aerosol scattering will be minimized with increasing wavelength. Therefore, a higher confidence of scene-dependent normalization can be achieved in this channel.

2.2 Application of surface model in BAER AOT retrievals

With the described BAER approach, aerosol optical thickness was retrieved for the first seven shortwave channels of MERIS. One example was shown for channel 1 (0.412 µm) of 14 February 2007 scene over south-east Asia (Fig. 1), where Taiwan is located in the center of this subset image and most areas are cloud free with exception that the northern part was affected by the cloud system coming from mainland China. Within this scene and time frame (14 February 2007, 24 February 2007, 30 March 2007), four AERONET stations (Central Weather Bureau, Lulin, Environmental Protection Administration, and Cheng-Kong Uni.) could be used for the comparison. The validation results suggested that BAER AOT and ground-based observations are generally well correlated (Fig. 2). However, a tendency for overestimation during low AOT events, and underestimation during high AOT events could also be observed. These deviations may result from inhomogeneous surface properties or un-accounted surface contribution from current two-source linear model. An evaluation of BAER surface model is essential to characterize its deficiency and to potentially enhance its global applicability.

3 Simulation of surface reflectance

BAER approach has been applied to multi-spectral sensors such as SeaWiFS and MERIS. However, the validation with ground-based measurements from AERONET stations indicates an overestimation of BAER AOT during low aerosol events. Since land surface is characterized by inhomogeneous cover pattern, estimated surface reflectance might present a high uncertainty for the AOT retrieval. An evaluation of BAER surface model is essential and with potential to improve the current surface model. Several questions concerning about the surface model include: (1) can two-source linear model account for variant surface reflectance due to heterogeneous land cover? (2) Is NDVI appropriate for parameterization of vegetation fraction? Are there alternatives? (3) Are there alternative approaches which can derive a better estimate for surface reflectance? (4) Is the reference reflectance approach suitable for surface reflectance estimation for the entire seasons? To answer these questions, simulation tests have been performed on BAER surface model, such that BAER two-source approach and a land cover type dependent approach have been conducted, and the resultant surface reflectance have been compared with other satellite data. We also evaluated the capability for using VCF, instead of NDVI, for parameterization of vegetation fraction. Meanwhile, the two-source model and surface parameters such as vegetation fraction (C_{veg}) and reference reflectance (ρ_{veg}, ρ_{soil}) have been evaluated, while we kept the BRDF as constant (BRDF = 1) in our simulation processes.

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3.1 Data preparation

Since MODIS and MERIS have similar spectral channels and observation time, we used MODIS collection 5 surface reflectance product (MOD09GA) as our reference dataset, which contains daily spectral data (Band 3: 0.459–0.479 µm, Band 4: 0.545–0.565 µm, Band 1: 0.620–0.670 µm, Band 2: 0.841–0.876 µm, Band 5: 1.230–1.250 µm, Band 6: 1.628–1.652 µm, Band 7: 2.105–2.155 µm) with spatial resolution of 500 m. Data accuracy has been assessed over a widely distributed set of AERONET sites and time periods by several validation efforts (Vermote and Vermeulen, 1999).

For simulation and comparison purposes, MODIS scenes of south-east Asia on 30 January, 14 February, 4 February, 30 March, 19 April, 10 May, 30 June, 8 July, 16 August, 15 September, 23 October, 16 November, and 27 December in 2007 were acquired and cloud screened. Test sites of surface reflectance were specifically chosen for major land cover types of Taiwan, including evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), mixed forest (MF), grassland (Gr), cropland (Cr), bare soil (Ba), and urban (Ur) area, with each site covering a 5 km × 5 km area with homogeneous cover pattern (Table 1). Consequently, surface reflectance for each land cover (ρ_{ENF}, ρ_{EBF}, ρ_{MF}, ρ_{Gr}, ρ_{Ba}, ρ_{Ur}) was retrieved for each data scene (Fig. 3), and reference reflectance for vegetation and bare soil ($\rho_{veg\_testarea}$, $\rho_{soil\_testarea}$) was derived with consideration of the corresponding cover ratio for the weighting process (Fig. 4). Meanwhile, NDVI was calculated based on the surface reflectance in red (0.620–0.670 µm) and NIR spectral channels (0.841–0.876 µm).

Other affiliated dataset acquired for the simulation includes MODIS land cover product (MOD12) and VCF. Land cover map was used to test the capability of an alternative land cover dependent approach for reflectance estimation. The VCF, which defines the coverage ratio of green vegetation in a specific area, was retrieved based on an empirical relation between MODIS NDVI and fraction of vegetation from fine-scaled SPOT HRV data.

3.2 Simulation of surface reflectance based on BAER surface model and alternative approaches

3.2.1 Simulation based on two-source model

To evaluate if BAER surface model can address the variability of surface reflectance, a simulation was performed based on the two-source approach with reference reflectance (ρ_{veg}, ρ_{soil}) derived from test areas of each MODIS scenes, and NDVI as input parameter for vegetation fraction (C_{veg}) as Eq. (5)

$$A_{\text{Surf\_Sim1}}(\lambda) = C_{\text{veg}} \cdot \rho_{\text{veg\_testarea}}(\lambda) + \left(1 - C_{\text{veg}}\right) \cdot \rho_{\text{soil\_testarea}}(\lambda). \tag{5}$$

This simulation results will be compared with surface reflectance of each MODIS scenes (Sect. 5) and serve as the reference data for alternative approaches.

3.2.2 Simulation with VCF as vegetation fraction

In highly vegetated areas, the saturation problem for red energy absorption implies that the inverse relationship between red reflectance and chlorophyll concentration is no longer effective (Huete et al., 1996). Low reflected red energy causes a highly saturated NDVI close to 1. Therefore, NDVI and fraction of vegetation cover do not present a simple linear relation. To account for this difference, VCF was applied to the two-source model and serve as an alternative for NDVI as parameterization for vegetation fraction (C_{veg}) as Eq. (6)

$$A_{\text{Surf\_Sim2}}(\lambda) = \text{VCF} \cdot \rho_{\text{veg\_testarea}}(\lambda) + (1 - \text{VCF}) \cdot \rho_{\text{soil\_testarea}}(\lambda). \tag{6}$$

The simulated surface reflectance $A_{\text{Surf\_Sim2}}$ will be validated with MODIS surface reflectance to determine if VCF can derive better reflectance with the current two-source approach.

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3.2.3 Simulation based on land cover type dependent method

An alternative to two-source model is the combination with reference reflectance for each land cover pattern (ρ_{ENF}, ρ_{EBF}, ρ_{MF}, ρ_{Gr}, ρ_{Ur}), rather than generalized surface reflectance ρ_{veg} and ρ_{soil}. Such a method would require a prior knowledge of the land cover pattern, either from a database approach or from its recognition from concurrent satellite observation. In the presented study, MODIS land cover product (MOD12) was applied for the simulation test. The spectral surface property for each pixel areas was assumed to be a linear mixture of spectral behavior between dominant land cover pattern and the bare soil, with VCF as characterization for this linear combination, as Eq. (7)

$$A_{Surf\_Sim3}(\lambda) = VCF \cdot \rho_{landcover\_veg\_testarea}(\lambda) + (1 - VCF) \cdot \rho_{soil\_testarea}(\lambda). \quad (7)$$

With a land cover map as reference, $\rho_{landcover\_veg\_testarea}$ could be determined from spectral signature amongst vegetated land cover (ρ_{ENF}, ρ_{EBF}, ρ_{MF}, ρ_{Gr}).

3.2.4 Simulation based on constant reference surface reflectance

The original BAER two-source approach relies on pre-defined reference reflectance ρ_{veg} and ρ_{soil} as constants for its linear mixture of surface spectral property. To evaluate surface model and enhance AOT retrieval, the simulation also needs to take into account the reference reflectance currently used in our BAER model. This reflectance database was taken from the measurements by a CASI radiometer during LACE-98 in Lindenberg of Germany (von Hoyningen-Huene et al., 2003). Since surface reflectance is also temporally and spatially dependent (Table 2), the evaluation of BAER surface model based on constant spectral reflectance is necessary to justify its capability for global and all seasonal application. With MODIS NDVI as parameterization for C_{veg}, we simulated the surface reflectance for seven MERIS spectral channels as Eq. (8)

$$A_{Surf\_Sim4}(\lambda) = C_{veg} \cdot \rho_{veg}(\lambda) + \left(1 - C_{veg}\right) \cdot \rho_{soil}(\lambda). \quad (8)$$

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However, contrary to $A_{\mathrm{Surf\_sim1}}$, an inland water mask was applied to the simulation result $A_{\mathrm{Surf\_sim4}}$, in order to demonstrate the applicability of two-source approach in the inland water areas. This simulated reflectance will be compared with MODIS counterpart to evaluate our BAER surface model.

4 Results and discussion

4.1 Evaluation of two-source approach

To evaluate the two-source approach, it was applied to simulate surface reflectance in the shortwave channels with NDVI and reference reflectance derived from each MODIS scene, and the simulation results were further validated with concurrent MODIS surface reflectance. The comparisons indicated that with the two-source approach, a linear dependence of surface reflectance can be found with vegetation fraction expressed by NDVI. However, BAER approach also tends to overestimate surface reflectance for low reflectance regions, and underestimate for high reflectance regions (Fig. 5), due to the averaging process in the two source model. Since vegetation fraction is defined between 0 and 1, reference reflectance ρ_{soil} and ρ_{veg} will determine the upper and lower bounds of the estimated reflectance. Meanwhile, BAER surface model did not predict well in the inland water districts and the places affected by terrain shadows, since these low NDVI regions would imply high reflectance based on the BAER concept, but in reality it is contrary to the satellite observation. This deviation may have an impact on our AOT retrieval.

An inspection of spectral reflectance histogram can give us insights about the capability of two-source approach for reflectance estimation. For seven MODIS channels, the distributions in Band 3 (0.459–0.479 µm), Band 4 (0.545–0.565 µm), and Band 1 (0.620–0.670 µm) are quite similar with two distinct peaks dominated by vegetated and non-vegetated areas (Fig. 6), which implies that a better estimation result can be expected with the two-source linear model. On the other hand, the spectral properties

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in Band 2 (0.841–0.876 µm), Band 5 (1.230–1.250 µm), and Band 6 (1.628–1.652 µm) cannot be fully described simply by vegetation and non-vegetation difference (Fig. 7). Features such as surface water content may also influence surface reflectance. Meanwhile, the correlation of spectral behavior between Band 7 and Band 3, 4, 1 also justify the inter-correlated spectrum approach developed by MODIS science team for AOT retrieval.

4.2 Evaluation of VCF as vegetation fraction

VCF is defined as the proportional estimates for vegetative covers. It may depict areas of heterogeneous land cover better than discrete classification scheme. Compared to NDVI, VCF provides an absolute physical measure of the surface property. Therefore, this study modified linear mixing model and simulated surface reflectance with VCF as parameterization for C_{veg}. In Fig. 8, the comparison between simulated reflectance and MODIS counterpart has suggested that the slope of the regression line has increased (compared to Fig. 5). However, the modification will also introduce more uncertainty from VCF retrieval to the estimated reflectance. The use of NDVI can still better preserve a linear relation and the correlation (Table 3).

4.3 Evaluation of land cover type dependent method

In the two-source approach, spectral surface property is assumed to be a generalization between vegetation cover and bare soil. In reality, land surface is characterized by various land cover patterns, while each with its distinct spectral behavior. An attempt was to incorporate this land cover difference into generalized two-source model. The simulated surface reflectance was validated with MODIS counterpart. However, the comparison suggested that the modified method would result in large scattering of the retrieval results (Fig. 9). In areas covered by inhomogeneous land cover pattern, the mixing spectral property would possibly lead to misclassification, and such errors would further introduce more uncertainty to the estimated reflectance. Since there may

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be multiple land cover types coexisted in a certain region, the spectral property based on discrete classification may not explain well about the continuous surface reflectance.

4.4 Evaluation of surface model based on reference surface reflectance

The evaluation of BAER surface model based on test area reflectance have shown that the estimated reflectance can retain a linear relation with MODIS counterpart, despite of some deviation due to the averaging characteristic of two-source model. To account for this deviation and potentially improve the surface model, the simulation also needs to take into account the reference reflectance (based on LACE-98) that is currently used in the BAER surface model. Surface reflectance were simulated according to Eq. (8) for seven MERIS bands (Band 1: 0.407–0.417 µm, Band 2: 0.437–0.447 µm, Band 3: 0.485–0.495 µm, Band 4: 0.505–0.515 µm, Band 5: 0.555–0.565 µm, Band 6: 0.615–0.625 µm, Band 7: 0.660–0.670 µm) and compared with those of MODIS spectral channels (Band 3: 0.459–0.479 µm, Band 4: 0.545–0.565 µm, Band 1: 0.620–0.670 µm). Due to channel mismatch between two sensors, we have to compare simulated MERIS Band 1 to Band 4 results with those of MODIS Band 3, simulated Band 5 with MODIS Band 4, and simulated Band 6 and 7 with MODIS Band 1. The comparison indicated a similar scenario as the simulation based on test area reflectance, such that deviation has occurred but the linear relation has been preserved (Fig. 10). Meanwhile, the correlation has been somehow improved (Table 3) because inland water regions were excluded in the comparison process.

Based on the comparison results, an attempt has arisen to rectify the simulated reflectance A_{surf_sim4} so as to improve the AOT retrieval, as Eq. (9)

$$A_{Surf\_Sim}(\lambda) = (d \cdot (A_{Surf\_Sim4}(\lambda) - e)) \cdot f. \quad (9)$$

In this equation, a channel-dependent offset e and scalar factor d were introduced to simulated reflectance A_{surf_sim4}, such that the estimated reflectance and MODIS one would have a simple one to one ratio. However, since we compared simulated results from MERIS Band 1 to Band 4 with those of MODIS Band 3, the scalar and offset derived based on this comparison would introduce identical spectral reflectance for MERIS, which is not theoretically correct. Due to such channel mismatch between MODIS and MERIS, another scalar factor f is required to account for the smooth change of spectral behavior among MERIS channels (Band 1 to Band 4). The same problem also occurred for Band 6 and Band 7 results. Therefore, a scaling process based on the spectral slope ($\Delta\rho/\Delta\lambda$) has performed to retain the smoothly changing spectral behavior. For illustration, the modification has been applied to the reference reflectance ρ_{soil} and ρ_{veg}, which defines the upper and lower boundary for the original simulated reflectance $A_{\text{Surf\_sim4}}$. The comparison suggested that a much wider range and smooth spectral change of the estimated reflectance $A_{\text{Surf\_sim}}$ could be expected following the introduction of these offset and scalar factors (Fig. 11). Subsequently, this modified reflectance $A_{\text{Surf\_sim}}$ will be applied to the BAER surface model for calculation of spectral AOT.

Retrieved AOTs with modification of surface reflectance have been compared with those without modification (Fig. 12). The correlation plot indicated that the two scenarios are generally well correlated, and an increase of AOT (about 9 %) for high AOT regions and a decrease for low AOT regions have been found for MERIS channel 1 (0.412 µm) following the correction for surface reflectance. This will somehow account for the AOT deviation based on previous validation results (Fig. 2). For the coastal zones (red circles) mainly covered by urban city and rice paddy, high variant surface reflectance and positive NDVI- reflectance relation for the inland water regions would imply uncertainty for AOT retrieval based on the two-source model. The correction procedure for surface reflectance may also not predict well for these regions, and the following normalization and reiteration process may further enlarge the difference for retrieved AOT.

For MERIS channel 2 (0.443 µm) and channel 4 (0.510 µm), similar results were found. About 12 % and 20 % increases of AOTs in high AOT regions could be seen for channel 2 and 4, respectively. Meanwhile, a slight decrease for low AOT cases had also been found. Thus the changes in AOT following modification of BAER surface

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model go into the right direction, which reduces the underestimation for high AOT and the offset values for low AOT cases in the AERONET inter-comparisons.

5 Conclusions

Satellite retrieval of optical aerosol property requires an estimation procedure for surface reflectance to separate surface contribution from top-of-atmosphere reflectance. Unlike ocean surface, land surface is characterized by heterogeneous cover pattern, and lower surface reflectance is presented in the shortwave regions. Therefore, estimation of spectral surface reflectance in these shortwave channels is essential for accurate retrieval of aerosol optical thickness over terrestrial environment. BAER uses spectral properties of solar radiation which interact with atmospheric aerosols for separation of surface and aerosol reflectance components. Over land, a two-source linear model is applied to estimate shortwave surface reflectance, with an assumption that surface spectral properties can be described by a linear mixture of spectra between green vegetation and bare soil. This linear mixture, which describes vegetation cover fraction, is tuned by the NDVI. Therefore, this approach requires no observation in the mid-infrared range and can be applied for multi-spectral sensors such as MERIS and SeaWiFS. Since estimated surface reflectance might present a high uncertainty for the AOT retrieval, this study evaluated BAER surface model and simulated surface reflectance based on current two-source linear mixing model and alternative surface parameters.

Based on the comparison with MODIS collection 5 surface reflectance products, a linear dependence of surface reflectance can be described by the two-source approach with vegetation fraction expressed by NDVI. The high correlation ($R \sim 0.91$) has also justified the capability for the two-source approach to account for spectral behavior of heterogeneous land cover pattern for the shortwave regions, with the possibility that some deviation may even be improved by introducing BRDF effect in our simulation process. However, BAER approach tends to overestimate surface reflectance for low

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reflectance regions, and underestimate for high reflectance regions. This deviation is mainly due to the averaging process in the two-source model, in which the reference reflectance has defined the upper and lower bounds of the estimated reflectance. Meanwhile, the two-source approach may not perform well for the inland water regions and areas affected by the terrain or cloud shadows. Since lower NDVI values in these regions would imply higher surface reflectance with two-source approach, which is not theoretically correct.

An alternative approach to the two-source model is to incorporate reference reflectance for each land cover type, instead of generalized spectral behavior between vegetative covers and bare soil. This method would require predefined land cover information, either determined from a database approach or from concurrent satellite scenes. However, the comparison has suggested that the land cover type dependent approach did not provide a better estimation, because the discrete classification scheme may not explain well for the continuous spectral property, especially for the heterogeneous land cover regions. Meanwhile, by introducing VCF as parameterization for vegetation fraction in the two-source model, more uncertainty resulting from VCF retrieval will further be transferred to the estimated surface reflectance. With atmospherically corrected NDVI, the BAER approach can still better reflect the spectral behavior governed by heterogeneous land cover pattern in the shortwave regions.

Since surface reflectance is also temporally and spatially dependent, the study has also evaluated the use of constant reference reflectance in the current BAER surface model, in order to justify its capability for global and all seasonal application. The comparison results indicated that a linear relation is retained between simulated reflectance and MODIS one, despite of some deviation for the absolute reflectance level due to averaging property of two-source model and seasonal difference. A channel-dependent offset and scalar factor was therefore introduced to the estimated surface reflectance. The retrieved AOT between modified and original versions were generally well correlated. However, a 9 % increase of retrieved AOT for high AOT regions and a decrease for low AOT regions have been found for the modified cases. This correction

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procedure could offset certain deviation between retrieved and AERONET-based AOT, and improve our AOT retrieval based on the current BAER approach.

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Table 1. Test areas of surface reflectance for major land cover types of Taiwan (ENF: evergreen needleleaf forest, EBF: evergreen broadleaf forest, MF: mixed forest, Gr: grassland, Cr: cropland, Ba: bare soil, Ur: urban).

land cover	num. of sites	center location of the test areas – Lon. (°), Lat. (°)
ENF	2	(121.01, 23.47) (121.38, 24.08)
EBF	5	(120.58, 24.05)(120.87, 24.55)(120.79, 22.31) (120.83, 22.71) (121.51, 24.78)
MF	2	(121.00, 24.23) (120.89, 22.85)
Gr	1	(120.72, 24.51)
Cr	3	(120.30, 22.93) (120.49, 23.63) (120.23, 23.01)
Ba	1	(120.50, 23.05)
Ur	2	(120.41, 23.35) (120.67, 24.15)

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Table 2. Reference reflectance used for BAER and reference reflectance derived from test areas based on MODIS scenes on 30 January 2007 and 16 August 2007.

	30 January 2007		16 August 2007		BAER	
	$\rho_{veg\_testarea}$	$\rho_{soil\_testarea}$	$\rho_{veg\_testarea}$	$\rho_{soil\_testarea}$	ρ_{veg}	ρ_{soil}
B (0.459–0.479 µm)	0.0098	0.0500	0.0199	0.0825	0.0500	0.0705*
G (0.545–0.565 µm)	0.0244	0.0885	0.0639	0.1535	0.1080	0.1130**
R (0.620–0.670 µm)	0.0193	0.0975	0.0396	0.1590	0.0820	0.1520***

* Average of reference reflectance for MERIS channel 2 (0.442 µm) and channel 3 (0.490 µm).

** MERIS channel 5 (0.560 µm).

*** Average of reference reflectance for MERIS channel 6 (0.620 µm) and channel 7 (0.665 µm).

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Table 3. Correlation and regression between MODIS reflectance and simulated reflectance (0.459–0.479 µm).

X ($Y = aX + b$)	Y	A	b	R	Purposes
MODIS reflectance	$A_{\text{surf\_sim1}}$	0.4712	0.1410	0.9079	evaluation of two-source approach
MODIS reflectance	$A_{\text{surf\_sim2}}$	0.6230	0.0024	0.6980	evaluation of VCF for C_{veg}
MODIS reflectance	$A_{\text{surf\_sim3}}$	0.3582	0.0183	0.4077	evaluation of land cover dependent approach
MODIS reflectance	$A^{*}_{surf\_sim4}$	0.2654	0.0336	0.9322**	evaluation of reference reflectance ρ_{veg} ρ_{soil}

* Simulated reflectance is based on reference reflectance for MERIS channel 2 (0.437–0.447 µm).

** An inland water mask has been applied to simulated reflectance before comparison.

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Table 4. Offset/scalar factor ($A_{surf\_sim}(\lambda) = (d(A_{surf\_sim4}(\lambda) - e))f$) for scenes on 14 February 2007, 24 February 2007, and 30 March 2007.

Date	14 February 2007			24 February 2007			30 March 2007		
MERIS band	*d*	*e*	*f*	*d*	*e*	*f*	*d*	*e*	*f*
1 (0.412 µm)	5.653	0.027	0.543	5.230	0.029	0.534	5.672	0.028	0.549
2 (0.442 µm)	3.768	0.034	0.783	3.487	0.036	0.780	3.781	0.035	0.785
3 (0.490 µm)	3.282	0.053	1.167	3.037	0.055	1.170	3.282	0.054	1.167
4 (0.510 µm)	3.179	0.060	1.330	2.942	0.063	1.336	3.190	0.061	1.325
5 (0.560 µm)	9.524	0.096	1.000	9.132	0.098	1.000	9.470	0.097	1.000
6 (0.620 µm)	3.021	0.083	0.977	2.458	0.085	1.002	2.856	0.085	0.988
7 (0.665 µm)	1.984	0.074	1.019	1.617	0.078	0.998	1.873	0.077	1.009

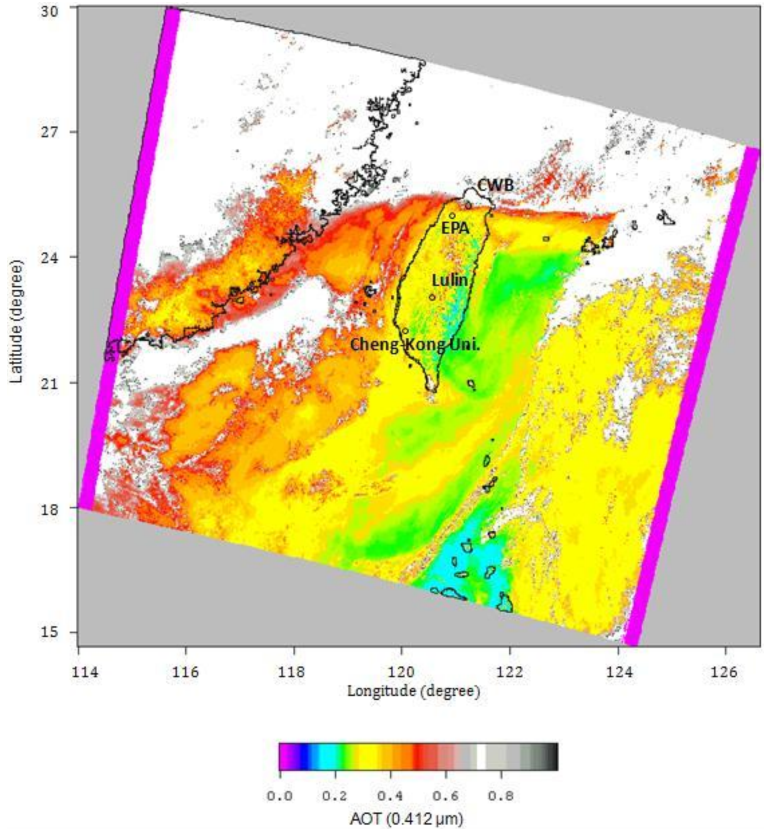

Fig. 1. Retrieval of AOT for MERIS channel 1 (0.412 µm) on 14 February 2007 over south-east Asia, where Taiwan is located in the center of this subset image and most areas are cloud free except at the northern tip affected by the climate system from mainland China. Four AERONET stations in Taiwan (CWB, Lulin, EPA, and Cheng-Kong Uni.) are also illustrated in the image.

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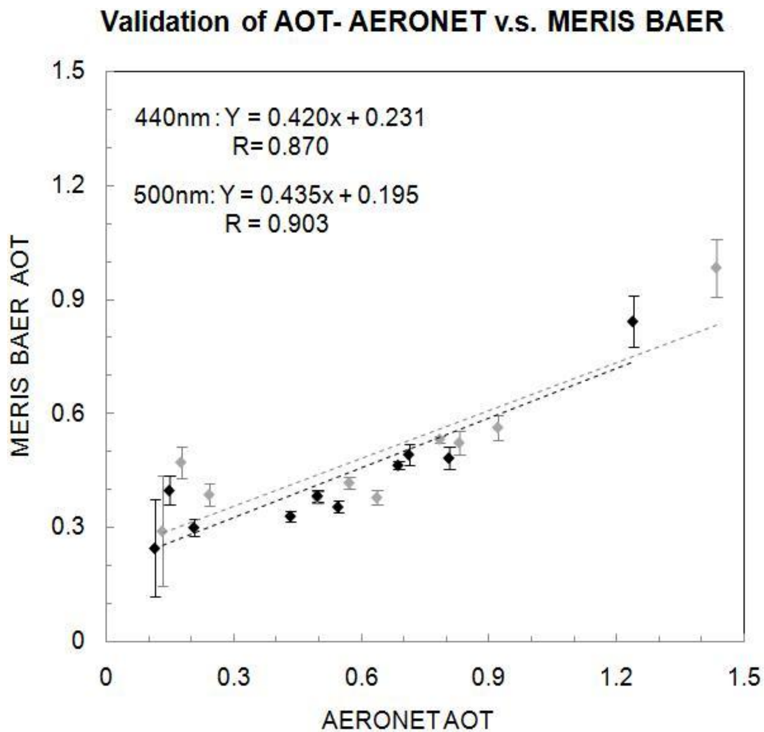

Fig. 2. Comparison of AERONET observations and BAER AOT for MERIS scenes on 14 February 2007, 24 February 2007, and 30 March 2007.

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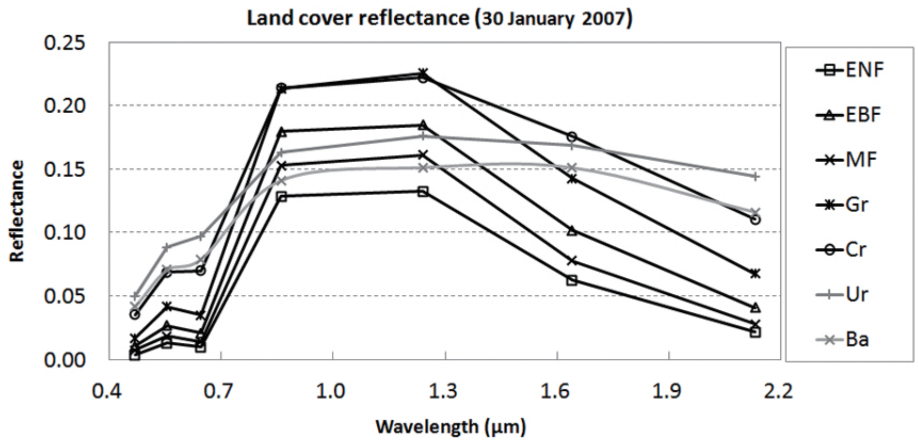

Fig. 3. Spectral reflectance of MODIS channel 1–7 (30 January 2007) for each land covers with test sites covering ENF, EBF, MF, Gr, Cr, Ba, and Ur.

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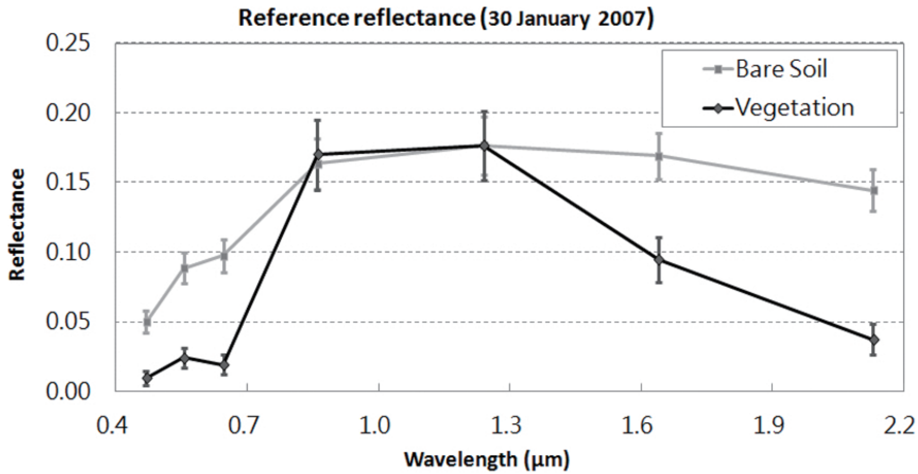

Fig. 4. Spectral reference reflectance $\rho_{veg\_testarea}$ and $\rho_{soil\_testarea}$ (30 January 2007) ($\rho_{veg\_testarea}$) was derived based on reflectance of the vegetated cover types (ρ_{ENF}, ρ_{EBF}, ρ_{MF}, ρ_{Gr}), while weightings depend on the cover ratio for each land cover; $\rho_{soil\_testarea}$ was derived according to reflectance of non-vegetated cover types (ρ_{Ur}, ρ_{Ba}).

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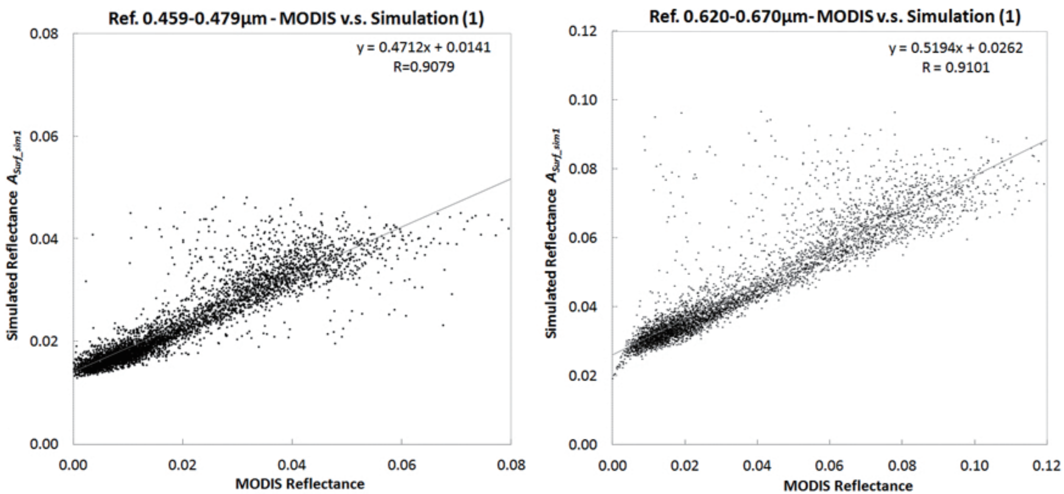

Fig. 5. The comparison between MODIS surface reflectance product and simulated reflectance from BAER approach in the 0.459–0.479 µm and 0.620–0.670 µm channels.

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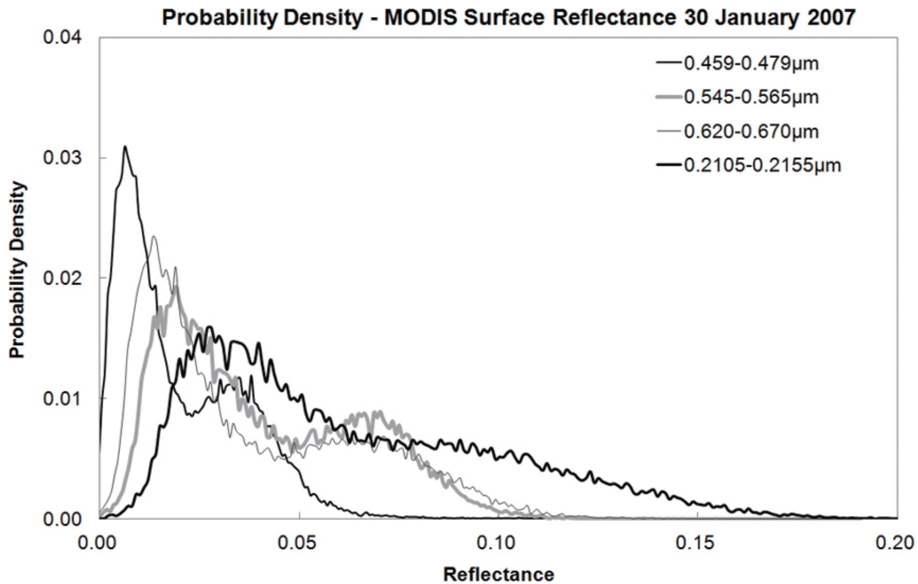

Fig. 6. Probability density of MODIS reflectance (30 Jan.uary 2007) for Band 3 (0.459–0.479 µm), Band 4 (0.545–0.565 µm), Band 1 (0.620–0.670 µm), and Band 7 (2.105–2.155 µm).

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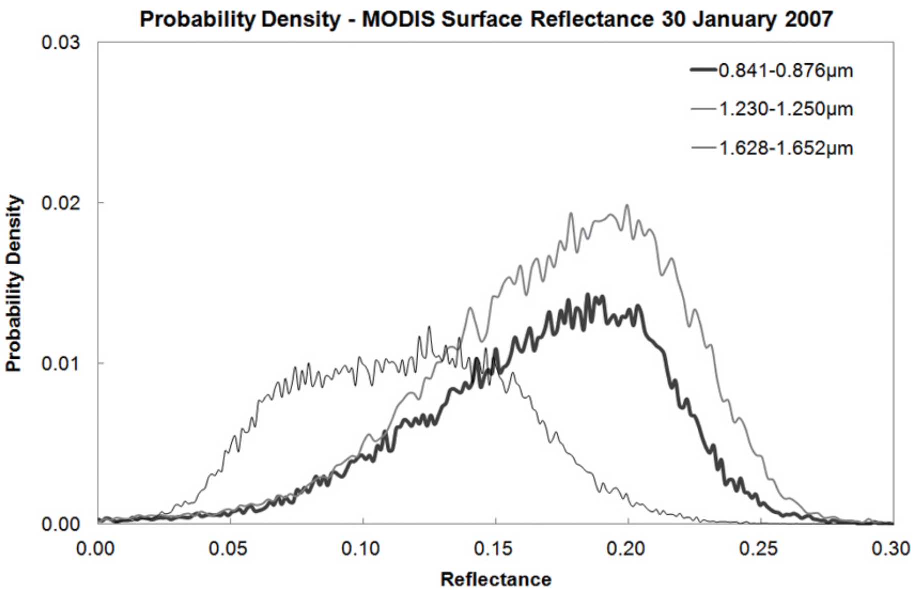

Fig. 7. Probability density of MODIS reflectance (30 January 2007) for Band 2 (0.841–0.876 µm), Band 5 (1.230–1.250 µm), and Band 6 (1.628–1.652 µm).

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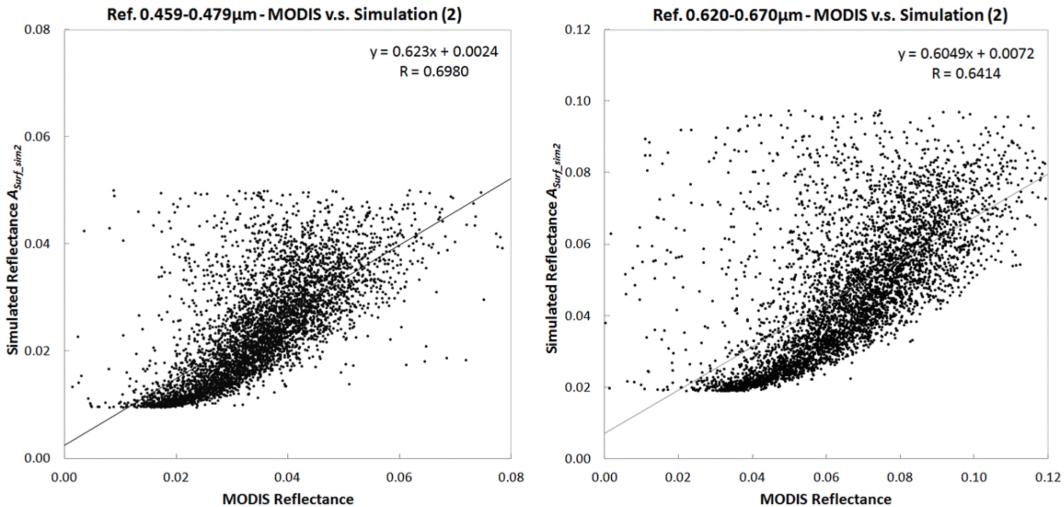

Fig. 8. Comparison between MODIS surface reflectance and simulated reflectance with VCF as parameterization for C_{veg}.

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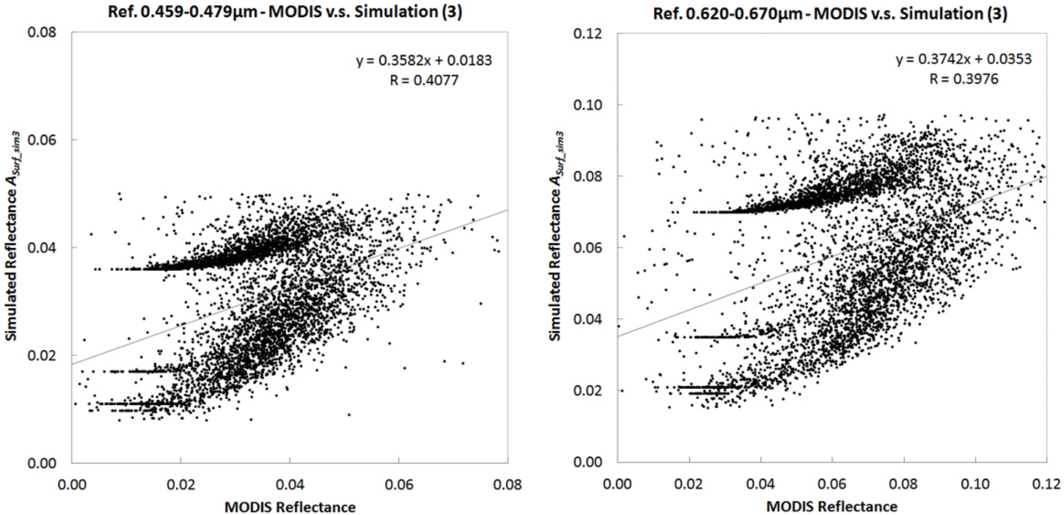

Fig. 9. Comparison between MODIS surface reflectance and simulated reflectance based on land cover dependent approach.

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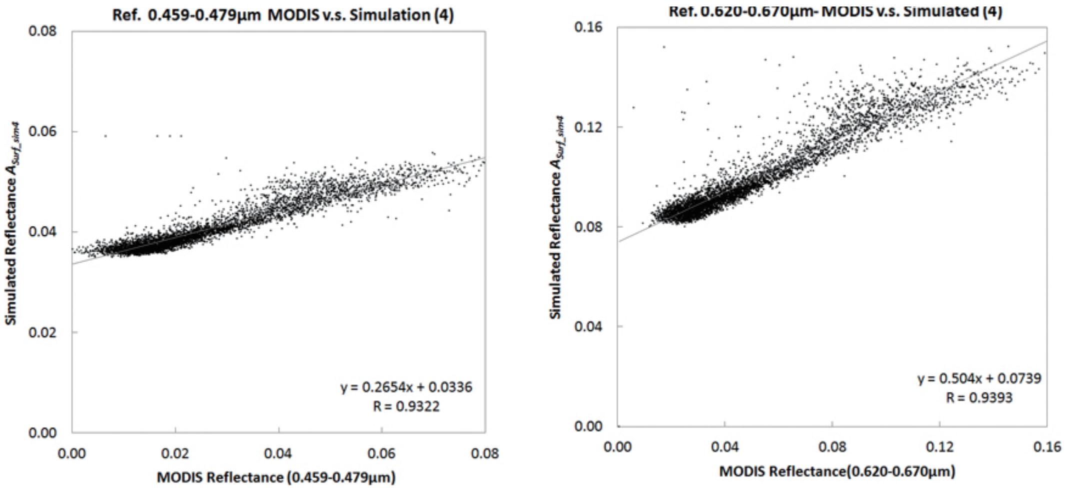

Fig. 10. Comparison between MODIS surface reflectance and simulated reflectance based on BAER reflectance database. Surface reflectance data from inland water regions were excluded from the comparison.

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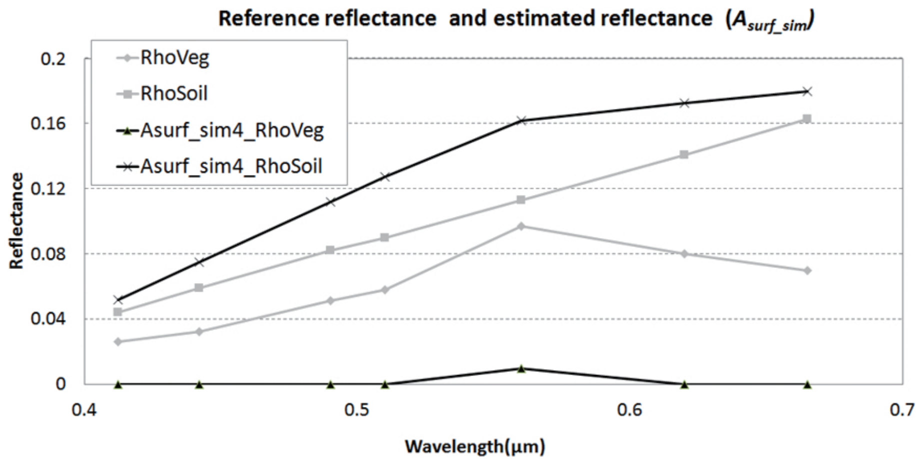

Fig. 11. Reference reflectance (ρ_{veg}, ρ_{soil}) and modified reflectance based on Eq. (9).

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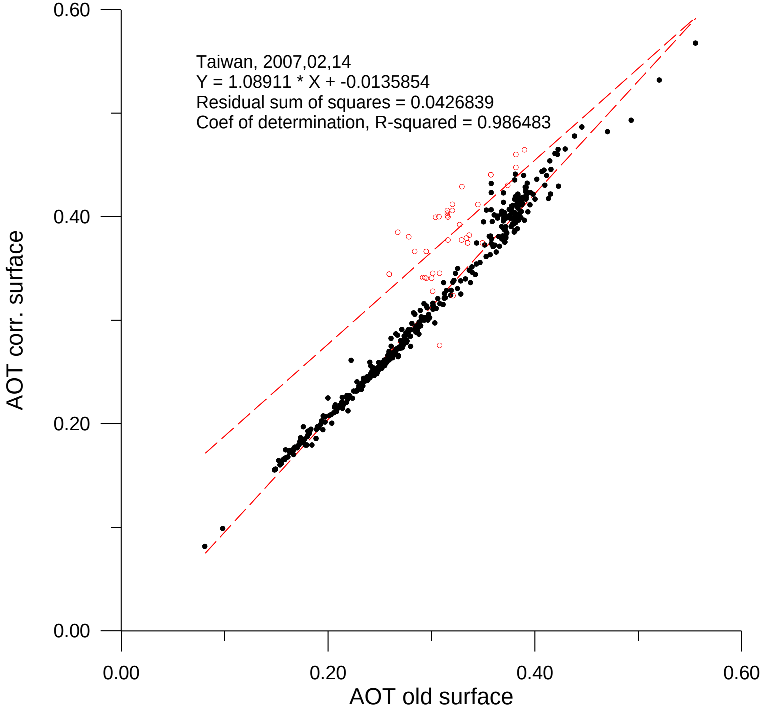

Fig. 12. Comparison of retrieved AOT for MERIS channel 1 (0.412 µm) with and without modification of estimated surface reflectance.