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Synergy of MODIS and AATSR for better retrieval of aerosol optical depth and land surface directional reflectance

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ABSTRACT

This paper presents a new algorithm to simultaneously retrieve Aerosol Optical Depth (AOD) and land surface Bidirectional Reflectance Distribution Function (BRDF) from Advanced Along-Track Scanning Radiometer (AATSR) by adopting gradient optimization method. Different from traditional method the approach presented here can perform simultaneous retrieval from each individual AATSR swath rather than multiple days. A theoretical sensitivity study proves the proposed method is insensitive to the distortion of initial BRDF. The presented algorithm is tested on AATSR data around four different Aerosol Robotic Network (AERONET) sites representing various types of land surface. Compared with the four selected AERONET sites' AOD and BRDF-derived albedo from AERONET-based Surface Reflectance Validation Network (ASRVN) data in corresponding four AERONET sites, the presented algorithm proves considerable accuracy for various type of land surface with correlation of AOD ranging from 0.647 to 0.911 and correlation of BRDF-derived albedo ranging from 0.483 to 0.944. The intersensor comparison with Moderate Resolution Imaging Spectroradiometer (MODIS) 3 km AOD dark target product reveals high coverage rate of the presented method especially in bright surface or nonvegetation area and the correlation between the two sensors reaches up to 0.967. The improved estimation of BRDF from AATSR retrieval in AERONET Beijing site is compared with MODIS MCD43B1 product. The relative differences in hemispherical albedo calculated from average BRDF shape function parameters between AATSR and MODIS product are 1.33%, 1.52%, 2.60% and 4.28% at 550 nm, 670 nm, 870 nm and 1600 nm respectively.

1. Introduction

Atmospheric aerosol has a significant influence on global climate change by both direct and indirect ways (Charlson et al., 1992; Kaufman and Nakajima, 1993; Kaufman et al., 2002; Kiehl and Briegleb, 1993; Twomey et al., 1984). Air quality and human health are also severely influenced by atmospheric aerosol (Brunekreef and Holgate, 2002). Even though the significance of aerosol is well recognized, considering the high spatio-temporal heterogeneity of aerosol distribution, atmospheric aerosol is one of the largest uncertainties in climate change modeling (IPCC, 2007) and air quality monitoring (Alsaadi et al., 2005).

Remote sensing observation can reduce the aerosol uncertainty by providing systematic observations in adequate spatial coverage. The signal obtained by the spaceborne remote sensing sensor measures the upwelling radiance at the top of the Earth's atmosphere (TOA). The upward radiance at TOA can be separated heuristically into two basic components, i.e., the radiance scattered by atmosphere and the radiance reflected by the surface. To derive high-precision aerosol information, surface contribution at TOA should be removed accurately (Hu et al., 1999; Wanner et al., 1997). Unfortunately, the land cover type varies and the reflectance over land exhibits spatio-temporal heterogeneity, bringing difficulty to surface contribution estimation. And the existence of directional effect of land surface further exacerbates the decoupling problem. Considering the inseparable nature of surface-atmospheric coupling, simultaneous retrieval method of aerosol properties and BRDF is crucial.

Multiple-view sensors, such as the Along-Track Scanning Radiometer (ATSR) series and the Multi-angle Imaging SpectroRadiometer (MISR), provide multi-angle observation of one object, which qualifies the capability of AOD retrieval considering BRDF effect. Martonchik et al. (1998) proposed an aerosol properties retrieval method from MISR observations over heterogeneous land surface using empirical orthogonal functions (EOFs). Veefkind et al. (1998) developed a dual-view algorithm using both the directional and spectral information in the ATSR-2 data to separate between atmospheric and surface contributions. But the assumption that the form of the BRDF is spectral invariant remains doubtful. Thomas et al. (2009) used the MODIS land surface bidirectional

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reflectance product to define the a priori surface reflectance for the derivation of the atmospheric aerosol properties from ATSR-2 and AATSR data. However, the a priori MODIS land surface bidirectional reflectance is directly used as input without further modification bringing error in the aerosol retrieval result (Sayer et al., 2012). Qin et al. (2015) presented a novel method to simultaneously retrieve aerosol properties and BRDF over Australia from AATSR based on scaling approach. Qin's method uses a stack of long time series observations ranging from multiple months to several years to encompass significant variation in solar zenith angle for land surface BRDF shape function fitting.

Almost all simultaneous retrieval methods use a stack of time series observations and assume the BRDF shape function doesn't change during the compositing period. However, these methods are only capable over certain areas such as arid and semi-arid rangeland or tropical savannas, where BRDF shape function remains stable all year round. It fails to depict BRDF when it comes to the regions where BRDF shape function changes with time such as deciduous broadleaf forest (Gao et al., 2003; Zhao et al., 2003). Such assumption sets obstacles for accurate simultaneous retrieval. A new method is desired to grasp the change of BRDF shape function with time and, in turn, improve the AOD retrieval accuracy.

In this paper, we propose an algorithm to retrieve AOD and improve the estimation of BRDF simultaneously from multi-angle data using scaling approach and gradient optimization method (Snyman, 2005). AATSR 1 km observation data in four visible and near infrared channels (550 nm, 670 nm, 870 nm and 1600 nm) at nadir and forward view is used as multi-angle data (Birks, 2007; Llewellyn-Jones et al., 2001). Contrary to traditional simultaneous retrieval method the proposed method produces AOD and BRDF shape function from each individual AATSR swath rather than multiple days allowing BRDF shape function to change with time.

The paper is organized as follows. The proposed simultaneous retrieval methodology is described in Section 2. Afterwards, the presented algorithm is tested and validated on AATSR images around four different Aerosol Robotic Network (AERONET) sites in Section 3. Finally, the summary and conclusion is derived in Section 4.

2. Methodology

2.1. Radiative transfer theory with coupled BRDF

For Lambertian surface under a plane-parallel atmosphere, the upward reflectance at the TOA can be described as follows (Liou, 2002):

$$R_{TOA}(\tau,\mu_s,\mu_v,\Delta\varphi) = R_{atm}(\tau,\mu_s,\mu_v,\Delta\varphi) + \frac{\rho_{surf}T(\tau,\mu_s)T(\tau,\mu_v)}{1-\rho_{surf}S(\tau)} \tag{1}$$

where R_{TOA} is the TOA reflectance, R_{atm} is atmospheric path reflectance, ρ_{surf} is the Lambertian surface albedo, T is the total downward or upward flux transmittance, and S is the spherical albedo of the atmosphere. In Eq. (1), τ is the optical depth of the atmosphere, μ_s and μ_v are the cosine of solar zenith angle and view zenith angle respectively, $\Delta\varphi$ is the relative azimuth angle.

However, Lambertian assumption is only an ideal condition. In real cases, the surface BRDF effect needs to be considered. The radiative transfer with coupled BRDF can be expressed as (Tanre et al., 1983; Vermote et al., 2006; Vermote et al., 1997):

$$\begin{aligned} R_{TOA}(\tau,\mu_s,\mu_v,\Delta\varphi) = {} & R_{atm}(\tau,\mu_s,\mu_v,\Delta\varphi) \\ & + e\frac{-\tau}{\mu_s}e\frac{-\tau}{\mu_v}r_{surf}(\mu_s,\mu_v,\Delta\varphi) \qquad \text{(a)} \\ & + e\frac{-\tau}{\mu_v}t_d(\tau,\mu_s)\overline{r}(\tau,\mu_s,\mu_v,\Delta\varphi) \qquad \text{(b)} \\ & + e\frac{-\tau}{\mu_s}t_d(\tau,\mu_v)\overline{r'}(\tau,\mu_s,\mu_v,\Delta\varphi) \qquad \text{(c)} \\ & + t_d(\tau,\mu_s)t_d(\tau,\mu_v)\overline{\overline{r}} + \frac{T(\tau,\mu_s)T(\tau,\mu_v)S(\tau)\overline{\overline{r}}^2}{1-S(\tau)\overline{\overline{r}}} \qquad \text{(d)} \end{aligned} \tag{2}$$

where r_{surf} is the directional surface reflectance explained detailedly in Eq. (7), t_d represents the diffuse transmittance and has the following relationship with T:

$$T(\tau,\mu) = e\frac{-\tau}{\mu} + t_d(\tau,\mu). \tag{3}$$

In Eq. (2), the contribution of the target to the signal at TOA is decomposed as the sum of four terms: (a) the signal directly transmitted to the target and directly reflected back to the sensor; (b) the signal scattered by the atmosphere then directly reflected back to the sensor; (c) the signal directly transmitted to the target but scattered by the atmosphere on their way to the sensor; and (d) the signal having at least two interactions with the atmosphere and one with the target.

In Eq. (2), $\overline{r}$, $\overline{r'}$ and $\overline{\overline{r}}$ are the coupling terms representing, respectively, the surface hemispherical-directional, directional-hemispherical and hemispherical-hemispherical reflectances. The coupling terms are defined as:

$$\overline{r}(\tau,\mu_s,\mu_v,\Delta\varphi) = \frac{\int_0^{2\pi}\int_0^1 \mu L^{\downarrow}(\tau,\mu_s,\mu,\Delta\varphi')r_{surf}(\mu,\mu_v,\Delta\varphi'-\Delta\varphi)d\mu d\Delta\varphi'}{\int_0^{2\pi}\int_0^1 \mu L^{\downarrow}(\tau,\mu_s,\mu,\Delta\varphi')d\mu d\Delta\varphi'} \tag{4}$$

$$\overline{r'}(\tau,\mu_s,\mu_v,\Delta\varphi) = \overline{r}(\tau,\mu_v,\mu_s,\Delta\varphi) \tag{5}$$

$$\overline{\overline{r}} = \overline{\overline{r'}(\tau,\mu_s,\mu_v,\Delta\varphi)} \approx \frac{\int_0^1\int_0^{2\pi}\int_0^1 r_{surf}(\mu,\mu',\Delta\varphi)\mu\mu' d\mu' d\mu d\Delta\varphi}{\int_0^1\int_0^{2\pi}\int_0^1 \mu\mu' d\mu' d\mu d\Delta\varphi} \tag{6}$$

where $L^{\downarrow}$ is the atmospheric diffuse radiance reaching the ground in a particular direction. Eq. (5) is constructed according to reciprocity theory. Eq. (6) is approximated by taking $\overline{\overline{r}}$ equal to the hemispherical albedo of the target which brings efficiency and negligible error for computation.

To describe the directional reflectance of land surface, linear kernel-driven model is used for its simplicity and notable performance. This model can be written as the sum of three theoretically constructed parts representing basic scattering types: isotropic effect, geometric effect and volumetric effect. The model is defined as follows:

$$\begin{aligned} r_{surf}(\lambda,\theta_s,\theta_v,\Delta\varphi) = {} & f_{iso}(\lambda) + f_{geo}(\lambda)K_{geo}(\theta_s,\theta_v,\Delta\varphi) \\ & + f_{vol}(\lambda)K_{vol}(\theta_s,\theta_v,\Delta\varphi) \end{aligned} \tag{7}$$

where r_{surf} is the surface directional reflectance, and λ is the wavelength. In Eq. (7), θ_s, θ_v and Δ are the solar zenith angle, view zenith angle and relative azimuth angle respectively, representing the sun-view geometry. K_{geo} and K_{vol} are the geometric and volumetric kernel respectively. $f_{iso}(\lambda)$, $f_{geo}(\lambda)$ and $f_{vol}(\lambda)$ are coefficients of the kernels, equal to the reflectances for three basic scattering types.

However, the directional reflectance is often changed as time goes by. To restrain the change, factorization of the directional reflectance is carried out to separate Eq. (7) into the product of two terms, i.e.,

$$r_{surf}(t,\lambda,\theta_s,\theta_v,\Delta\varphi) = \rho(t,\lambda)\left[1+\alpha_1(\lambda)K_{geo}(\theta_s,\theta_v,\Delta\varphi)+\alpha_2(\lambda)K_{vol}(\theta_s,\theta_v,\Delta\varphi)\right] \tag{8}$$

where ρ is the "reflectance magnitude" which changes rapidly and is a function of time (symbolized t). The remaining part in the square bracket is the "BRDF shape function" which changes slowly especially among the same period of years (Vermote et al., 2009). The different performance of the two terms is caused by the internal attribute they represent. The reflectance magnitude is governed by the microphysical properties of surface elements, while the BRDF shape function is governed by the structure of the surface (Qin et al., 2015). In BRDF shape function, α_1 is the geometric factor and α_2 is the volumetric factor.

Among various kernels, the combination of LiSparseReciprocal (Li and Strahler, 1992) for geometric kernel and RossThick (Lucht et al., 2000; Ross, 1981; Roujean et al., 1992) for volumetric kernel is widely