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Error Analysis of Retrieved Aerosol Optical Depth due to Adjacency Effect for ROCSAT-2 RSI Bands

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ABSTRACT

The adjacency effect (AE), caused by the scattering of reflected radiance from an inhomogeneous surface, is known to introduce a blurring effect on remotely sensed data, especially for high spatial resolution data. The retrieval of aerosol optical depth (AOD) by the dark target (DT) method usually neglects the AE. Hence, significant errors may be induced in aerosol retrieval. In this study, the errors of retrieved AOD due to AE by the DT method for very high spatial resolution data of 8 m in the multi-spectral bands of ROCSAT-2 RSI are investigated. A fast, accurate simple atmospheric correction model is applied. Target size is considered the same as the spatial resolution. The errors are mainly studied for both low and medium contrasts, in both clear and hazy skies for both continental and urban aerosol models. The results indicate that for the continental model, AE may cause significant retrieval errors for AOD over DTs for medium contrast in both skies in blue and red bands. Error becomes negligible if the inhomogeneous surface is for low contrast in clear sky. It is larger for the urban model where there is more absorption than for the continental model, due to the less sensitivity of top-of-atmosphere reflectance to AOD for DTs in inhomogeneous surfaces. This suggests that AE be considered for medium contrast in both skies, especially for urban-industrial regions for ROCSAT-2 RSI.

(Key words: Adjacency effect, Aerosol optical depth, Dark target, ROCSAT-2 RSI)

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1. INTRODUCTION

Remote sensing of aerosols has been of considerable interest, because of the fact that increasing atmospheric aerosol concentrations scatters more sunlight back into space, increases planetary albedo and decreases the temperature of the Earth (McCormick and Ludwig 1967). Researchers have estimated that an increase in the tropospheric aerosol optical depth (AOD) of 0.1 would decrease the temperature about 1°C on Earth's surface (Hansen and Lacis 1990). Owing to its highly spatial and temporal variability, accurate determination of AOD is also very important to correct the atmospheric effect of remotely sensed data and retrieve surface reflectance. An increase in AOD of 0.2 can decrease the surface reflectance by 0.02 in the green band of SPOT high resolution visible (HRV) for the target reflectance of 0.03, when AOD is 0.33 (see Fig. 7, Liu et al. 1996). Consequently, it is of great importance to retrieve AOD accurately from remotely sensed data, especially for the very high spatial resolution data of 8 m in the multi-spectral bands of the ROCSAT-2 remote sensing instrument (RSI) (Table 1), which was launched on May 21, 2004.

The Dark Target (DT) method, which was first proposed over one and-a-half decades ago by Kaufman and Sendra (1988) (KS88), is probably the most popular method to retrieve AOD from remotely sensed data. Since the top-of-atmosphere (TOA) signal contains larger atmospheric reflectance and the surface reflectances are very low in the visible bands for DTs, the errors of retrieved AOD due to the errors of the assumed reflectances over DTs are expected to be much lower than those over bright targets. The DTs are identified by taking advantage of the low opacity of most aerosol types in the mid-IR bands. Their reflectances in the blue and red bands are estimated using constant regression coefficients with reflectances in mid-IR band (Kaufman et al. 1997). The reflectance of the background surrounding the DT is considered the same as that of DT. Then, the lookup table approach, given in the specified aerosol model, can be used to determine AOD (Ouaidrari and Vermote 1999). This method has been operationally applied to Earth observing system (EOS) moderate resolution imaging spectroradiometer (MODIS) data (Kaufman et al. 1997) and Landsat thematic mapper (TM) data (Ouaidrari and Vermote 1999). For sensors without mid-IR bands, such as SPOT HRV and ROCSAT-2 RSI, DTs can be identified as the pixels with low near-IR signal and high vegetation index (KS88). Their reflectances can be assumed by reasonable values in the visible bands.

The adjacency effect (AE) has a systematic nature, which brightens the dark target and darkens the bright target at the TOA level (Lyapustin 2001; Lyapustin and Kaufman 2001). It originates from the reflected radiance of the surrounding areas, out of the field of view, and is scattered by the atmosphere into the field of view (Kaufman 1989), thus causing a blurring effect and reducing the contrast of an image. Therefore, it becomes very important for remote sensing applications when dark or bright targets are used. Significant errors of retrieved surface reflectance at the red wavelength due to AE can be up to 0.07 at the viewing zenith angle of 53.1° in a hazy sky even at 1 km resolution (Lyapustin and Kaufman 2001). Therefore, it is suggested that AE be taken into account not only in the atmospheric correction algorithms but also in aerosol retrieval. Nevertheless, the AOD retrieval algorithms of EOS-MODIS (Kaufman et al. 1997) and Landsat TM data (Liang et al. 1997) did not consider the AE over DTs.

Table 1. Comparison of the central wavelengths and spectral ranges of ROCSAT-2 RSI and Landsat ETM+ bands.

Band	Central wavelength[a] (μm)		Spectral range (μm)	
	RSI	ETM+	RSI[b]	ETM+ [c]
Blue	0.484	0.476	0.451-0.515	0.450-0.515
Green	0.561	0.561	0.526-0.594	0.525-0.605
Red	0.661	0.661	0.630-0.690	0.630-0.690
Near-infraed	0.821	0.835	0.760-0.887	0.750-0.900
Panchromatic	0.678	0.720	0.46-0.89	0.52-0.90

a. determined from the moments method (Palmer and Tomasko 1980; Asrar 1989); (please note that there is a small deviation (~0.004 μm) in near-infrared from the central wavelength denoted in Liu (2003), which should be corrected as equivalent wavelength)

b. full width at half maximum;

c. available from http://geo.arc.nasa.gov/sge/health/sensor/sensors/landsat.html.

Consequently, there is ample room for improvement of these algorithms (Vermote et al. 2002), especially for the multi-spectral data of ROCSAT-2 RSI with a pixel size of 8 m.

Recently, a new DT method of aerosol retrieval for Landsat enhanced thematic mapper plus (ETM+) has been developed (Lyapustin et al. 2004). Based on 3D radiative transfer theory, it can remove the positive error of retrieved AOD in 1D theory due to AE over inhomogeneous surface. This method simultaneously retrieves the aerosol model and AOD. Furthermore, their results show that the accuracy of aerosol retrieval can be significantly improved based on so-called surface climatology, which describes the regional and seasonal distribution of the regression coefficients. On the contrary, these coefficients are considered as constants in MODIS algorithm. Since the spectral characteristics of RSI are very similar to those of ETM+ (Table 1), albeit their lack of middle infrared bands, their study may be very helpful for aerosol retrieval from ROCSAT-2 RSI data.

In this paper, a study analyzing errors of retrieved AOD due to AE for ROCSAT-2 RSI bands is presented. Only the DT method is considered, although contrast reduction method also obtains satisfactory results for SPOT HRV (Lin et al. 2002) and NOAA AVHRR (Liu et al. 2002) data. Numerical simulations are conducted using a fast and accurate simple atmospheric correction model (SACM) (Liu 2003). The retrieved AOD errors due to AE are also studied at different solar, viewing zenith angles and relative azimuthal angles in different levels of haziness. Both continental and urban aerosol models (CM and UM) are considered. Though target size affects error, it is considered the same as the spatial resolution of ROCSAT-2 RSI in this study, as the error of retrieved AOD due to AE in the red band 0.65 μm for different spatial resolutions has been excellently studied by Laypustin and Kaufman (2001).

2. METHODOLOGY

SACM is implemented to estimate the errors of retrieved AOD, $\delta\tau_a$, due to AE for ROCSAT-2 RSI bands. The look-up table of environment function, defined as the probability of scattered photons reaching the sensor from assumed uniform circular target over inhomogeneous surface in the second simulation of the satellite signal in the solar spectrum (6S) (Vermote et al. 1997), is compiled with radius of 4 m in SACM, i.e. half of spatial resolution of ROCSAT-2 RSI. The rmse values of TOA reflectances ρ_{TOA} simulated by SACM are less than 0.001 (about 0.0008 and 0.0006 in blue and red bands) for both CM and UM, when compared with 6S for wide ranges of parameters. Numerical studies have been conducted to estimate the induced errors of retrieved AOD due to the rmse of ρ_{TOA} by SACM. A DT with the reflectances ρ_c of 0.01 in the blue band is assumed at a solar zenith angle (θ_s) of 30°, viewing zenith angle (θ_v) of 45° and the relative azimuthal angle (ϕ) of 0°. Two contrasts over DT are considered. The low contrast (LC) and medium contrast (MC) denote that DT is surrounded by the background with its reflectance ρ_b = 0.06 and ρ_b = 0.12, respectively. The results show that the induced errors are only 0.005 and 0.010 in clear sky (τ_a = 0.23) and hazy sky (τ_a = 0.76) for MC, respectively, when aerosol is CM. As for UM, the errors are about 0.01 for LC and MC in clear sky, respectively, however, the errors can be 0.07 and up to 0.14 for LC and MC in hazy sky, respectively. Therefore, though for both contrasts the errors are negligible for CM in both skies as well as for UM in clear sky, they will be significant in hazy sky for UM, especially for MC. One should note that it is because UM with single scattering albedo ω_0 of 0.65 is more absorptive than CM with ω_0 of 0.90 in blue band. Detailed explanation of the significant errors for UM in hazy sky will be presented in the later section. For simplicity, these errors are neglected in the following discussion. Hence, the estimated AOD errors due to AE should be moderate in the latter conditions.

Numerical simulations under different conditions are conducted to study the errors of retrieved AOD. Visibilities (VIS) are set to 23 km (clear sky) and 5 km (hazy sky), which correspond to the τ_a values of 0.23 and 0.76 at 550 nm, according to 6S. θ_s are set to 30° and 60°. θ_v is fixed as 45° by the design of ROCSAT-2 RSI. The values of ϕ are set to 0° (backscattering) and 180° (forward-scattering). To assess the errors, relative error $\delta\tau_a / \tau_a$(%), absolute standard error (ASE) and relative standard error (RSE) (%) are used. The value of

$\delta\tau_a$ is defined as the estimated AOD minus the true AOD; RSE is defined as the ratio of standard error of estimated AOD to true AOD. In the numerical experiments, the true AOD is used to simulate ρ_{TOA} by considering AE; the estimated AOD is then retrieved by inverting ρ_{TOA} with all the same parameters given in the simulation of ρ_{TOA}, except assuming the uniform surface ($\rho_b = \rho_c$).

3. RESULTS AND DISCUSSIONS

Figures 1a, b, c, and d illustrate $\delta\tau_a/\tau_a$(%) due to AE for different ρ_c and ρ_b in different VIS in the blue and red bands of ROCSAT-2 RSI for CM. θ_s, θ_v and ϕ are 30°, 45° and 0°, respectively. The values of ρ_c and ρ_b are all from 0.00 to 0.12 for both visibilities and both bands. For a given ρ_c, $\delta\tau_a/\tau_a$ increases monotonically as ρ_b increases in both bands and both VIS. On the other hand, $\delta\tau_a/\tau_a$ decreases monotonically as ρ_c increases for given ρ_b. If the background is brighter than the target, i.e., $\rho_b > \rho_c$, τ_a is over-estimated ($\delta\tau_a > 0$) due to the under-estimation of ρ_b. On the contrary, τ_a is under-estimated ($\delta\tau_a < 0$) due to the over-estimation of ρ_b, if the target is brighter than the background. These errors are all due to the negligence of the scattered radiance reflected from the inhomogeneous surface, i.e. uniform surface assumption. Since this phenomenon is quite similar to those cases of θ_s = 60° and/or ϕ = 180°, their figures are neglected. However, quantitative analysis will be discussed as in the following. The values of $\delta\tau_a/\tau_a$ range from -253.3% to 118.3% and -323.0% to 110.0% for blue and red bands in clear sky, and they range from -101.8% to 66.7% and -162.5% to 70.0% for both bands in hazy sky. In fact, $\delta\tau_a$ are enhanced in the hazy sky compared with those in the clear sky, because of the negligence of the stronger scattered radiance reflected by the inhomogeneous surface.

To better understand the values of $\delta\tau_a$, ASE and RSE (%) of the retrieved τ_a due to AE over DT at various θ_s, ϕ, different contrasts, and in different VIS in the blue and red bands of ROCSAT-2 RSI are studied. Both CM and UM are considered. The reflectance of DT, ρ_c, is considered to range from 0.01 to 0.06, since there will exist various degrees of darkness of DT used in remote sensing AOD. The definitions of DT and these two contrasts over DT are similar to those of Lyapustin and Kaufman (2001). In the following discussion, ASE_AOD and RSE_AOD represent the ASE and RSE of the retrieved τ_a.

First, CM is considered. As shown in Table 2, RSE_AOD (ASE_AOD) increases as VIS increases (decreases) and/or contrast increases. When θ_s and ϕ are 30° and 0°, respectively, RSE_AOD can increase from 18.19% to 31.20% as VIS increases from 5 km to 23 km for LC in the red band; it can be up to 96.66%, which is the maximum RSE_AOD, for VIS = 23 km and MC in the same band. In the blue band, the maximum RSE_AOD is 99.88% for the same VIS and contrast. When the viewing direction is changed from backscattering to a forward-scattering direction, the RSE_AOD is decreased. This is because of the less scattered radiance from the inhomogeneous surface in the forward-scattering direction. When θ_s increases to 60°, the RSE_AOD due to AE is decreased. This is because the increasing atmospheric reflectance over DT dominates the ρ_{TOA} (Lyapustin and Kaufman 2001). When θ_s and ϕ are 60° and 180°, ASE_AOD are almost negligible (less than 0.1) except for VIS = 5 km and MC in

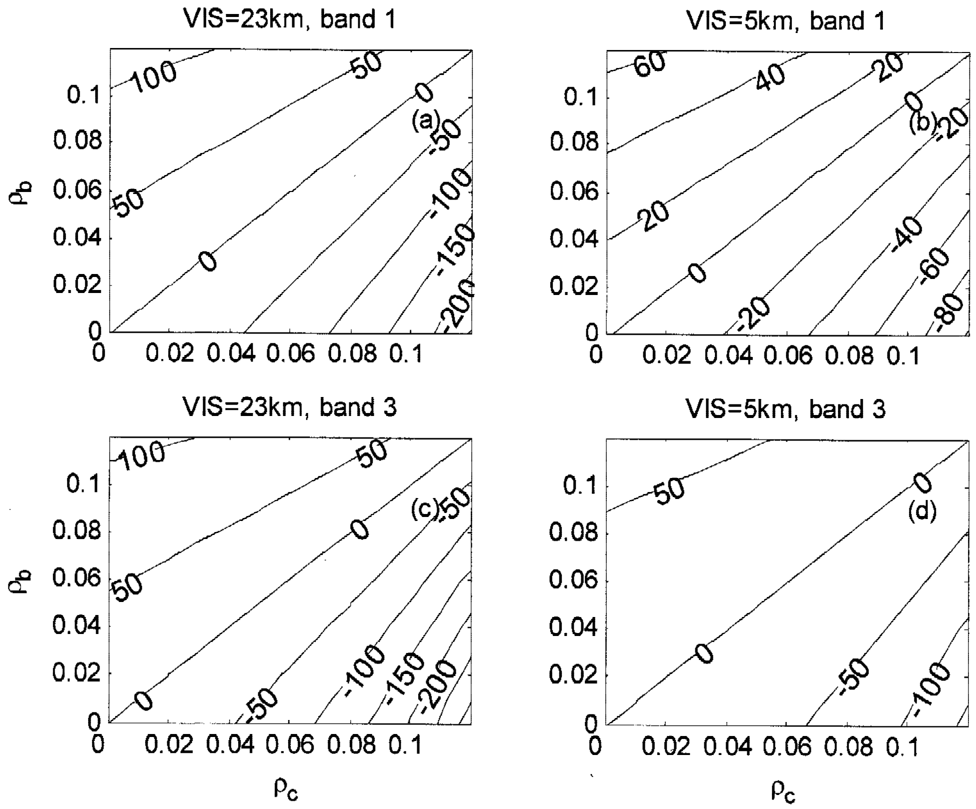

Fig. 1. Relative errors of retrieved aerosol optical depth $\delta\tau_a / \tau_a (\%)$ due to AE for different target reflectances ρ_c and background reflectances ρ_b in different VISs in the blue and red bands of ROCSAT-2 RSI for continental aerosol model. (a) and (b) are in the blue band; (c) and (d) are in the red band. VISs are 23 km in (a), (c) and 5 km in (b), (d). θ_s, θ_v and ϕ are 30°, 45° and 0°, respectively.

both bands. In general, the differences of ASE_AOD in both bands are small (less than 0.05). As shown in Fig. 3 of Lyapustin and Kaufman (2001), the SE_AOD reached up to maximum value 0.31 for MC (average ρ_b = 0.11) at the nadir view, in the hazy sky (τ_a = 0.8) for a spatial resolution of 25 m, in the red band. Compared with their study, it is not surprising that the maximum ASE_AOD can be up to 0.45, for a VIS of 5 km and MC in the red band, when θ_s and ϕ are 30° and 0° (Table 2). It is likely due to the higher resolution (8 m) in this work. The behavior of the ASE_AOD with VIS, θ_s and contrast over DT, as described above, is also consistent with their study. It is also interesting to note that for a given contrast, when τ_a increases from 0.23 (VIS = 23 km) to 0.76 (VIS = 5 km) (about three times larger), the ASE_AOD increase is only about twice as large. However, for a given VIS, when the contrast increases from LC (ρ_b = 0.06) to MC (ρ_b = 0.12) (only twice as large), the ASE_AOD increases approximately threefold. This indicates that the ASE_AOD due to AE is about twice as sensitive to the contrast variation than τ_a variation.

Table 2. The absolute and relative standard errors (%, in parenthesis) of the retrieved τ_a due to AE for DTs (ρ_c = 0.01~0.06) at various θ_s, ϕ, different contrasts, and for different VISs in km in the blue and red bands of ROCSAT-2 RSI. Continental aerosol model is considered. LC and MC denote that the dark target is surrounded by ρ_b = 0.06 and ρ_b = 0.12, respectively.

Blue band					
θ_s	ϕ	LC		MC	
		VIS=23	VIS=5	VIS=23	VIS=5
30°	0°	0.07 (32.29)	0.13 (17.10)	0.23 (99.88)	0.42 (54.57)
30°	180°	0.06 (26.64)	0.10 (13.63)	0.18 (80.93)	0.32 (42.19)
60°	0°	0.05 (20.41)	0.10 (13.48)	0.14 (61.96)	0.32 (42.39)
60°	180°	0.02 (10.21)	0.06 (7.77)	0.07 (29.98)	0.17 (22.25)
Red band					
θ_s	ϕ	LC		MC	
		VIS=23	VIS=5	VIS=23	VIS=5
30°	0°	0.07 (31.20)	0.14 (18.19)	0.22 (96.66)	0.45 (58.35)
30°	180°	0.06 (26.16)	0.11 (14.82)	0.18 (79.93)	0.35 (45.86)
60°	0°	0.04 (18.04)	0.09 (11.69)	0.12 (54.94)	0.27 (35.80)
60°	180°	0.02 (8.21)	0.05 (6.79)	0.05 (24.08)	0.15 (19.27)

For UM, RSE_AOD for LC in clear sky increases to 84.00% as compared with 32.29% for CM in the blue band for $\theta_s = 30°$ and $\phi = 0°$. It is because sensitivity of TOA reflectance to τ_a for more absorptive UM is less than that for CM in the case of LC. Look-up tables of TOA reflectance as a function of τ_a (Fig. 2) for CM (solid curve) and UM (dashed curve) for $\rho_c = 0.03$ in the case of MC could explain this result. θ_s, θ_v and ϕ are 30°, 45° and 0°, respectively. LUTs are determined as $\rho_c = \rho_b = 0.03$. The labeled values of horizontal lines are TOA reflectances for different VISs and aerosol models for $\rho_c = 0.03$ and $\rho_b = 0.12$. As VIS decreases from 23 km to 5 km, TOA reflectance increases from 0.1604 to 0.2117 for CM, however, it increases only from 0.1398 to 0.1467 for UM. One could also notice that no feasible value of τ_a, which ranges from 0.05 to 2.0, could best fit the TOA reflectance for UM in case of MC in clear and hazy skies. When the sky is hazy, no feasible value of τ_a could be retrieved for LC. Although UM is more absorptive, the large scattered radiance from the inhomogeneous surface should be accounted for by the large or even no feasible , as compared to

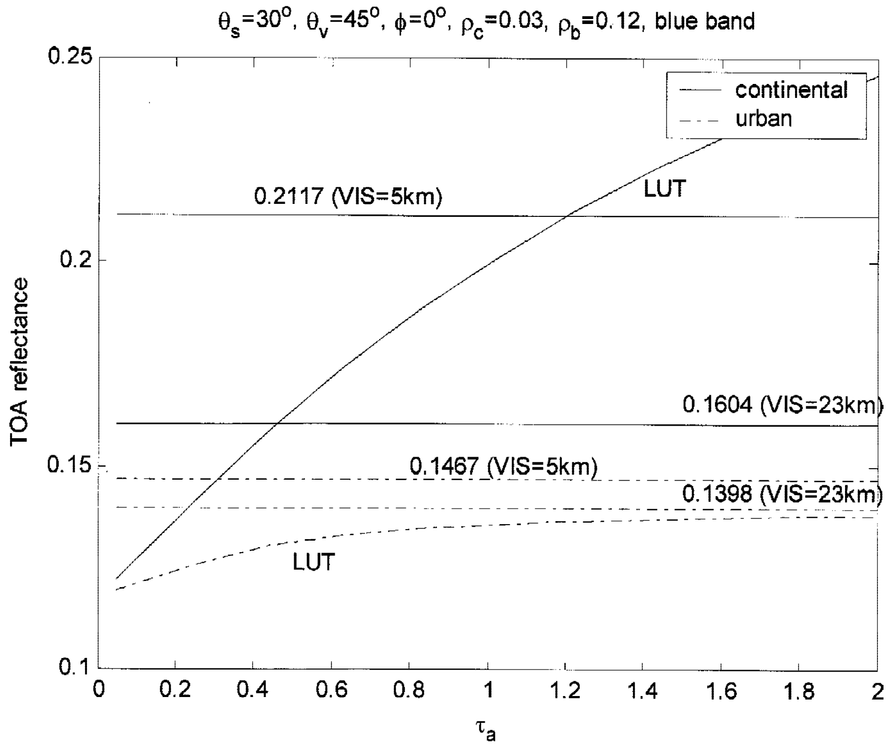

Fig. 2. TOA reflectance as a function of τ_a in blue band of ROCSAT-2 RSI. Solid and dashed curves (look-up tables (LUT)) and lines are for continental and urban aerosol models, respectively. LUTs are determined as $\rho_c = \rho_b = 0.03$. The labeled values of horizontal lines are TOA reflectances for different VISs and aerosol models for $\rho_c = 0.03$ and $\rho_b = 0.12$, when θ_s, θ_v and ϕ are 30°, 45° and 0°, respectively.

the case for CM. These results also explain the reason why the induced errors of retrieved AOD due to the rmses of ρ_{TOA} by SACM are significant in hazy sky for UM, especially for MC, as mentioned above. This reveals the difficulty of aerosol remote sensing over urban-industrial regions, where highly inhomogeneous surfaces exist with the small size of sparsely distributed DTs (Lyapustin et al. 2004).

4. CONCLUSIONS

In this study, the errors of retrieved AOD due to AE by the DT method for ROCSAT-2 RSI bands are investigated with aid of the fast and accurate SACM. Target size is considered the same as the spatial resolution. The results show that the induced error of retrieved AOD by SACM are negligible for CM in both skies as well as for UM in clear sky; however, they are significant in hazy sky for UM, especially for MC. AE becomes negligible if the inhomogeneous surface is not highly reflective; however, it may cause large RSE_AOD up to 100% and 55% for MC over DTs in clear and hazy skies in blue band for CM, as θ_s and ϕ are 30° and 0°. RSE_AOD is larger for UM compared with CM, due to the lesser sensitivity of TOA reflectance to τ_a. This suggests that AE be considered for MC in both skies, especially for urban-industrial regions.

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