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Retrieval of Aerosol Optical Depth over Land using two-angle view Satellite Radiometry during TARFOX

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Abstract. A new aerosol optical depth retrieval algorithm is presented that uses the two-angle view capability of the Along Track Scanning Radiometer 2 (ATSR-2). By combining the two-angle view and the spectral information this so-called dual view algorithm separates between aerosol and surface contributions to the top of the atmosphere radiance. First validation of the dual view algorithm was performed during the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), which was conducted at the mid-Atlantic coast of the United States in July 1996. The satellite retrieved spectral aerosol optical depth is in good agreement with the aerosol optical depth from ground-based Sun/sky radiometers in three out of four cases. This shows the potential of aerosol retrieval over land using two-angle view satellite radiometry.

1. Introduction

Atmospheric aerosol particles play an important role in the Earth's radiation balance. They scatter and absorb solar radiation (direct effect) and affect the albedo and lifetimes of clouds (indirect effect). The radiative forcing by man-made aerosols of the combined direct and indirect effects is estimated to be of the same order of magnitude, but opposite of sign, as the radiative forcing by the anthropogenic greenhouse gases. Aerosols are considered one of the largest uncertainties in today's climate modelling. To a large extent this uncertainty is caused by a lack of data on a global scale. Due to the short lifetimes of aerosols in the troposphere (hours to days) and due to the occurrence of many different sources with different spatial extents and emissions, the aerosol is highly variable in both space and time. This applies to the concentration, the size distribution, and the chemical composition, and therefore also to the aerosol optical properties. Only satellite remote sensing can provide the spatial and temporal resolution to measure the inhomogeneous aerosol fields.

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However, retrieval of aerosol properties from satellite measured radiances is not straightforward. The radiance at the top of the atmosphere is the sum of several components, including aerosol scattered light and light reflected by the underlying surface. When the surface albedo is high, as is often the case over land, the contribution of aerosol scattering to the total radiance may be relatively small, which renders the retrieval of the aerosol contribution rather uncertain. Several methods have been proposed to distinguish between contributions to the satellite measured radiance by aerosols and by the surface (for a review see *Kaufman et al.*, [1997a]). The use of multi-angle satellite radiometry for aerosol retrieval was proposed by *Martonchik and Diner* [1992]. However, data from multi-angle satellite radiometers is scarce. *Flowerdew and Haigh* [1996] presented an algorithm that uses the two-angle view data from the Along Track Scanning Radiometer 2 (ATSR-2). In this contribution, we present a new algorithm based on ATSR-2 data in which the surface reflection is treated in a similar way as by *Flowerdew and Haigh* [1996]. However, the new algorithm uses not only the information from the two-angle view, but also the spectral information to distinguish between atmospheric and surface contributions to the top of the atmosphere radiance. The spectral aerosol optical depth (AOD) is computed using an aerosol model that fits the spectral measurements best. First validation of the dual view algorithm was performed during the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), which was conducted at the mid-Atlantic coast of the United States, in July 1996 [*Russell et al.*, 1998] by comparing satellite retrievals to ground based measurements. Validation in these so-called column closure experiments permits the assessment of measurement uncertainties, and can establish credibility for satellite remote sensing of aerosol properties.

2. The ATSR-2 sensor

The ATSR-2 was launched on board the European ERS-2 satellite in April 1995. ATSR-2 is a radiometer with 7 wavelengths, 4 of these bands are in the visible and near-infrared (effective wavelengths 0.555, 0.659, 0.865, and 1.6 μm) and potentially useful for aerosol retrieval. The spatial resolution of the ATSR-2 is 1x1 km^2 at nadir, and the swath width is 500 km. The ATSR-2 has a conical scanning mechanism, thus producing two views of each region: first a forward view (zenith angle approximately 55 degrees) and about two minutes later a nadir view. The horizontal distance of the lower troposphere covered by the combined forward and nadir measurements is less than 10 km. On these spatial and temporal scales the atmosphere is assumed to be invariable and horizontally homogeneous.

3. The dual view algorithm

The dual view algorithm applies only to cloud-free scenes. For such cases, the total (aerosol + Rayleigh) optical depth in the visible and near-infrared is usually less than 1. Over land, the contribution of the surface reflection in this optical depth regime is dominated by the direct contribution, i.e. photons that are reflected at the surface and transmitted on their downward and upward path through the atmosphere. Away from the surface hot-spot, a Lambertian surface may be assumed in such cases [*Flowerdew and Haigh*, 1996]. The orbit of the ERS-2 is such that the ATSR-2 rarely observes the surface hot-spot in the Northern Hemisphere [*Godsalve*, 1995]. For a Lambertian surface the reflectance at the top of the atmosphere (ρ) is given by:

$$\rho(\lambda) = \rho_{atm}(\lambda) + \frac{\rho_{sfc}(\lambda)}{1 - \rho_{sfc}(\lambda) \cdot s(\lambda)} T(\lambda) \tag{1}$$

where ρ_{atm} is the contribution of atmospheric scattering; ρ_{sfc} is the surface albedo; s is the spherical albedo of the atmosphere; T is the transmittance of the atmosphere; and λ is the wavelength.

The surface reflection depends both on the wavelength and on the geometry. However, the surface reflection can be approximated by a part that describes the variation with the wavelength and a part that describes the variation with the geometry [*Flowerdew and Haigh*, 1995]. Under this assumption, the forward view surface albedo ($\rho_{sfc,f}$) may be written as:

$$\rho_{sfc,f}(\lambda) = k \cdot \rho_{sfc,n}(\lambda) \tag{2}$$

where $\rho_{sfc,n}$ is the nadir view albedo; and k is the ratio between the forward and the nadir surface reflection. The ratio k depends only on the variation of the surface reflection with the geometry and is assumed to be independent of the wavelength. Experimental data shows that the surface reflectances at wavelengths in the visible (0.555 and 0.659 μm) are proportional to those in the mid-infrared (1.6 and 2.1 μm) [*Kaufman et al.*, 1997b]. Note that this does not apply to the 0.865 μm channel, which therefore can not be used.

For the forward view, substituting equation 2 into equation 1 yields:

$$\begin{aligned} \rho_f(\lambda) &= \rho_{atm,f}(\lambda) + \frac{k \cdot \rho_{sfc,n}(\lambda)}{1 - k \cdot \rho_{sfc,n}(\lambda) \cdot s(\lambda)} T_f(\lambda) \\ &\approx \rho_{atm,f}(\lambda) + \frac{k \cdot \rho_{sfc,n}(\lambda)}{1 - \rho_{sfc,n}(\lambda) \cdot s(\lambda)} T_f(\lambda) \end{aligned} \tag{3}$$

where the subscripts f are for the forward view. The approximation in Equation 3 has been made because in general $k \cdot \rho_{sfc,n}(\lambda) \cdot s(\lambda) \ll 1$.

For most continental aerosol types, except for desert dust, the aerosol extinction decreases rapidly with wavelength and the AOD at 1.6 μm will be small as compared to the AOD in the visible. Ignoring the atmospheric contribution at 1.6 μm, k is approximated as the ratio between the top of the atmosphere reflectances for the forward and for the nadir view at this wavelength. Since k is assumed independent of the wavelength, this value for k can also be used for the visible channels of the ATSR-2 (0.555 and 0.659 μm). The unknown sur-

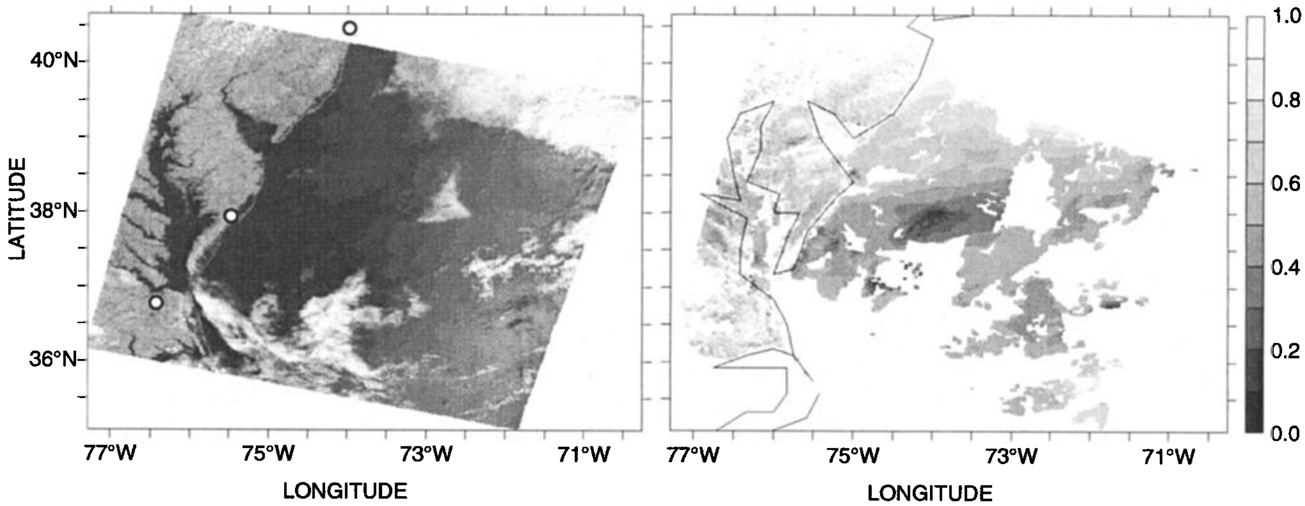

Figure 1. Near-infrared image (1.6 μm) (left) and aerosol optical depth retrieved using the dual view algorithm for 0.659 μm (right), for the ATSR-2 overpass over the TARFOX area on July 25, 1996, 15:52 UTC. In the near-infrared image, the symbols indicate the ground stations used in this study (see text).

face albedo can be eliminated by using Equation 1 for the nadir view and Equation 3 for the forward view:

$$\frac{\rho_n(\lambda) - \rho_{atm,n}(\lambda)}{T_n(\lambda)} = \frac{\rho_f(\lambda) - \rho_{atm,f}(\lambda)}{k \cdot T_f(\lambda)} \quad (4)$$

where the subscrips n are used for the nadir view. In Equation 4, ρ_n and ρ_f are measured and k is approximated as described above. All other terms are a function of the AOD. To compute the AOD from Equation 4, an aerosol model is applied. The dual view algorithm has been applied to an area at the east coast of the United States. The aerosol in this region is assumed to be an external mixture of seasalt aerosol and aerosol from anthropogenic sources. These two aerosol types are defined from the Navy Oceanic Vertical Aerosol Model (NOVAM) [*De Leeuw et al*, 1989]. The mixture of the two aerosol types that fits the spectral behavior of the measured reflectance in the 0.555, 0.659 and 1.6 μm channels best, is used to compute the AOD and the surface albedo for these channels.

4. Results and Discussion

During the TARFOX intensive field campaign from 10 to 31 July 1996, the ATSR-2 passed seven times over the area. Figure 1 shows the near-infrared image and the AOD as determined by the dual view algorithm for the ATSR-2 pass on 25 July 1996. Figure 1 illustrates the potential of the dual view algorithm for AOD retrieval over both land and water surfaces. The AOD image for this day shows a strong spatial gradient. A region with relatively low AOD values (0.2 at 0.659 μm) is centred around 38 N 74 W. This AOD pattern was supported by satellite retrievals from algorithms that compute the AOD over the ocean [*Veefkind et al.*, 1998], as well as by airborne Lidar measurements [*Ferrare*, 1997]. Despite the differences in surface reflective properties between land and ocean, Figure 1 does not show distinct jumps in the retrieved AOD across the land to sea boundaries. Over land, the uncertainty in the retrieved AOD is larger than over the ocean, due to the higher and less homogeneous surface albedo, and the non-perfect match between the forward and nadir view pixel. At the land to sea boundary the dual view algorithm tends to fail. This is caused by the small difference in scene between the forward and the nadir view of the ATSR-2, in combination with the suddenly changing surface albedo at the coastline.

During TARFOX the aerosol optical depth was measured at five ground-based stations. At each station a Sun/sky radiometer measured the direct solar radiation in six spectral bands (0.340, 0.380, 0.440, 0.670, 0.940 and 1.020 μm) [*Holben et al.*, 1998]. Figure 2a shows the comparison between the aerosol optical depth as determined with the Sun/sky radiometer at Wallops Island (37.93 N, 75.47 W) and the co-located AOD from the dual view algorithm, for 25 July 1996. The Sun/sky radiometer measurements and the ATSR-2 image were

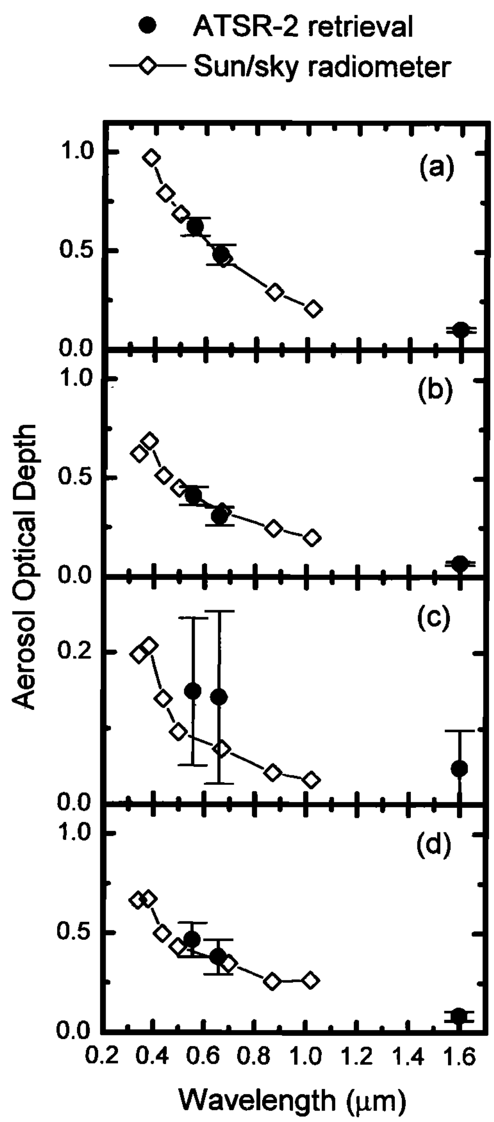

Figure 2. AOD determined from the Sun/sky radiometer measurements, and AOD from the dual view algorithm using ATSR-2 data. Error bars indicate the standard deviation. Fig. 2a is for Wallops Island (37.93 N, 75,47 W) for 25 July 1996; Figure 2b is for Wallops Island for 31 July 1996, Fig. 2c is for Sandy Hook (40.43 N, 73.98 W) for 28 July 1996, and Fig. 2d for Hampton Roads (36.77 N, 76.43 W) for 31 July, 1996.

within 3 minutes of each other. The AOD from the Sun/sky radiometer and the AOD retrieval over land are in excellent agreement. Not only the AOD at a single wavelength is retrieved accurately, but also the spectral behavior of the AOD. The latter contains important information on the aerosol size distribution. The high AOD observed on 25 July 1996, in combination with the rapid decrease of the AOD with the wavelength, indicates that the aerosol is predominantly of anthropogenic origin. This is supported by in situ measurements of physical and chemical aerosol properties [*Hegg et al.*, 1997].

The difficulty of comparisons, similar to the one shown in Figure 2a, is to find co-located ground-based and satellite measurements. Often the satellite retrieval or the Sun/sky radiometer data is missing due to clouds over the ground station at the time of the satellite overpass. When the AOD varies little in space and time, the Sun/sky radiometer measurements closest to the time of the overpass can be compared to satellite retrieval data closest to the ground station. Such a comparison is shown in Figure 2b for Wallops Island for 31 July 1996. In this case the Sun/sky radiometer measurement was taken approximately 1 hour after the satellite overpass, and the satellite retrieval is for an area within 20 km of the ground station. Figures 2c and 2d show similar comparisons for Sandy Hook (40.43 N, 73.98 W) for 28 July 1996, and for Hampton Road (36.77 N, 76.43 W) for 31 July. All the cases with high AOD (Figures 2a, b and d) show good agreement between AOD determined from the Sun/sky radiometer and from the dual view algorithm. Figure 2c shows the performance of the dual view algorithm for low AOD. For this case the retrieval in the visible is about a factor of two larger than Sun/sky radiometer derived AOD. However, the standard deviation in the retrieval is relatively large, and the satellite retrieved and Sun/sky radiometer derived values are within the experimental uncertainty. The large variation is caused by the difference scene between the forward and nadir view, in combination with the inhomogeneous surface albedo over land.

5. Conclusions

An aerosol optical depth retrieval algorithm is presented that uses both the two-angle view and the spectral information of the ATSR-2 measurements. This so-called dual view algorithm applies both over land and over the ocean. Aerosol optical depth retrievals over land are compared to Sun/sky radiometer measurements during TARFOX. For three cases with high aerosol optical depth (0.3-0.5 at 0.659 μm), the satellite retrieved aerosol optical depth and that derived from the Sun/sky radiometers are in good agreement. For one case with lower aerosol optical depth ($\sim$0.1 at 0.659 μm) the agreement is less good (difference about 100%), but still within the experimental uncertainty. The results of this validation are very encouraging, and new validation studies for different regions will be performed in the near future.

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