

Combined use of satellite and surface observations to infer the imaginary part of refractive index of Saharan dust

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Abstract. We present a method for retrieval of the imaginary part of refractive index of desert dust aerosol in the near UV part of spectrum. The method uses Total Ozone Mapping Spectrometer (TOMS) measurements of the top of the atmosphere radiances at 331 and 360 nm, and aerosol optical depth provided by the Aerosol Robotic Network (AERONET). Obtained values of imaginary part of refractive index retrieved for Saharan dust aerosol at 360 nm are significantly lower than previously reported values. The average retrieved values vary between 0.0054 and 0.0066 for different geographical locations. Our findings are in good agreement with the results of several recent investigations.

1. Introduction

Dust aerosols play an important role in Earth's radiative budget by absorbing and scattering of solar radiation [Sokolik and Toon, 1996]. The net effect of these two processes directly affects the sign of dust radiative forcing that could result in heating or cooling of the atmosphere system containing dust [Sokolik and Toon, 1999; Hsu et al., 2000]. The correct modeling of dust radiative forcing as well as the development of aerosol remote sensing techniques require precise knowledge of the optical properties of mineral dust in a wide spectral range.

Patterson et al., [1977] used Saharan dust samples and laboratory measurements to produce one of the most widely used data sets of imaginary part of refractive index (k) of mineral dust in the range 300-700 nm. However, due to the uncertainty associated with the measuring technique used in this and other studies [Sokolik et al., 1993], there is still a large uncertainty regarding the optical properties of desert dust. For example, the use of Patterson et al., [1977] values of k combined with typical aerosol particle size distribution (PSD) indicates rather high dust absorption [Sokolik and Toon, 1999]. However, recent remote sensing observations [Kaufman et al., 2001; Dubovik et al., 2002] support the conclusion that mineral dust is much less absorbing in the visible part of spectrum than previously assumed. Dubovik et al., [2002] derived a value of k of 0.0025 at 440 nm which is significantly smaller than $k \approx 0.01$ reported by Patterson et al. [1977]. Thus, the inconsistency between laboratory measurements and remote sensing results for dust absorption in the visible casts uncertainty on the accuracy of k at shorter wavelengths.

The issue of imaginary part of dust refractive index in the near UV has recently been addressed [Colarco et al., 2002] by combining TOMS observations of aerosol index with aerosol transport model. The method has been applied over the ocean and derived values of k were found to be less than those predicted by laboratory measurements. The aim of this work is to perform additional independent studies on dust absorption in the near-UV considering not only oceanic but also continental locations and extending analysis to different times of the year.

In this paper we present a retrieval method to infer the

imaginary part of the refractive index of Saharan dust aerosols in the near UV. The method combines satellite observations of radiances at two near UV channels by the Total Ozone Mapping Spectrometer (TOMS), and ground based observations of aerosol optical depth by the Aerosol Robotic Network (AERONET). Since the retrieval of aerosol properties in the UV is sensitive to the location of the aerosol layer [Torres et al., 1998], the retrieval method discussed here also derives the height of the aerosol layer. Retrieved values of k at 360 nm are compared to laboratory measurements and to results from other remote sensing techniques.

2. Retrieval method

The method retrieves imaginary part of refractive index of dust aerosols at 360 nm along with aerosol layer height above the ground. We used TOMS observations of the top of atmosphere radiances at 331 nm and 360 nm over Cape Verde (16° N, 22° W) and Dakar (14° N, 16° W) islands influenced by Saharan dust transported over the Atlantic Ocean [Prospero and Carlson, 1977] and over Bidibahn (14° N, 3° E, in Niger) and Bondoukou (11° N, 3° W, in Niger) sites located near the Sahara desert. These observations were combined with the independent collocated measurements of aerosol optical depth at 440 nm provided by AERONET [Holben et al., 1998].

Parameters of PSD for $\tau_{440}=0.58$	Fine mode	Coarse mode
σ_N (width)	1.72	1.79
R_N (modal radius), μm	0.05	0.69
N (number concentration), μm^{-2}	15.4	0.07

Parameters of PSD for $\tau_{440}=1.11$	Fine mode	Coarse mode
σ_N (width)	1.8	1.7
R_N (modal radius), μm	0.04	0.82
N (number concentration), μm^{-2}	26.5	0.11

Parameters of PSD for $\tau_{440}=2.18$	Fine mode	Coarse mode
σ_N (width)	1.99	1.54
R_N (modal radius), μm	0.03	1.1
N (number concentration), μm^{-2}	70.6	0.144

Table 1. Aerosol models used in retrieval method.

The retrieval algorithm relies on several aerosol model assumptions. The aerosol particle size distribution (PSD) used in our approach is based on seven years of AERONET retrievals of atmospheric column PSD of aerosols at Cape Verde [Dubovik et al., 2002]. These data suggest bi-modal lognormal PSD with parameters, which are functions of aerosol optical depth at 1020 nm. To take into account this dependence of PSD on aerosol

loading, we employed three different PSD's corresponding to different values of aerosol optical depth at 440 nm, which is close to the 360 nm TOMS channel. The relative spectral dependence of imaginary part of dust refractive index in the range 331-440 nm was assumed to be the same obtained by *Patterson et al.*, [1977]. Table 1 summarizes the parameters of the selected PSDs. Although spherical aerosol particles were assumed, a sensitivity analysis to quantify the error due to this assumption was carried out.

Our retrieval approach uses precalculated lookup tables of upwelling radiances at 331 and 360 nm for a number of aerosol laden atmosphere models of varying aerosol layer height (Z), optical depth (τ_{440}), and imaginary part of refractive index at 360 nm (k_{360}). In producing the tables the following ranges of variability of parameters were used:

$$\begin{aligned} 0.5 \leq Z \leq 5 \text{ (km)}, \\ 0.58 \leq \tau_{440} \leq 2.18, \\ 0 \leq k_{360} \leq 0.0158. \end{aligned} \quad (1)$$

To model aerosol vertical distribution we used a Gaussian profile with maximum aerosol concentration at height Z and width equal 1 km. The range of variability for aerosol optical depth was selected to represent a rather large aerosol loading in order to ensure sufficient sensitivity of the measurements to the retrieval parameters. For each of the aerosol models in Table 1 the imaginary part of refractive index in (1) varies from zero (no absorption) to the value reported by *Patterson et al.*, [1977] (strong absorption). Two intermediate values represent moderately (0.01) and weakly (0.004) absorbing aerosols. To describe real part of dust refractive index, the value 1.55 provided by *Patterson et al.*, [1977] was used.

The relationship between the 331/360 nm radiance ratio and the 360 nm radiance measured by TOMS for a known aerosol optical depth constitutes the basis of the retrieval method as depicted in Fig. 1. The aerosol layer height and imaginary part of refractive index increase in the direction of the arrows.

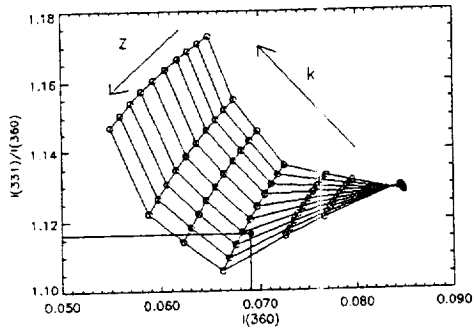


Fig. 1. Ratio of the top of atmosphere radiances at 331/360 nm as function of 360 nm radiance for fixed value of aerosol optical depth. The solid circle represents the retrieval of k_{360} and Z associated with a hypothetical set of satellite measurements.

In each case, the relationship depicted in Figure 1 was obtained for the value of aerosol optical depth measured by AERONET. Thus, the TOMS measurements are used to determine k_{360} and Z by using the PSD associated with the AERONET measured optical depth τ_{440} .

In combining TOMS and AERONET measurements the space and time collocation of satellite observations with ground-based measurements is an important issue. TOMS and AERONET measurements were collocated in space by restricting the positions of TOMS pixels to be within 1° latitude by 1° longitude box centered at the AERONET site. The time of

satellite overpass, in turn, was restricted to be within 30 minutes between two successive measurements of optical depth. Finally, an average value was obtained using retrieval results from all the pixels within the selected area.

Accurate cloud screening is an issue of critical importance in the application of this retrieval algorithm. Our method uses three basic quantities for cloud screening procedure: TOMS aerosol index (AI), Lambert equivalent reflectivity of pixel (R_p) and surface albedo (R_s). By definition AI is the difference between the measured 331/360 nm spectral contrast and the predicted one using Lambert equivalent reflectivity of pixel determined at 360 nm. The predicted spectral contrast is calculated by assuming that the atmosphere consists only of molecular scatterers and gas absorbers (ozone) bounded by Lambertian surface [*Torres et al.*, 1998]. Lambert equivalent reflectivity of pixel (R_p) is determined by the following condition

$$(I_{360})_{\text{meas}} = (I_{360}(R_p))_{\text{calc}} \quad (2)$$

The values of R_s are obtained from an existing climatology of minimum 380 nm TOMS reflectivity [*Herman and Celarier*, 1997].

The AI is a good indicator of aerosol presence [*Herman et al.*, 1997]. Indeed, UV surface albedo is practically spectral independent [*Herman and Celarier*, 1997] and AI is close to zero for pure molecular atmosphere (since R_p is spectrally independent). If the atmosphere contains aerosols, the value of AI becomes non-zero, because the multiple scattering interactions between molecular scatterers and aerosols introduce a spectral dependence of R_p . The larger aerosol loading, the stronger spectral dependence and the larger values of AI are observed. Clouds, however, produce nearly zero values of AI because the effect of clouds on radiances is equivalent to spectral independent increase in R_p [*Herman et al.*, 1997].

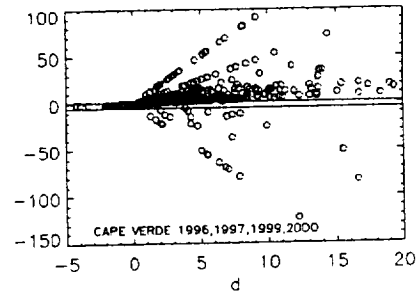


Fig. 2. The ratio as a function of the difference between Lambert equivalent reflectivity of pixel and surface albedo.

To reduce the effect of sub-pixel cloud contamination we used the parameters R_p , R_s , and AI combined in the expressions

$$d = R_p - R_s \quad (3)$$

and

$$r = \frac{R_p - R_s}{AI} \quad (4)$$

Fig. 2 illustrates the basic idea of employing these two quantities for cloud screening. It shows the relationship between the ratio (r) and the difference (d). The relationship is obtained by using collocated TOMS and AERONET observations over Cape Verde during four years. As illustrated (Fig. 2), the observed relationship allows the separation of the data into distinct branches, each corresponding to a constant value of AI and

increasing R_p . The increase in R_p while AI remains constant is indicative of cloud presence. Thus each branch of points corresponds to different levels of sub-pixel cloud contamination. By imposing a restriction on the range of variability of the ratio, the effect of sub-pixel cloud contamination is reduced. Of course, additional information is required to establish some certain boundary values of the range. We estimated the boundary values by comparison of TOMS [Torres *et al.*, 1998, 2002] retrievals and Aeronet cloud-screened optical depth observations [Smirnov *et al.*, 2000]. As a result the following restrictions on variability range of the quantity r were

$$-5 < r < 1.7 \quad (5)$$

established for positive values of AI. Figure 3 illustrates the TOMS-AERONET comparison before and after the application of the cloud-screening method. The use of the restriction in (5) results in increasing of correlation coefficient between the two data sets from 0.28 to 0.8. The corresponding boundaries for the ratio are shown in Fig. 2 with solid line.

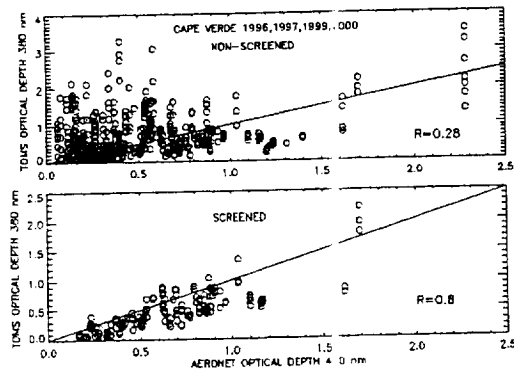


Fig. 3. Comparison between TOMS optical depth retrievals and AERONET measurements.

3. Sensitivity analysis

We performed the sensitivity analysis to estimate retrieval errors due to the assumptions made in our algorithm. Two dominating sources of errors were considered: the influence of dust particles non-sphericity and variability of actual optical depth within the area of collocation.

Natural dust aerosols are typically non-spherical [Mishchenko *et al.*, 1997]. In the sensitivity study we performed the following tests. Satellite measurements were simulated assuming dust particles to be spheroids with aspect ratio (the ratio of axes) equal to 1.8 and $k_{360} = 0.006$. These measurements then were used as input in our retrieval code, which assumes spherical aerosol particles. The selected value of k_{360} corresponds to mean value for this quantity retrieved by using spherical shape assumption. A similar aerosol model for non-spherical particles was used in sensitivity studies by Dubovik *et al.*, [2000]. They found agreement between the results of sensitivity analyses and the actual retrievals for AERONET data from several locations in the vicinity of the Saharan desert [Dubovik *et al.*, 2002]. The T-matrix code [Mishchenko *et al.*, 1994] was used to calculate light scattering by randomly oriented spheroids with the same volume size distribution as for spherical particles. The simulations were performed for the set of actual Sun and satellite geometries over Cape Verde. The results of our numerical tests show that the retrieval error in imaginary part of refractive index due to particles non-sphericity is a linear function of scattering angle and could be as large as

60%. A 25% in aerosol layer height is obtained. The analysis also demonstrates that considering only some specific geometrical conditions could reduce retrieval error to reasonably small level. We established such condition for maximum retrieval error to be 20% (10% in aerosol layer height) in absolute value

$$140^\circ \leq \theta_{scat} \leq 160^\circ. \quad (6)$$

The conditions (6) were applied to our retrieval results. Hence we consider maximum error in retrieval results of k_{360} due to influence of non-sphericity to be 20%.

We also estimated retrieval error due to variability of aerosol optical depth within the area of collocation. This source of error is possible because AERONET performs only point measurements. The 20% relative difference between AERONET measurements and actual optical depth was assumed. The number 20% is based on the value of average error in comparison of TOMS optical depth retrievals with AERONET measurements [Torres *et al.*, 2002]. The retrieval error is a function of k_{360} and aerosol layer height and is depicted by error bars in Fig. 4. It is seen from the plots that the prescribed uncertainty in optical depth produces maximum errors in imaginary part of refractive index of about 45% and could produce a rather large error in retrieved values of aerosol layer height (up to 3 km absolute error).

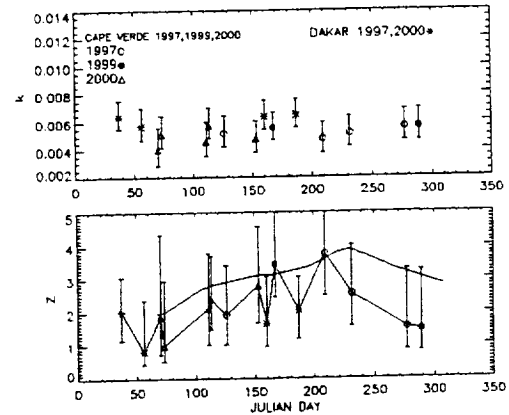


Fig. 4. Retrieval results for imaginary part of refractive index and aerosol layer height for Cape Verde and Dakar.

4. Retrieval results.

We applied the described retrieval method to EP-TOMS measurements over four selected AERONET sites on several days in 1997, 1999 and 2000. Fig. 4 presents the retrieval results of imaginary part of refractive index and aerosol layer height as functions of Julian day for Cape Verde and Dakar (the results for Bidibahn and Bondoukou are not displayed).

SITE	TOMS+ AERONET (This work)	AERONET	TRANSPORT MODEL+ TOMS
Cape Verde, Dakar	0.0054 (C, D) (0.004-0.0065)	0.0046 (C) (0.0036-0.0056)	0.004 (C) 0.005 (D)
Bidibahn, Bondoukou	0.0066 (0.0038-0.01)	N. A	N. A.

Table 2. Comparison between retrieval results obtained by using different methods. In the case of AERONET the value presented was obtained by linear extrapolating in logarithm scale of values at 440 nm and 670 nm. The range of variability of parameters is presented along with average values.

The values of imaginary part of refractive index obtained in this analysis are significantly lower than the value reported by Patterson *et al.*, [1977]. The largest retrieved values at the different sites are about one third of the laboratory measurements. Table 2 presents a comparison of the retrieval results in this analysis with those obtained by using other remote sensing techniques. They include AERONET retrieval results for Cape Verde [Dubovik *et al.*, 2002] and results [Colarco *et al.*, 2002] for Cape Verde and Dakar. The results of all the three approaches are in good agreement with each other.

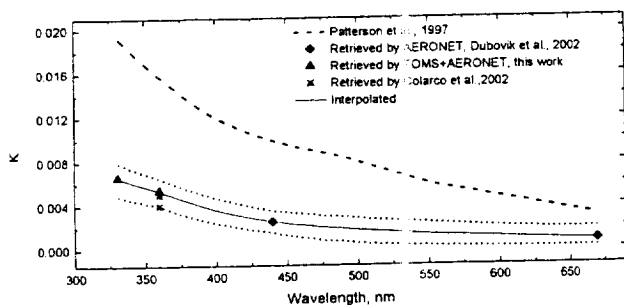


Fig. 5. The solid line represents the spectral dependence of k of Saharan dust obtained by means of linear interpolation using 331, 360, 440, and 670 nm values. The upper and lower limits (dotted lines) represent the observed range of variability. The dashed line shows the Patterson *et al.* [1977] data.

The retrieved values of aerosol layer height are, in general, smaller at the beginning and the fall of the year as compared to the values at the middle. This is consistent with the predictions of dust transport model [Ginoux *et al.*, 2001] for Cape Verde and Dakar. The solid line at the Fig. 4 represents the climatological values of aerosol layer height for Cape Verde produced by using this model.

Using the average values of k_{360} and k_{331} obtained in this work for Cape Verde and Dakar, and the values of k_{440} and k_{670} derived from AERONET we have inferred the imaginary part of refractive index of dust in the range 331–670 nm by means of linear interpolation in logarithmic scale. The obtained spectral dependence is shown in Figure 5.

5. Discussion and conclusions

We have presented the method for simultaneous retrieval of imaginary part of refractive index of Saharan dust and aerosol layer height above the ground. The approach uses TOMS measurements of top of atmosphere radiances at 331 nm and 360 nm and independent information on aerosol optical depth at 440 nm provided by AERONET measurements. The method was applied to the combination of TOMS and AERONET measurements over four AERONET sites, which are dust-dominated locations. The retrieved values of imaginary part of refractive index of dust aerosols are found to be lower than correspondent value reported by Patterson *et al.*, [1977] and are in qualitative good agreement with the results of several recent investigations [Kaufman *et al.*, 2001, Dubovik *et al.*, 2002, Colarco *et al.*, 2002].

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The paper presents a method for retrieval of the imaginary part of refractive index of desert dust aerosol in the near UV part of spectrum (360 nm). The method uses Total Ozone Mapping Spectrometer' (TOMS) observations of the top of the atmosphere radiances at 331 and 360 nm collocated in space and time with the ground-based measurements of aerosol optical depth provided by the Aerosol Robotic Network (AERONET) at 440nm. Since the retrieval of aerosol properties in the UV is sensitive to the location of the aerosol layer, the retrieval method also derives the aerosol layer height.

The cloud-screening algorithm, which uses the combination of Lambert equivalent reflectivity of pixel, TOMS aerosol index and surface albedo is proposed. The application of the algorithm makes it possible to reduce significantly the influence of sub-pixel cloud contamination on retrieval results. The sensitivity analysis is performed to estimate retrieval errors due to the assumptions made in retrieval method. Two dominating sources of errors are considered: the influence of dust particles non-sphericity and variability of actual optical depth within the area of collocation.

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