

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

**Please provide feedback**

Please support the ScholarWorks@UMBC repository by emailing [scholarworks-group@umbc.edu](mailto:scholarworks-group@umbc.edu) and telling us what having access to this work means to you and why it's important to you. Thank you.



## AEROSOL PROPERTIES FROM EP-TOMS NEAR UV OBSERVATIONS

O. Torres<sup>1</sup>, J.R.Herman<sup>2</sup>, P.K. Bhartia<sup>2</sup>, and A.Sinyuk<sup>1</sup>

<sup>1</sup>*Joint Center for Earth Systems Technology, University of Maryland Baltimore County,  
Baltimore, MD, 21250 USA*

<sup>2</sup>*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Code 916, Greenbelt, MD,  
20771 USA*

### ABSTRACT

A method of aerosol detection and characterization using satellite measured radiances in the near ultraviolet has recently been developed. The retrieval approach is based on the interaction between the processes of aerosol absorption and scattering and the strong near-UV Rayleigh scattering. That interaction produces spectral variations of the backscattered radiances that can be used to separate aerosol absorption from scattering effects. In this paper, we briefly discuss the physical basis of the near UV approach for aerosol sensing from space, and illustrate its application to specific aerosol events using data from the currently operational Total Ozone Mapping Spectrometer on the Earth Probe satellite (EP-TOMS). EP-TOMS derived optical depths of mineral, carbonaceous and sulfate aerosols are in good agreement with ground-based AERONET sun-photometer measurements. © 2002 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

### INTRODUCTION

Data on aerosol optical depth and single scattering albedo are required to quantify both direct and indirect radiative forcing effects, from atmospheric aerosols. It is well known that aerosols may have a direct cooling effect on climate by scattering back to space a fraction of the incoming solar radiation. In addition, aerosol absorption of short and long wave radiation may produce changes in atmospheric heating rates that may in turn produce changes in atmospheric circulation. Aerosols may also indirectly affect climate through its effects as cloud condensation nuclei. Since clouds reflect a major fraction of incoming solar radiation, changes in cloud optical properties and lifetimes may have a significant climate effect.

In addition to climate related effects, aerosol effects are also significant in non-climate related aspects. Determination of aerosol concentration is very important in the analysis of local, regional, and global air pollution. It is apparent that air pollution is not just a problem of local dimensions, since flow of huge smoke plumes resulting from large scale biomass burning and boreal forest fires can extend thousands of kilometers away from the source areas creating serious air quality and health related problems. Aerosol particles formed from biomass burning and urban/industrial activity, carry sulfate and organic material that is part of the air pollution, as recently experienced during the Indonesia (1997) and Mexico (1998) biomass burning events. The plumes form regional hazards and transfer pollution across geopolitical boundaries.

The role of iron-rich aerosol (mineral aerosols from deserts and other sources) as fertilizer of the global ocean is also of great importance. Dust deposited in the oceans may be an

important source of iron which, in some ocean regions, may be a limiting nutrient for phytoplankton.

Aerosols play also a fundamental role in the attenuation of UV-A and UV-B radiation at the Earth's surface. Increased levels of surface UV-B radiation (290-320 nm), following the stratospheric ozone layer depletion, have been reported at mid and high latitudes. Aerosols, through scattering and absorption in the ultraviolet, play an important role in the attenuation of the biologically harmful UV-B radiation reaching the surface of the Earth. In order to properly quantify the effects of global ozone decreases, the role of aerosol particles must be carefully taken into account in assessments and modeling studies of surface UV-B levels.

The importance of aerosols in many heterogeneous chemistry and photochemical processes in the atmosphere is well known. For instance, the critical role that Polar Stratospheric Clouds (PSC's) play in the seasonal formation of the Antarctic ozone hole has long ago been established. By the same token, the large global reduction of stratospheric ozone levels following the eruption of Mt. Pinatubo (Gleason *et al.*, 1993) is believed to be related to the combined effects of increased chlorine levels and the presence in the stratosphere of the sulfate aerosol layer that formed in the aftermath of the eruption. The importance of aerosols in tropospheric chemistry is currently receiving a great deal of attention. It has been suggested that desert dust aerosols may contribute to decreases in tropospheric ozone by providing the surfaces required for the many heterogeneous chemistry processes known to consume ozone (Dentener *et al.*, 1996). It has also been postulated that additional ozone reductions or enhancements may occur in the vicinity of tropospheric aerosol layer as the interaction of the aerosol scattering and absorption processes affect ozone (and other trace gases) photolysis rates (Dickerson *et al.*, 1997).

Finally, since aerosol also affect remote sensing of other geophysical parameters (ocean color, atmospheric ozone, surface albedo, etc), accurate knowledge of aerosol properties is required for the application of atmospheric correction processes to remove the aerosol effect (Torres and Bhartia, 1999; Gordon *et al.*, 1997).

## **AEROSOL MEASUREMENTS**

Until the TOMS (Total Ozone Mapping Spectrometer) UV measurements, satellite retrieved aerosol optical depth has only been available over the oceans. Because of the large visible reflectance of most land surfaces, satellite measurements in the visible and near infrared, such as AVHRR, cannot be applied over land masses. It is expected that recently launched aerosol missions such as MODIS (King *et al.*, 1999) and MISR (Diner *et al.*, 1991) will provide reliable estimates of aerosol optical depth over both the oceans and the continents. As a result of an effort to improve on both the quantity and quality of ground-based aerosol measurements, a federated network of aerosol measuring sites using CIMEL sun-photometers was established (Holben, *et al.*, 1998). The AERONET observations routinely measure spectral aerosol optical depth, single scattering albedo and particle size distribution.

The only available long-term record of atmospheric aerosols over both oceanic and continental areas is provided by TOMS. The TOMS technique of aerosol detection and characterization is based on spectral contrast in the near UV that results from the interaction between the processes of Rayleigh scattering, particle scattering and absorption. This interaction produces spectral variations of the backscattered radiances at the top of the atmosphere that can be used to separate aerosol absorption from scattering effects. Torres *et al.* (1998), discuss in detail the physical basis of the near UV technique of aerosol sensing.

There are two ways of using the aerosol information contained in the TOMS measurements. The first one consists on the qualitative description of the atmospheric aerosol load by means of a quantity known as Aerosol Index (AI), defined as the difference between observed and calculated spectral contrast at two wavelengths in the near UV range (Herman et al., 1997). In other words, the AI is just a form of the raw data where the molecular component has been removed. The magnitude of AI depends on aerosol optical depth, single scattering albedo, height of the aerosol layer and viewing geometry. Although it has been shown that the AI is proportional to optical depth (Hsu et al., 1998, Chiapello et al., 1999), the proportionality constant depends on aerosol type (i.e., single scattering albedo) and aerosol layer height. Since both single scattering albedo and aerosol vertical distribution vary in time and space, the quantitative interpretation of the AI is very difficult. The second approach consists of an actual inversion using pre-computed look-up-tables for a set of aerosol models. The inversion allows the retrieval of two aerosol parameters. A more detailed description of the retrieval algorithm is presented in a subsequent section.

### PHYSICAL BASIS OF THE NEAR UV METHOD OF AEROSOL SENSING

Because of the large Rayleigh scattering contribution characteristic of the near UV (340 to 390 nm), the use of measurements in this spectral region to retrieve aerosol information may appear counter-intuitive. The near UV, however, offers unique advantages with respect to standard visible and near IR (700 to 2000 nm) approaches. Neglecting particle multiple scattering effects, as well as other second order terms (reflected and then scattered radiation and vice-versa), the upwelling radiance ( $I$ ) at the top of an aerosol laden atmosphere as measured from a satellite instrument (for overhead sun and nadir viewing), is approximately given by

$$I = \frac{\omega_0 P(\Theta) F_0}{8\pi} [1 - e^{-2\tau_a}] + \left[ \frac{p_s - p_a}{p_s} \right] [I_s(\rho) + I_0] e^{-2(1-\omega_0)\tau_a} + \frac{p_a}{p_s} [I_s(\rho) + I_0] \quad (1)$$

where

$\omega_0$  is aerosol single scattering albedo

$\Theta$  is scattering angle

$P(\Theta)$  is aerosol scattering phase function

$\tau_a$  is aerosol extinction optical depth

$F_0$  is incoming solar flux

$I_s(\rho)$  is upward radiance reflected by the surface and transmitted through the atmosphere to the satellite

$\rho$  is surface albedo

$I_0$  is total Rayleigh scattered radiance

$p_s$  and  $p_a$  are surface and aerosol layer pressure levels respectively.

The first term represents the additional radiance generated by the single scattering effects of the aerosol layer. The second term describes the attenuation of the surface and atmospheric components due to aerosol absorption effects, while the third term represents the contribution of the fraction of atmosphere above the aerosol layer. A qualitative analysis of Eq. 1 clearly shows the fundamental difference of the near UV method of aerosol sensing with respect to standard visible and near IR approaches. In the visible and near IR spectral regions, the term  $I_0$  (mostly

singly scattered radiation) is generally small and can be neglected. The term  $I_s$  is also very small over water surfaces. Over most land surfaces, on the other hand,  $I_s$  is significantly larger than the contribution of aerosol scattering to the total radiance. Therefore, the separation of the aerosol effect is very difficult without a precise characterization of the surface albedo. For this reason, visible and IR satellite retrieval of aerosol properties is generally limited to dark water surfaces where the aerosol information is mainly contained in the aerosol single scattering term of Eq. 1, which for an optically thin atmosphere ( $\tau_a \ll 1$ ) can be further reduced to

$$I = \frac{\omega_0 P(\Theta) F_0 \tau_a}{8\pi} \quad (2)$$

where the aerosol reflectance is proportional to the product of the single scattering albedo and the aerosol optical thickness. Thus, at small optical depths there is no way to distinguish non-absorbing aerosols with a given optical depth, from absorbing particles and a larger optical depth.

The near UV  $I_s$  term in Eq. 1 is generally low over both water and land surfaces. As shown by the climatological record of minimum UV reflectivity developed by Herman and Celarier (1997), the ocean reflectivity is seldom larger than about 10%, whereas all vegetated surfaces show a reflectivity no larger than about 5%. The largest reflectivity of ice/snow free surfaces in the near UV corresponds to deserts with a typical value of about 8%. The low surface contribution to the total radiance at the top of the atmosphere is a unique advantage in the near UV that allows the retrieval of aerosol information over both water and land surfaces. The quantity  $I_0$  in Eq. 1 is significantly larger than its counterpart in the visible since it contains multiple molecular scattering. The interaction of aerosol absorption and multiple Rayleigh scattering in the near UV can be used for the retrieval of information concerning aerosol absorption. The length of photons' paths through an absorbing aerosol layer is increased by multiple Rayleigh scattering so that the chance of aerosol absorption is enhanced.

Since molecular scattering depends strongly on pressure, the magnitude of the second term of Eq. 1 is also a function of the height of the aerosol layer. The higher the layer of absorbing particles above the surface, the larger the amount of molecular scattered radiation subject to absorption by aerosols. The sensitivity to aerosol-plume height is largest for strongly UV-absorbing aerosols and decreases rapidly with increasing single scattering albedo (Torres *et al.*, 1998). For non-absorbing aerosols (i.e.,  $T_0 = 1$ ), the dependence on aerosol layer height is negligible. Thus, in the application of the near UV technique of aerosol sensing, knowledge of the location in the atmosphere of the absorbing aerosol layer is required.

## THE NEAR UV ALGORITHM

### Radiative Transfer Calculations

Measurements of the backscattered radiance ( $I$ ) at two wavelengths  $\lambda_1$  and  $\lambda_2$ , ( $\lambda_2 > \lambda_1$ ) in the near UV range are required. Aerosol properties are retrieved by means of an inversion algorithm that makes use of a set of pre-computed look up tables (LUT) of radiances at the top of the atmosphere as they would be measured by a space-borne sensor. The LUT were built using radiative transfer calculations for an aerosol laden atmosphere, using realistic aerosol models (Torres *et al.*, 1998) at several values of solar and satellite zenith angles, relative azimuth angles, surface albedo, terrain pressure, and several aerosol vertical distributions. The concentration of sulfate (S) aerosol type is maximum at surface levels and decreases exponentially with altitude.

The UV-absorbing aerosols are assumed to be concentrated in a single layer above surface level. Its profile is represented by a gaussian distribution. Calculations were carried out for several values of aerosol layer height. The pre-computed look up tables (LUT) are separated in two sets: 1) a mineral dust - sulfate aerosol (DS) set and 2) a carbonaceous aerosol - sulfate aerosol set (CS).

**Table 1. Aerosol Models**

Aerosol Model	Particle size distribution		Complex refractive index	
	$r_0$ ( $\mu\text{m}$ )	$\sigma$	331 nm	360 nm
Sulfate (S)	0.07	2.03	1.43-0.0000i	1.43-0.0000i
Carbonaceous 1 (C1)	0.08	1.45	1.55-0.0150i	1.55-0.0150i
Carbonaceous 2 (C2)	0.08	1.45	1.55-0.0150i	1.55-0.0150i
Carbonaceous 3 (C3)	0.08	1.45	1.55-0.0150i	1.55-0.0150i
Mineral dust 1 (D1)	0.07	1.95	1.58-0.0207i	1.58-0.0175i
Mineral dust 2 (D2)	0.12	2.20	1.58-0.0207i	1.58-0.0175i
Mineral dust 3 (D3)	0.25	2.20	1.58-0.0207i	1.58-0.0175i
Mineral dust 4 (D4)	0.50	2.20	1.58-0.0207i	1.58-0.0175i

The selected aerosol models are representative of the most commonly observed aerosol types: sulfate aerosols, carbonaceous particulate generally associated with biomass combustion (i.e., agriculture related biomass burning and boreal forest fires) and mineral aerosols resulting from the lifting by the winds of dust particles in the arid and semi-arid regions of the world. The micro-physical properties of the aerosol models at the EP-TOMS wavelengths are summarized in Table 1. Notice that the refractive index of the C family of models is taken to be wavelength independent, whereas the imaginary component of the refractive index for the D set of models is taken to be spectrally dependent in the near-UV range based on measurements (Patterson et al., 1977, Sokolik et al., 1993). Torres et al. (1998), discusses in detail the rationale for the choice of aerosol models.

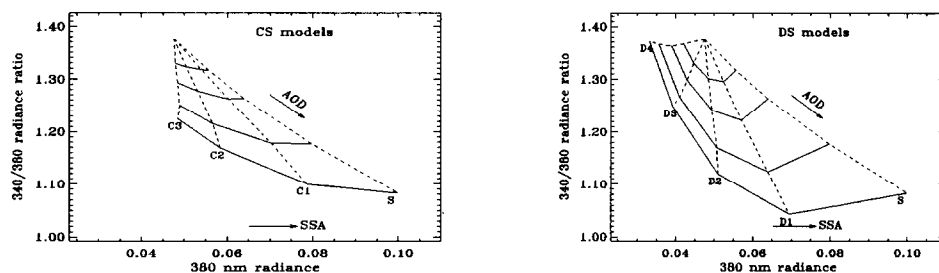
### Retrieval Procedure

Scattering and absorption effects of aerosol particles are easily detected by examining the variability of the relationship between spectral contrast ( $I_{81}/I_{82}$ ) and the radiance at the longer wavelength ( $I_{82}$ ). Figure 1 illustrates the look-up-table retrieval approach for the two model arrays. As illustrated in Figure 1, a set of measured radiances ( $I_{81}$ ,  $I_{82}$ ) are, within the domain of the assumed models, associated with a set of values of optical depth and dust particle size (if the DS LUT is used) or carbonaceous aerosols optical depth and imaginary refractive index (if the CS LUT is assumed). Since different micro-physical parameters (i.e., effective particle size or imaginary refractive index) are inferred depending on the aerosol type, the single-scattering albedo associated with the assumed particle size (smoke) or imaginary refractive index (dust) and the inferred refractive index (smoke) or particle size (dust) is calculated. Note that none of the aerosol models are assumed to identically represent the actual atmospheric aerosol load. The aerosol models are just nodal points as interpolation between different aerosol models is carried out. The incorrect choice of aerosol models array (i.e., DS instead of CS or vice-versa) introduces large errors in the retrieved optical depths. The aerosol type must therefore be prescribed along with the required input of surface albedo and aerosol layer height above the

surface. An analysis of errors in the retrieved parameters associated with uncertainties in prescribed surface albedo and aerosol layer height are discussed elsewhere (Torres *et al.*, 1998).

### Aerosol type and other input data

The choice of aerosol type is based on a combination of factors. A database on surface scene type compiled by the CERES (Cloud's and the Earth's Radiant Energy System) project is used for retrievals over land. The DS array of models is chosen when the underlying scene type is characterized as an arid or semi-arid environment. The CS family of model is selected for all other land types. Over the oceans, aerosol type is directly specified. In general, the CS array is prescribed over the Southern Hemisphere oceans, and the DS array over the Northern



**Fig. 1.** Graphical representation of LUT approach for CS (left) and DS (right) arrays of aerosol models. Single scattering albedo is constant along the dashed lines whereas optical depth remains constant along solid lines.

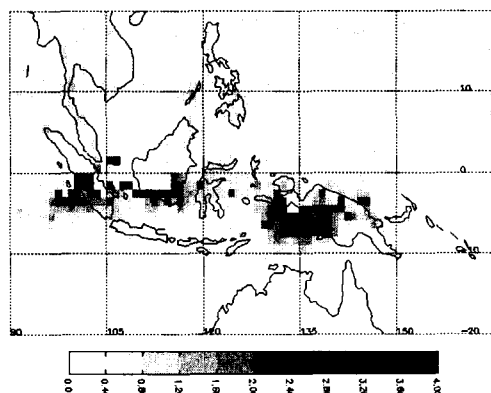
Hemisphere, except over specific geographic regions where carbonaceous aerosols are the most likely aerosol type present (i.e., South China Sea and oceanic regions in the vicinity of Central America). Since the retrieval approach does not consider mixtures of mineral and carbonaceous aerosols, retrieval errors are likely to take place in the Sahelian region where dust-smoke mixtures are possible in winter. A global data set on near UV surface reflectivity (Herman and Celarier, 1997) is used to prescribe the surface albedo. The height of the absorbing aerosol layer is assumed to be 3 km for carbonaceous aerosols. For mineral dust, the aerosol layer height has been taken from a climatology of monthly mean values using calculations from the chemical transport model of Ginoux *et al.* (2001).

### Cloud and Sun-glint Masks

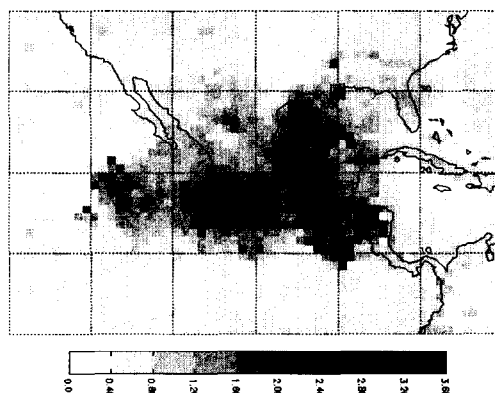
One of the most difficult steps in the retrieval of aerosol properties from satellite measurements is the selection of cloud free pixels. Because of the large EP-TOMS footprint (40x40 km at nadir and even larger off-nadir) sub-pixel cloud contamination is the largest source of uncertainty in the TOMS aerosol data. Pixel-size cloud effects are easily excluded by rejecting data for pixels with reflectivity larger than 15%. The effect of sub-pixel cloud contamination is reduced by further constraining the reflectivity threshold depending on the magnitude of the TOMS AI. This approach is based on the fact the AI is minimum in the presence of clouds (Torres *et al.*, 1998). Sun-glint effects are excluded by rejecting those observations when the viewing geometry over the oceans favors sun-glint occurrence.

## SAMPLE RETRIEVALS AND VALIDATION

The near UV technique of aerosol characterization has been applied to measurements by the Nimbus7 and Earth-Probe TOMS sensors to derive a long-term record of aerosol optical depth and single scattering albedo (Torres et al., 2001). In this section we present retrieval results during specific aerosol events using Earth-Probe TOMS observations. Figure 2 shows the September 1997 average value of optical depth retrieved over the South China Sea. The optically dense aerosol layer produced by out-of-control burning of tropical rain forest in Indonesia extended over an area of about  $7 \times 10^8 \text{ km}^2$ . Optical depth values as large as 4 were retrieved close to the sources.



**Fig. 2. Spatial distribution of the 360 nm optical depth over Indonesia in September 1997.**

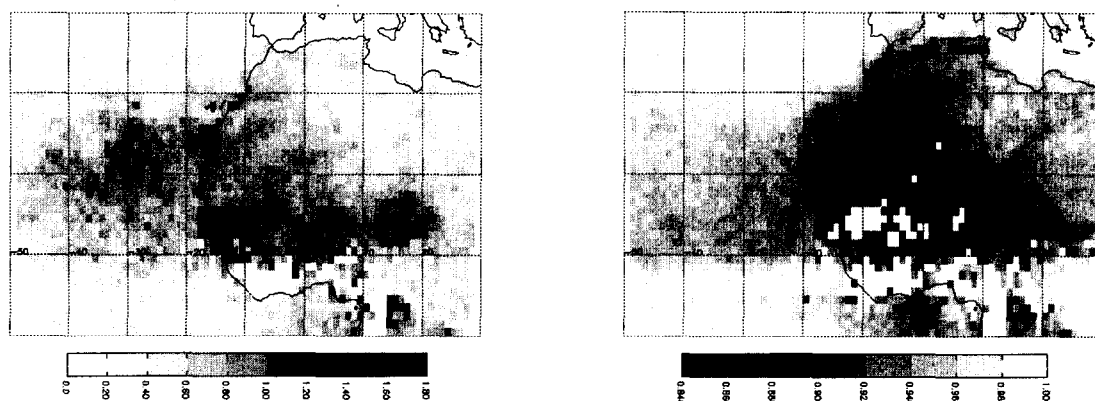


**Fig. 3. As in Fig.2., during the biomass burning events of Spring 1998 in Central America.**

Another significant biomass burning event took place in the northern hemisphere 1998 spring season. The spatial distribution of the smoke optical depth produced by intense fires in southern Mexico in May 1998 is depicted in Figure 3. The aerosol layer extended over a huge area that included most of Central America, the entire Gulf of Mexico and a large region over the Pacific Ocean. Smoke from these fires traveled over the continental United States and was detected as far north as Washington D.C. Unlike the seasonal biomass burning known to take place in South America and Africa as a land clearing practice, the Indonesian and Mexican fires documented here, were the result of the unusual drought conditions associated with the 1997-98 El Niño event.

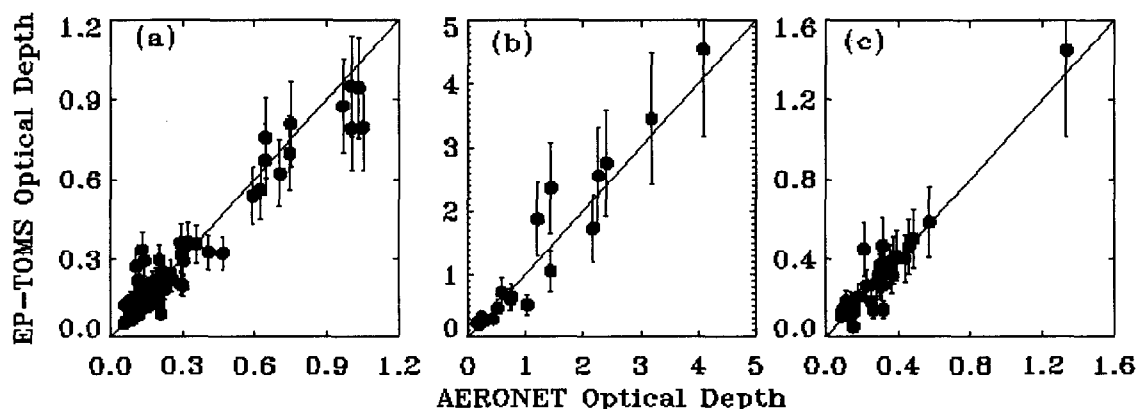
Retrieved optical depth and single scattering albedo of mineral dust particles over northern Africa and the Atlantic Ocean are shown in Figure 4. Optical depth values as large as 2 are observed in the vicinity of the sources. Smaller values, in excess of 1, were retrieved over the ocean. The spatial distribution of single scattering albedo shows values in the 0.83-0.87 range in the vicinity of the source areas. As the dust plume flows away from the source regions the aerosol becomes less absorbing as indicated by the larger values of the retrieved single scattering albedo. Since in the TOMS retrieval of mineral dust the refractive index is kept constant, the implicit assumption is that increased absorption is associated with large particles and vice-versa. Thus, according to the TOMS retrieval the effective particle size becomes smaller as the plume moves westward yielding higher values of single scattering albedo than in the vicinity of the sources.





**Fig 4.** Optical Depth (left) and single scattering albedo (right) of the Saharan aerosol layer as retrieved from EP-TOMS observations in July 1998.

Validation of the EP-TOMS aerosol product is carried out by comparing the satellite optical depth to AERONET (Aerosol Robotic Network) observations. AERONET, a federated network of CIMEL sun-photometers (Holben *et al.*, 1998), measures aerosol optical depths at 8 wavelengths (340, 380, 440, 500, 670, 870, 940 and 1020 nm) every fifteen minutes at over one hundred sites around the world (Eck *et al.*, 1999). Since the ground based measurements of aerosol optical depth data are available at near UV wavelengths, the TOMS and AERONET aerosol products can be compared directly. In addition, the variety of environments covered by AERONET network allows the ground-satellite comparisons for different conditions of atmospheric aerosol load. Depicted in Figure 5 is the comparison of satellite retrieved optical depths to AERONET measurements at three sites with distinct aerosol types. Urban pollution is



**Fig. 5.** Comparison of EP-TOMS derived optical depth to AERONET measurements at three sites: a) NASA Goddard Space Flight Center (39N, 77W), 1998, b) Altafloresta, Brazil (10S, 56W), 1999, c) Banizombou (13.5N, 2.6E), 1997. AERONET measurements 380 nm are used at the NASA and Altafloresta sites, whereas the 440 nm optical depth is used at Banizombou.

the predominant aerosol type at the Goddard Space Flight Center (GSFC, Maryland, United States). In Alta Floresta (Brazil, South America) the aerosol load is typically associated with carbonaceous particulate from biomass burning. On the other hand, the aerosol load at the Banizombou (Burkina Faso, Northern Africa) site is representative of mineral dust.

Satellite observations within a 1EX1E box centered at the AERONET site are compared to sun-photometer observation within 30 minutes of the satellite overpass. The comparison at the sites where UV-absorbing aerosols are present (AltaFloresta and Banizombou) shows that, in most cases, the satellite retrieved value is within about 30% of the ground based measurement. This level of agreement results from the combined effect of sub-pixel cloud contamination and uncertainty on the assumed aerosol layer height. At the GSFC site, where aerosols are typically non-absorbing, the TOMS retrieval is within about 20 % of the AERONET observation. The improved accuracy at GSFC has to do with the reduced sensitivity of non-absorbing aerosols to aerosol layer height.

## SUMMARY

We have discussed the aerosol detection and characterization method using near-UV satellite measurements. The physical basis of this retrieval technique has been briefly explained, and the retrieval algorithm, as applied to measurements by the TOMS sensor, has been described. Retrieval results for specific events observed by the Earth-Probe TOMS sensor were presented. Comparison of aerosol optical depths derived from Earth-Probe TOMS observations to AERONET sun-photometer measurements at three locations show that, in most cases, the satellite measurements are within 30% of the ground-based values. This level of agreement can be regarded as satisfactory given the instrumental limitations (i.e., large spatial resolution) and uncertainty on the height of absorbing aerosol layers.

## ACKNOWLEDGMENTS

We thank Brent Holben and the AERONET processing team at NASA GSFC, and Didier Tanre at Universite des Sciences et Techniques de Lille, France for the sun-photometer data used in this study.

## REFERENCES

- Chiapello, I., J.M. Prospero, J.R. Herman and N.C. Hsu, Detection of mineral dust over the North Atlantic Ocean and Africa with the Nimbus 7 TOMS, *J.Geophys. Res.*, **104**, 9277-9291, 1999.
- Dentener, F.J., G.R. Carmichael, Y. Zhang, J. Lelieveld, and P.J. Crutzen, Role of mineral aerosols surface in the global troposphere, *J. Geophys. Res.*, **101**, 22,869-22,889, 1996.
- Dickerson, R.R., S. Kondragunta, G. Stenchikov, K.L. Civerolo, B. Doddridge and B.N. Holben, The impact of Aerosols on Solar Ultraviolet Radiation and Photochemical Smog, *Science*, **278**, 827-830, 1997.
- Diner, D.J., C.J. Bruegge, J.V. Martonchik, G.W. Bothwell, E.D. Danielson, et al., A multi-angle imaging spectroradiometer for terrestrial remote sensing from the Earth Observing System, *Int. J. Imaging Syst. Technol.*, **3**, 92-107, 1991.
- Eck, T.F., B.N. Holben, J.S.Reid, O. Dubovik, N.T. O'Neill, I. Slutker, and S. Kinne, Wavelength dependence of the optical depth of biomass burning, urban and desert dust aerosols, *J.Geophys. Res.*, **104**, 31333-31349, 1999.

- Ginoux, P., M. Chin, I. Tegen, D. Savoie, J. Prospero, B. Holben, and S.J. Lin, Sources and distributions of dust aerosols simulated with the GOCART model, *J. Geophys. Res.*, **106**, 20255-20274, 2001.
- Gleason, J.F., P.K. Bhartia, J.R. Herman, R. McPeters, P. Newman, R.S. Stolarski, L. Flynn, G. Labow, D. Larko, C. Seftor, C. Wellemeyer, W.D. Komhyr, A.J. Miller, and W. Planet, Record low Global Ozone in 1992, *Science*, **260**, 523-526, 1993.
- Gordon, H.R., Atmospheric correction of ocean color imagery in the Earth Observing System era, *J. Geophys. Res.*, **102D**, 17,081-17,106, 1997.
- Herman, J.R. and E. Celarier, Earth surface reflectivity climatology at 340 and 380 nm from TOMS data, *J. Geophys. Res.*, **102**, 12,059-12,076, 1997.
- Herman, J.R., P.K. Bhartia, O. Torres, C. Hsu, C. Seftor and E. Celarier, Global Distribution of UV-absorbing aerosols from Nimbus7/TOMS data, *J. Geophys. Res.*, **102**, 16911-16922, 1997.
- Holben, B.N., T.F. Eck, I. Slutsker, D. Tanre,, J.P. Buis, A. Setzer, E. Vermote, J.A. Reagan, Y.J. Kaufman, T. Nakajima, F. Lavenue, I. Jankowiak, and A. Smirnov, AERONET - A Federated Instrument Network and Data Archive for Aerosol Characterization, *Remote Sens. Environ.*, **66**, 1-16, 1998.
- Hsu, N.C., J.R. Herman, O. Torres, B.N. Holben, D. Tanre, T.F. Eck, A. Smirnov, B. Chatenet and F. Lavenue, Comparison of the TOMS aerosol index with Sun\_photometer aerosol optical thickness: Results and applications, *J. Geophys. Res.*, **104**, 6269-6279, 1999.
- King, M.D., Y.J. Kaufman, D. Tanre, and T. Nakajima, Remote Sensing of Tropospheric Aerosols from Space: Past, present and future, *Bull. Am. Meteorol. Soc.*, **80**, 2229-2259, 1999.
- Patterson, E.M., D.A. Gillette, and B. Stockton, Complex index of refraction between 300 and 700 nm for Saharan aerosols, *J. Geophys. Res.*, **82**, 3153-3160, 1977.
- Sokolik, I., A. Andronova, and T.C. Johnson, Complex refractive index of atmospheric dust aerosols, *Atmos. Environ.*, **27(A)**, 2495-2502, 1993.
- Torres, O., P.K. Bhartia, J.R. Herman, Z. Ahmad and J. Gleason, Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation, Theoretical Basis, *J. Geophys. Res.*, **103**, 17099-17110, 1998.
- Torres, O., and P.K. Bhartia, Impact of tropospheric aerosol absorption on ozone retrieval from backscattered ultraviolet measurements, *J. Geophys. Res.*, **104**, 21569-21577, 1999.
- Torres, O., P.K. Bhartia, J. Herman, A. Sinyuk, P. Ginoux, and B. Holben, A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements, submitted to *J. Atmos. Sci.*, 2001.