Retrieval of aerosol optical depth from satellite measurements using single and dual view algorithms

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ABSTRACT

To retrieve aerosol properties from the radiance measured at the top of the atmosphere in clear sky conditions, the contributions of the surface and the various atmospheric constituents need to be separated. This is easiest done over dark surfaces, i.e. with a negligible reflectance that can relatively easily be accounted for. This principle has been used for the retrieval of aerosol optical depth (AOD) over water from satellite observations in the near-infrared. The AOD at wavelengths in the UV can be determined both over water and over land, using the same principle of a dark surface. For longer wavelengths, the dual view provided by ATSR-2 is used to separate the aerosol reflectance from the surface contribution. Single and dual-view algorithms have been developed by TNO-FEL and tested for the US east coast and over Europe. Currently the algorithms are extended with other aerosol types and tested versus data over the Indian Ocean (INDOEX area) and South Africa (SAFARI experiment). The initial results indicate that the AOD can be retrieved within reasonable limits. Apart from the ATSR-2, algorithms aimed at the determination of aerosol optical depth and composition are developed for AATSR and SCIAMACHY (ENVISAT) and OMI (EOS-TERRA).

Keywords: Aerosols, Optical Depth, Ångström parameter, chemical composition, ATSR-2, OMI, AATSR, SCIAMACHY

1. INTRODUCTION

Aerosols affect, among others, climate[1], air quality[2], health[3], weather and electro-optical observations. Examples of the latter are the effect of aerosols on the retrievals of surface properties from satellite observations, or the range degradation of electro-optical systems used for, e.g., military purposes. Both effects are due to the extinction of radiation at wavelengths in the UV, the visible and the IR, due to scattering and absorption.

The effect of aerosol scattering and absorption on the Earth' radiation balance has been recognized in the late 1980's[4]. Scattering results in cooling, while absorbing aerosols contribute to warming. The radiative effect of aerosols is thought to be of similar magnitude as that of greenhouse gases (GHG), but of opposite sign. Indirectly, aerosols affect the Earth' radiation balance because of their influence on cloud formation and cloud albedo. Aerosols are the major uncertainty in the climate system[5].

The absorption of radiation is used to identify aerosols by satellite remote sensing and providing an aerosol index. However, most of the aerosol types that are important for climate, such as ammonium sulphate and ammonium nitrate that are mainly produced due to anthropogenic activity's, have negligible absorption.

To assess the effects of aerosols on climate, both natural and anthropogenic aerosols must be considered. Aerosols are either directly emitted, or formed from their precursor gases. The particles have a relatively short life time, typically on the order of three days. Nevertheless, aerosols are transported over long distances while experiencing transformations of several kinds[6]. Natural aerosols such as sea salt, although usually occurring in relatively low concentrations, are formed over large parts of the globe. For example, sea salt is the dominant submicrometer scatterer in most ocean regions with a contribution of 44% to the global aerosol optical depth[5].

To assess the influence of antropogenic and natural aerosols it is important to monitor their concentrations and to discriminate between the major aerosol types, with appropriate resolution on regional to global scales. The

Remote Sensing of Clouds and the Atmosphere VII, Klaus Schäfer, Olga Lado-Bordowsky, Adolfo Comerón, Richard H. Picard, Editors, Proceedings of SPIE Vol. 4882 (2003)

concentrations and occurrence of aerosols are highly variable in both space and time[7] due to many direct emission sources with strongly different source strengths, atmospheric residence times of several days, and a variety of transport mechanisms that disperse the aerosol throughout the atmosphere. The latter depends on the meteorological situation. In addition, the emission of gaseous aerosol precursors constitute distributed sources for the formation of secondary aerosol.

Satellites offer a unique opportunity to provide information on the regional and global distributions of aerosols, and thus on their effects on climate and other important issues such as health and environmental effects, and algorithms have been developed to retrieve aerosol properties from the radiance received at the top of the atmosphere (TOA). The aerosol index mainly applies to absorbing aerosols. However, most of the aerosols that are important for climate forcing (taken as the effect of anthropogenic perturbations), such as ammonium sulphate and ammonium nitrate, have negligible absorption. One of the goals of the research presented here is to discriminate between different aerosol types. Different satellite instruments are available that have been designed to derive specific information that can also be used for aerosol retrieval. Dedicated aerosol instruments are currently not available.

A drawback of the use of satellites is that aerosol information can only be retrieved in cloud-free situations. Therefore satellite data are assimilated in chemistry transport models to provide continuous coverage, while the model results are constrained by the observations.

2. AEROSOL RETRIEVAL FROM SATELLITES

In cloud-free situations, the radiance received by satellites at the top of the atmosphere (TOA) is composed of contributions due to scattering by gases and aerosols, and reflection at the surface. Absorption by molecular species and aerosols further modify the TOA radiance. Hence the signal received by electro-optical instrumentation on satellites in principle contains information on the surface properties and on the atmospheric composition. A major problem to derive aerosol properties from radiation received by satellite-based sensors is to separate the contribution due to reflection at the surface from the contribution due to scattering by aerosols, both of which are modified by atmospheric gases and depend on the sun-satellite geometry. Until recently it was thought that aerosol retrieval was only possible over water, i.e. dark surfaces with very low reflection. Over the oceans, aerosol optical depth (AOD) has been retrieved since more than two decades using data from the various AVHRR satellites. This provides a long time series of observations which is of great value for trends analysis.

Over land no such data are available, except for the aerosol index provided by TOMS data, based on aerosol absorption. The dual view algorithm was developed at TNO Physics and Electronics Laboratory (TNO-FEL)[8] to retrieve aerosol properties over land from ATSR-2 (ERS-2 satellite) data. The retrieved AOD and the AOD spectral variation compare favourably with AERONET[9] sunphotometer data. This algorithm uses the dual view and the 4 spectral bands in the visible and near-IR offered by ATSR-2. A second algorithm for application over land was developed for use with GOME (ERS-2) data at wavelengths in the UV, where the surface reflection is very low[10]. These algorithms are extensively described in the PhD thesis of Veefkind[11] and have been applied to and tested with data obtained during the TARFOX campaign off the United States east-coast in July 1997[9,12] and over NW Europe. The results compared favourably with sunphotometer data from the AERONET station in Lille, as well as with data obtained in The Netherlands from sunphotometers in De Bilt and from UV measurements in Petten. Furthermore, the analysis showed a favourable comparison with aerosol measurements at ground level in Petten[10]. The feasibility to retrieve the AOD over land has further been demonstrated with data from MISR which offers nine view angles to separate the aerosol and surface contributions, and with data from POLDER by taking advantage of polarization to discriminate between surface and aerosol contributions to the reflectance.

The instruments currently used by the TNO Physics and Electronics Laboratory (TNO-FEL) are AVHRR, ATSR-2, and GOME (cf. ref. 11), and algorithms are being developed for OMI, AATSR and SCIAMACHY. The ATSR-2/AATSR algorithms are briefly discussed below. OMI and SCIAMACHY algorithms, for which data are currently not available, are briefly discussed in the discussion.

3. ATSR-2/AATSR

The ATSR-2 on board the European Remote Sensing Satellite ERS-2 is a radiometer with seven wavelength bands, four of which are in the visible and near-infrared part of the spectrum (effective wavelengths 0.555, 0.659, 0.865 and 1.6 μm). The ATSR-2 has a conical scanning mechanism that offers both a nadir view and a forward view (viewing zenith angle approximately 56°) of the same ground pixel with a separation of about two minutes. The spatial resolution is approximately 1x1 km^2 at nadir. The swath width of the ATSR-2 is 512 km. For the midlatitudes, this results in an overpass over a given location once every three days. The Advanced Along Track Scanning Radiometer (AATSR) is a similar instrument on board ENVISAT. Algorithms developed for ATSR-2 will therefore also be suitable for use with AATSR data.

The single view algorithm is used for application over water, where it is assumed that the sea surface reflectance is low and constant. The dual view algorithm takes advantage of both views to eliminate the influence of the surface reflection on the TOA radiance. Assumptions are that the ratio of the nadir and forward view of the ATSR-2 is independent of the wavelength[13] and that the contribution of the aerosols is relatively small for the 1.6 μm channel.

To retrieve the AOD, the reflectance measured by the ATSR-2 radiometer is first corrected for atmospheric effects (i.e. absorption and scattering by molecules) and for surface effects. Then the corrected reflectance is compared with the pre-computed look up tables (LUT) in order to know which aerosol type best fits the spectral reflectance of the aerosols present in the atmospheric column. LUT's are pre-computed tables with the reflectance due to chosen aerosol type as function of the wavelength and the sun-satellite geometry. For each aerosol type or mixture a LUT should be computed. To create the LUT the DAK (Doubling and Adding method) radiative transfer model[14] was used. In the algorithms up to 4 LUT's are used to determine the most probable aerosol mixture. Aerosol mixtures are created as combinations of the different aerosol types such as black carbon, water-soluble (sulphate, nitrate, some organic), sea salt and dust particles. The mixtures have been selected based on results from aerosol measurements conducted in the INDOEX region[15,16,17]. The scattering properties of the aerosol mixtures are calculated using a Mie program and the results are used to create LUT's. The retrieval algorithm uses the Least Median Squares (LMS) method[18] to determine which LUT best fits the measured reflectance at various wavelengths.

Both the single and the dual view algorithms are based on a simple aerosol model describing the vertical distribution of an aerosol mixture consisting of 'continental' aerosols and seaspray. These algorithms have been applied over the east coast of the United States[8, 12] and over Europe[7]. However, for other areas more aerosol types than continental and sea spray need to be included, such as dust, biomass aerosol and black carbon. Algorithms including such aerosol types are tested with data over the Indian Ocean for which a large number of data are available from the INDOEX experiment, and with data over South Africa for which data are available from the SAFARI experiment.

Thus far SAFARI retrievals were only compared with airborne data from the AATS, over the Atlantic Ocean west of the African continent. Because these measurements were made over water, the single view algorithm was applied and the results compare favorably[19]. Further tests will be made with data from the SAFARI experiment over land where sunphotometer data are available for comparison.

More extensive tests have been made for the INDOEX area. Different sets of LUT's have been created based on measurements done during the INDOEX campaign. Quinn et al.[17] used the aerosol sample inlet, nephelometer, and particle sizers on board the RV Ronald H. Brown to determine various properties of eight air masses depending on the source region. Only four of them (southern hemisphere Indian Ocean (SHIO), northern hemisphere Indian Ocean (NHIO), Indian Subcontinent (IS), and Arabia/Indian Subcontinent (A/IS) are used in this study to create the same number of LUT's. Chowdhury et al.[15] used cascade impactors to determine the chemical composition of the aerosols at the KCO during February 11-26, 1999. Dubovik et al.[16] retrieved optical information of the aerosols using CIMEL ground-based radiometers from the AERONET[9] data-base. From this study also four aerosol types are selected: the mixture at KCO during some periods of 1999 and 2000, over Saudi Arabia in 1998-2000, over the African Savanna in 1995-2000 and sea salt particles in Hawaii, 1995-2000. Size distributions based on the OPAC aerosol model[20] are used to complete the information needed to create the LUT for every aerosol mixture.

The initial comparison of the retrieved AOD at 0.659 μm with sun photometer data at Male Island on 16th February 1999 from AERONET [9] shows agreement within 0.05[22]. However, the INDOEX tests show that the inclusion of several aerosol types which can be reflecting and absorbing is not straightforward. The aerosol over the Indian Ocean consists of 5 major aerosol types with similar mass concentrations which renders it difficult to select the most probable aerosol mixture. The challenge is to reproduce the changing aerosol composition as function of fetch using satellite data. Preliminary results show the transition from continental to maritime aerosols.

To handle these large amounts of data, the dual view algorithm has been extended with an automated cloud detection over land, based on the cloud-screening scheme developed by Koelemeijer and Stammes[21] which requires manual interference. The method is based on the differences in the brightness temperature and in the reflectance of clouds and land. Three tests are applied to distinguish between them. Cloud-free areas are selected only when all of these tests indicate the absence of clouds. The first test takes advantage of the lower temperature of clouds as compared to the land surface. In the second test the reflectances of the land surface and of clouds are compared, higher reflective pixels are selected as cloudy. The third test is based on the ratio of reflectances at 0.865 μm to 0.659 μm. Over clouds this ratio should be around 1. Higher values are selected as cloud-free land areas. The threshold values is automatically selected by application of numerical methods[22]. The results compare satisfactorily with those from the semi-automatic algorithm.

4. INTEGRATION WITH CHEMISTRY TRANSPORT MODELS

ATSR-2 data have been used for comparison with models on regional[25] and global[23] scales to provide information on the contribution of different aerosol types to the AOD. Next, ATSR-2 data have been assimilated in the chemistry transport model (CTM) LOTOS[24] and TM3.

4.1 Aerosol Optical Depth over Europe

The single and dual view algorithms were applied to data over Europe, for all ATSR-2 overpasses in August 1997. The single view algorithm was applied over water because of problems encountered with the dual view algorithm caused by large differences in the surface reflectance for the two look-angles. The results show the contributions of various industrial and urbanised areas[7], with AOD at 0.555 μm of up to 0.8, whereas in clean areas the AOD may be lower than 0.1. The results were further interpreted by using the chemistry transport model LOTOS which includes ammonium sulphate and nitrate aerosols[25]. The computed aerosol fields were converted to AOD using a simple mass-extinction relationship[26]. The results for sulphate show similar trends as the observed AOD. From comparison between the retrieved and the model-derived AOD, the relative contributions of sulphate and nitrate to the total AOD could be estimated. Similar trends are observed in the spatial variations of the calculated and retrieved AOD values. For the specific month studied (August 1997), the contribution of sulphate to the total light scattering varies from less than 30% over the cleanest areas to 70% over the most polluted areas in central Europe. Nitrate may contribute up to about 10-15% in most of Europe[27].

4.2 Data assimilation

The August 1997 ATSR-2 AOD data have been assimilated in the CTM LOTOS to derive the PM2.5 distribution over Europe. Initial results were presented in ref. 24. In a separate effort, ATSR-2 data from the INDOEX experiments in the winter of 1999 were assimilated in TM3 with the aim is to both constrain the model results and to use the model to provide an initial estimate for the retrieval algorithm. The results clearly show the influence of the assimilation of satellite data on the modeled aerosol concentrations[28].

5. ÅNGSTRÖM PARAMETER

Aerosol particle size distributions are often approximated by a power law function, generally referred to as the Junge[29] distribution:

$$\log\left(\frac{dN}{dD}\right) = C(\log D)^{-\nu} \tag{1}$$

where N is the number of particles per cm^{-3}, D is the particle diameter, C is a constant referred to as the Junge constant, and ν is the Junge coefficient. The Junge constant C gives the number of particles for a wavelength of 1 μm. For very clean atmospheres C can have very small values, on the order of 1, whereas in a polluted atmosphere the value of C can be on the order of 10^3-10^4. Likewise, the value of the Junge coefficient ν can vary from about 3 to about 5. A low value of ν indicates the presence of very low concentrations of sub-micron particles and relatively high concentrations of particles larger than 1 μm. This situation may occur over the ocean, where large concentrations of sea spray particles may occur at elevated wind speeds in a relatively clean atmosphere. *Vice versa*, large values of ν are indicative of very high concentrations of sub-micron aerosol particles. Over land, common values are $\nu \approx 4$.

The aerosol extinction coefficients, which can be calculated from an aerosol size distribution with the appropriate refractive index[30], vary with wavelength λ. For a Junge size distribution, the wavelength dependence follows a power law distribution, with a coefficient $\alpha = \nu - 2$. For a situation where the aerosol is well-mixed over the vertical column, or alternatively, the aerosol extinction coefficient is invariable with height, a similar relation applies to the AOD (AOD is the product of extinction coefficient and optical path length). In the literature, the variation of the AOD with the wavelength is often referred to as the Ångström law:

$$\mathrm{AOD}(\lambda) \propto \lambda^{-\alpha} \tag{2}$$

where α is the Ångström parameter.

ATSR-2 has four channels (0.555, 0.659, 0.865 and 1.6 μm) which are used for aerosol retrieval. The application of eq. 2 to derive the Ångström parameter is illustrated in Fig. 1, where the AOD is plotted versus the wavelength, on a log-log scale. The slope of the fitted line gives the Ångström coefficient α..

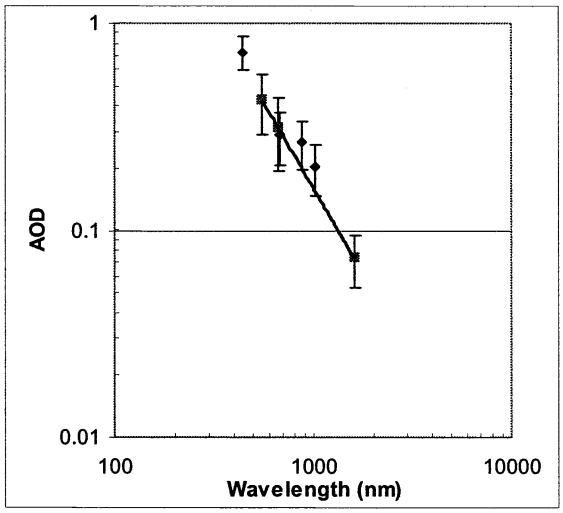

Fig. 1. AOD as function of wavelength. The line is a least squares fit to the data, the slope of which gives the Ångström parameter α..

The AOD was retrieved for all available cloud-free pixels over Europe in August 1997, for all available wavelengths. Ångström coefficients were derived from these data. Since $\alpha = \nu - 2$, small values of the Ångström parameter indicate the dominance of large particles, such as sea salt or dust, whereas large Ångström parameters are usually obtained when

small particles such as sulfate or nitrate dominate. The large variations in the satellite retrieved Ångström parameters indicate the variability of the aerosol size distributions.

The Ångström paramters and their variation across Europe and the European regional seas are discussed in ref. 27. High AOD values of around 0.5-0.6 at 0.555 μm related to Ångström coefficients between 0.8 and 1.6 found over the most industrialised areas indicate the presence of small particles from anthropogenic sources i.e. sulphate and nitrate aerosols. AOD and Ångström coefficient values around 0.23 and 1.2 respectively were found over the seas presumably due to larger particles such as sea spray aerosols. The complementary use of satellite data and model results allows the deduction of information on the contribution of the individual aerosol components to the total AOD. The values are in reasonable agreement with other values mentioned in the literature, based on aerosol climatology[20], sunphotometer[31, 32] observations, or retrievals from other satellites[33]. Observed discrepancies are discussed based on aerosol transport in relation to meteorological situations.

6. RELATION BETWEEN ÅNGSTRÖM COEFFICIENTS AND CHEMICAL COMPOSITION

As discussed above, the Ångström coefficient gives information on the shape of the particle size distribution, which in turn is connected with the origin of the aerosols, and thus to a certain extent also with the chemical composition. The latter has been investigated using simultaneous measurements of the aerosol optical depth, with a sunphotometer, and aerosol chemical composition over the Baltic[34]. The measurements were made during two periods of two weeks each, the first one in the summer (July) of 1997, the second one in the winter (March) of 1998. The results have been used to derive relations between concentrations of certain aerosol components, the total particulate matter (TPM) and the Ångström parameter. For instance, the Na fraction was observed to be high for low Ångström coefficients, and decreases strongly with increasing Ångström coefficient, confirming the qualitative arguments presented in the previous section. Empirical relations were derived for the aerosol components sodium, black carbon, organic carbon, water solubles, and dust.[34,35]

7. DISCUSSION AND CONCLUSIONS

An overview has been presented of aerosol retrieval work at TNO-FEL, focused on data from the European satellites ERS-2 (ATSR-2 and GOME), but also using AVHRR (NOAA). A significant result is the retrieval of aerosol properties over land, using the possibilities offered by, especially, ATSR-2, but also from GOME data, when available. This has resulted in maps of AOD and Ångström coefficients over Europe for August 1997, yielding a wealth of data for further interpretation. These maps are based on data obtained from ERS-2 overpasses in cloud free situations, i.e. at best every third day. The good agreement between the monthly averaged AOD values of the satellite data and the ground based sunphotometer data renders credibility to these values, within the limits of experimental uncertainty. The results are interpreted using a chemical transport model, from which AOD field of sulphate and nitrate were calculated. Taking into account the various uncertainties, as well as model deficiencies, estimates can be made of the contributions of these aerosol types to the total AOD, which in turn can be used to derive conclusions as regards climate forcing. Absolute assessment of the contributions of the various aerosol types to the total AOD is not possible, except for areas for which reliable experimental data are available for validation, such as The Netherlands. For most other areas only trends can be indicated and model uncertainties need to be accounted for. Therefore this study is regarded as a demonstration of the complementary use of aerosol retrievals and model results. This allows for the deduction of information on the contribution of the independent species to the total light scattering, which cannot be obtained from each of these methods separately.

The AOD provides the column integrated value for the total aerosol attenuation. The Ångström coefficient is an indicator of the shape of the aerosol size distribution. These parameters are also indicative of the types of aerosols present in the column: large Ångström coefficients indicate the presence of small particles from anthropogenic sources, whereas small Ångström coefficients indicate the dominance of larger particles, such as sea spray aerosol. Measurements over the Baltic were used to derive empirical relations between aerosol composition and Ångström coefficients. These relations were used in turn to retrieve the aerosol composition from Ångström coefficients, obtained from sunphotometer measurements, using an independent data set over the Baltic, for a different season.

Experience with the algorithms developed thus far will be applied to future missions such as ENVISAT (AATSR and SCIAMACHY), MSG, and EOS-AURA, cf. Table 1 for an overview. The ozone monitoring instrument (OMI) will be aboard the AURA satellite, part of the NASA Earth Observation System (EOS), scheduled for launch in January 2004. The instrument has daily global coverage with a 13 x 24 km^2 surface resolution and a continuous spectrum between 270 and 500 nm. The OMI aerosol algorithm will use 19 well-spaced and carefully selected 1 nm wide wavebands between 330 and 500 nm. Five major aerosol types; urban/industrial, biomass burning, desert dust, oceanic and volcanic with several sub-classes will be distinguished from their spectral behaviour. The algorithm will combine the 'residuals' method used in TOMS aerosol retrieval with a new multi-wavelength non-linear fitting method[36].

Other algorithms will be developed for AATSR and SCIAMACHY. It is expected that the ATSR-2 algorithm can also be used for AATSR. For the SCanning Imaging Absorption SpectroMeter for Atmospheric ChartographY (SCIAMACHY, on ENVISAT), two aerosol retrieval algorithms are developed one for for application over land and the other for application over water. The algorithm for application over water uses IR spectral channels to obtain information (first guess) about spectral characteristics of aerosols. Next, this information is used to evaluate the TOA radiance expected in the visible channels by taking into account observed spectral relations for the water-leaving reflectance in Case I and Case II waters. The results are compared with the measured TOA radiance. This information over a wide wavelength region allows for a better separation of the contributions from different aerosol types. The algorithm for application over land uses the UV channels to get information about spectral characteristics of aerosols. Next, this primary information is used to evaluate the expected TOA radiances in the VIS/IR channels, taking into account the surface reflectance over different surface[37].

Table 1. Characteristics of satellite sensors used for atmospheric aerosol retrieval at TNO-FEL

Sensor/Satellite	Channels (nm) in UV,VIS and NIR	Spatial resolution (km)	Swath width (km)	Comments
AVHRR NOAA	640, 840	1-4	2000	No in-flight calibration Water vapour absorption
ATSR-2 ERS-2	555, 659, 865, 1600	1-4	512	In-flight calibration Dual view capability
GOME ERS-2	Continuous in 240-790	340 x 40 or 80 x 40	960 or 240	Spectrometer
SCIAMACHY ENVISAT		30 x 240 to 30 x 27	960 or 120	3 viewing geometries and vertical information
AATSR ENVISAT	555, 659, 865, 1600	1	512	In-flight calibration Dual view capability
OMI EOS-AURA	Continuous in 270-500	13 x24	2600	Spectrometer Daily earth coverage
MSG	635, 810, 1640	1-3	Full earth disc image	Geo-stationary 15 minute interval

ACKNOWLEDGEMENTS

The work presented in this paper is supported by the Netherlands Space Research Organisation (SRON), contracts EO-008 and EO-037. ATSR-2 and GOME data are provided by the European Space Agency (ESA) through DLR and ESRIN. Modeling work on LOTOS is undertaken with Peter Builtjes, Maarten van Loon and Martijn Schaap (TNO-MEP) and on TM3 with Peter van Velthoven, Ge Verver and Bas Henzing (KNMI).

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