Deliverable D_D-SAT_3.2.3

ATSR-DV product description, initial validation and QC

Version 1.0

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Executive Summary

This document describes the AATSR dual view algorithm for aerosol retrieval (ADV) and its use in the MACC project for the near-real time (NRT) provision of aerosol data on European and Global scale. ADV is described and results are presented. Validation is discussed and illustrated. Data provision in NRT has recently started and is being tested. Steps for further development and improvements are indicated.

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1. Introduction

Aerosols are an important constituent of the atmospheric boundary layer. Aerosol particles provide a surface for heterogeneous chemical processes, they act as a condensation sink for atmospheric trace gases and hygroscopic particles serve as cloud condensation nuclei. The chemical and physical properties of aerosol particles are very variable in both space and time and depend on the presence of sources and sinks and the chemical and physical transformation during their atmospheric lifetime. Particle sizes may vary from a few nm to some tens of μm. Physical processes depend on particle size, in particular the vertical transport and removal of particles by dry deposition to the surface. Very small particles are subject to growth by condensation and coagulation and transport is determined by turbulent transport and Brownian diffusion. Very large particles having sufficient mass are subject to gravitational forces resulting in sedimentation. These processes, in addition to formation by direct emission and secondary processes, chemical transformations and in-cloud processing, determine the number concentrations of aerosol particles which may vary by 10 orders of magnitude depending on size. The particle size distribution describes the variation of the aerosol number concentration as function of particle size (radius or diameter, specified for a certain relative humidity to account for differences due to hygroscopic growth). As a result of the various processes, the aerosol particles that are most abundant in the atmosphere are those with a radius of a few tenths of a μm, with a minimum in the dry deposition curve, and the number particle size distribution peaks for these sizes which therefore are often referred to as accumulation mode particles. The atmospheric lifetime of these particles is relatively long, on the order of a few days to a few weeks depending on the surface roughness and related deposition velocity, and the main removal mechanism is wet deposition.

Aerosols have a strong impact on climate both direct due to scattering and absorption of solar radiation (direct effect) and indirect due to their influence on cloud properties (indirect effect). Optical properties of aerosol particles are determined by their size relative to the wavelength of incident light and their chemical composition which determines their complex refractive index. The optical properties such as angular scattering (the aerosol phase function) and absorption for a given aerosol size distribution and chemical composition can be computed using a Mie code [Mie, 1908]. The scattering and absorption efficiency are near zero for very small particles and near 2 for very large particles. Hence the particles most important for climate, as determined by the product of the particle size distribution and the scattering efficiency, are in the accumulation mode.

Overall our understanding of the effects of aerosols on climate is poor [IPCC, 2007] and hence it is important to quantify the aerosol properties on regional to global scales. Satellite remote sensing using optical instruments such as radiometers or spectrometers provides a unique method to determine aerosol properties on such scales with the same instrument and the same method, but often with a smaller accuracy than in-situ instruments. Satellite remote sensing of aerosols is a relatively young science and aerosol retrieval methods are continuously improving. Techniques are developed to determine the information that can be obtained from satellites (e.g. Kahn et al. [2009]).

The retrieval of aerosol properties from satellite-based observations started some three decades ago [Lee et al., 2009] using data from the Advanced Very High Resolution Radiometer (AVHRR) [Stowe et al., 2002] onboard TIROS-N and from the Total Ozone Mapping Spectrometer (TOMS) [Torres et al., 2002] which were both launched in

October 1978. Initially, retrievals were obtained only for measurements over water; aerosol retrieval results over land have started to become available on a regular basis only in the last decade. Aerosol retrieval over ocean could be accomplished relatively easy due to the low surface reflectance in the near-infrared channels. In that case, the signal registered on a satellite is largely determined by light scattered in the atmosphere and the contribution of the surface (outside the glint) is comparatively low. These long time series been analyzed to investigate the occurrence of temporal trends in aerosol optical depth (AOD, i.e. the column-integrated aerosol extinction) [Mishchenko et al., 2007]. However, Levy et al. [2010] report for MODIS the possibility of small, but significant calibration uncertainties of <2%, which could lead to spurious long-term aerosol trends. Several instruments have been used for the retrieval of aerosol properties with as principal parameter the AOD. Comparison of the results shows differences between different instruments (e.g., Myhre et al. [2005]). More recent comparisons of MISR and MODIS aerosol products over ocean shows very good correlation between the AOD products (correlation coefficient 0.9) and the Ångström exponent (correlation coefficient 0.67 when MISR AOD values > 0.2 are considered) [Kahn et al., 2009]. Kahn et al. emphasize the proper interpretation of the satellite products. In particular data-quality statements should be followed to ensure proper interpretation and use of the satellite aerosol products.

The Along Track Scanning Radiometer (ATSR-2) on the ESA (European Space Agency) satellite ERS-2 and it successor AATSR (Advanced Along Track Scanning Radiometer) on the ESA polar orbiting Environmental Satellite ENVISAT launched in March 2002 were developed to measure surface temperature. However, the ATSR instrument characteristics make them also suitable for aerosol retrieval over ocean (Veefkind et al., 1998a, 1999; Veefkind 1999) and, taking advantage of the single and dual view algorithms, over land (Veefkind et al., 1998b, 2000; Veefkind, 1999). AATSR is used for aerosol retrieval by several groups in Europe, cf. Kokhanovsky and de Leeuw [2009] for detailed descriptions of the approaches. The ATSR dual view algorithm was developed at TNO in The Netherlands and applied over various regions such as Europe [Veefkind et al., 2000; Robles Gonzalez et al., 2000], the North Atlantic [Veefkind et al., 2008a], India and the Indian Ocean [Robles Gonzalez et al., 2006] and Africa [Robles Gonzalez and de Leeuw, 2008]. These applications were mainly connected to campaigns such as TARFOX, INDOEX and SAFARI.

In 2007 the work at TNO on the retrieval of aerosol properties from satellite data was stopped and the algorithms were transferred to Helsinki for implementation at the Finnish Meteorological Institute (FMI) and the Department of Physics at the University of Helsinki (UHEL). The transfer included training of UHEL students at TNO during several days and TNO support to UHEL and FMI in the first few months. The implementation implied familiarization of the UHEL and FMI personnel with the subject and debugging and optimization of the AATSR dual view algorithm which is now referred to as ADV. ADV was initially applied to case studies and as part of larger projects providing data necessary to test the retrieval results and explore the information that can be obtained in various conditions including very low AOD over Northern Europe [Sogacheva et al., 2008] and the Boreal Forest [Sogacheva et al., 2010], highly polluted areas in Europe [Curier et al., 2009; Kolmonen et al., 2010] and Asia (Sunström et al.,

2010) with high AODs, the detection of smoke and ash plumes [Sundström et al., 2008; Kolmonen et al., 2009] and applications over the global ocean [Sogacheva et al., 2009]. However, no systematic routine retrievals were made and results from the campaigns were made available on request.

The MACC requirements of retrievals on the European and Global scales and the near-real time (NRT) provision of the data demanded that the ATSR aerosol retrieval was automated, routines would be developed to download, read and process the data very quickly after observation and transfer the results to a webpage from where they can be downloaded by MACC partners. This requires:

- The development of a webpage where the data are made available
- The development of scripts to automatically download from the ESA rolling archives in NRT
- The development of scripts to automatically run ADV with the NRT data
- The development of aerosol models that can be applied with ADV on a global scale to retrieve AOD with a reasonable accuracy as determined from comparison with independent data
- The validation of the aerosol products to determine the quality of the data
- To determine where the algorithm needs improvement and / or the quality is so low that retrieval products are unreliable, such as over bright surfaces, including development of criteria to identify such conditions
- The development of routines for the NRT data provision on the website
- The development of data visualization tools

In this report the current status of ADV is described, including validation and evaluation of the aerosol products.

2. (A)ATSR

The Advanced Along-Track Scanning Radiometer (AATSR) instrument onboard the European ENVISAT satellite flies at an altitude of approximately 800 km in a sun-synchronous polar orbit. Like its predecessor ATSR-2 on ERS-2, the AATSR has seven wavelength bands in the visible and infrared parts of the spectrum (0.55, 0.67, 0.87, 1.6, 3.7, 11 and 12 μm). The instrument has a conical scanning mechanism providing two views of the same location with a resolution of 1×1 km^2 at nadir view. The radiometer views the surface at a forward angle of 55° and 150 seconds later at nadir view. The swath width of 512 km results in an overpass over a given location once every three days at mid-latitudes.

The features of the instrument enable the development of retrieval methods for aerosol optical properties over land. There are a number of algorithms developed for aerosol retrieval using AATSR imagery. These include the dual-view algorithm by Veefkind et al. [1998], the multi-view algorithm by Grey et al. [2006] and the Oxford-RAL algorithm by Thomas et al. [2009]. These algorithms differ significantly in the way the ground reflectance is handled. In the Grey algorithm, a ground reflectance model is used which makes it possible to retrieve aerosol properties and ground reflectance simultaneously [North et al., 1999]. The Oxford-RAL algorithm relies on information from the retrieval of another instrument: the land surface bi-directional reflectance product of MODIS (MODerate resolution Imaging Spectrometer). The surface reflectance treatment of the last algorithm, which is called the ADV (AATSR Dual-View) algorithm, is described in this work. An overview of the instrument characteristics of AATSR and other sensors and presentations of various retrieval algorithms can be found in Kokhanovsky and de Leeuw [2009].

3. The AATSR Dual View Algorithm for Aerosol Retrieval

3.1 Formal background of the dual-view algorithm

The AATSR dual-view algorithm ADV is developed for the retrieval of aerosol optical properties over land from the AATSR-measured radiances [Veefkind et al., 1998; 2000; Robles Gonzalez et al., 2000]. These properties include AOD for three wavelengths (nominally 0.555, 0.659 and 1.61 μm). In addition, an aerosol model is retrieved. The model is a mixture of two aerosol types which must be prescribed *a priori*.

The algorithm is based on a number of assumptions:

- The TOA reflectance ρ is of the form [Wang and Gordon, 1994]:

$$\rho(\mu_1,\mu,\phi,\lambda)=\rho_a(\mu_1,\mu,\phi,\lambda)+\frac{T(\mu_1,\mu,\phi,\lambda)\rho_g(\mu_1,\mu,\phi,\lambda)}{1+s(\lambda)R_s(\lambda)}, \tag{1}$$

where ρ_a is the reflectance due to atmosphere, ρ_g is the ground reflectance, T is the multiple of downward and upward atmospheric transmittance, s is the atmospheric backscatter ratio, and R_s is the surface albedo. Reflectance and transmittance parameters: μ_1 is the solar zenith angle, μ is the viewing (satellite) zenith angle, φ is the relative azimuth angle between the sun and the satellite, and λ is the wavelength. Multiple scattering between ground and atmosphere is assumed here to be angle-independent for method development purposes. It has also been suggested that the multiple scattering in the surface-atmosphere system will lead to isotropically distributed scattering [Wanner et al., 1997].

- Atmospheric reflectance:

$$\rho_a(\mu_1,\mu,\phi,\lambda)=\rho_R(\mu_1,\mu,\phi,\lambda)+\rho_{aer}(\mu_1,\mu,\phi,\lambda), \tag{2}$$

where ρ_R is reflectance due to Rayleigh scattering and ρ_aer is reflectance due to aerosols.

- Reflectance due to aerosols is computed using the modified linear mixing method by Abdou et al. [1997]. The method as adapted to ADV is:

$$\rho_{aer}=b_1\frac{\omega_{mix}}{\omega_1}e^{-\tau_1|\omega_1-\omega_{mix}|}\rho_1+b_2\frac{\omega_{mix}}{\omega_2}e^{-\tau_2|\omega_2-\omega_{mix}|}\rho_2 \tag{3}$$

where ω is the single scattering albedo (SSA) and τ is OD. Subscripts *1* and *2* refer to two aerosol types while mix refers to the linear mixture of the two types. For the weighting coefficients $b_1 + b_2 = 1$. The modified linear mixing method is applied to take better into account the effects of mixing two aerosols with different absorbing properties. This is done by introducing the single scattering albedo into linear mixing. If the SSAs of the two aerosol types are identical, equation (3) simplifies to

$$\rho_{aer} = b_1\rho_1 + b_2\rho_1 \tag{4}$$

- The atmospheric reflectance is approximated as a linear function of AOD [Durkee et al., 1986]. The function is of the form

$$\rho_a(\mu_1, \mu, \phi, \lambda) = \rho_R(\mu_1, \mu, \phi, \lambda) + c(\mu_1, \mu, \phi, \lambda)\tau(\lambda) \tag{5}$$

where τ is AOD and c is the slope of the linear function.

- The ratio k between the ground reflectance of the forward and nadir views is independent of wavelength [Flowerdew and Haigh, 1995]:

$$k = \frac{\rho_g^f(\mu_1, \mu, \phi, \lambda)}{\rho_g^n(\mu_1, \mu, \phi, \lambda)} \tag{6}$$

where ρ_g^f and ρ_g^n are the forward and nadir ground reflectances, respectively. Also, because reflectance due to aerosols at 1600 nm is small compared to ground reflectance, the k-ratio is computed using

$$k = \frac{\rho^f(\mu_1, \mu, \phi, 1600nm)}{\rho^n(\mu_1, \mu, \phi, 1600nm)} \tag{7}$$

The 0.865 µm channel is excluded from the retrieval because the k-ratio assumption is usually not valid at that wavelength because of a strong reflectance by vegetation [Robles Gonzalez et al., 2000].

The dual-view method for AOD retrieval is derived based on the above assumptions. Equation (1) can be written separately for the forward and nadir views. By combining these equations while keeping in mind that the multiple scattering is assumed to be angle independent, relation

$$\frac{\rho^n(\mu_1, \mu, \phi, \lambda) - \rho_a^n(\mu_1, \mu, \phi, \lambda)}{\rho_g^n(\mu_1, \mu, \phi, \lambda)T^n(\mu_1, \mu, \phi, \lambda)} = \frac{\rho^f(\mu_1, \mu, \phi, \lambda) - \rho_a^f(\mu_1, \mu, \phi, \lambda)}{\rho_g^f(\mu_1, \mu, \phi, \lambda)T^f(\mu_1, \mu, \phi, \lambda)} \tag{8}$$

can be made formally. The key aspect of the dual-view algorithm is to introduce the k-ratio (7) to equation (8) to obtain:

$$\frac{\rho^n(\mu_1, \mu, \phi, \lambda) - \rho_a^n(\mu_1, \mu, \phi, \lambda)}{T^n(\mu_1, \mu, \phi, \lambda)} = \frac{\rho^f(\mu_1, \mu, \phi, \lambda) - \rho_a^f(\mu_1, \mu, \phi, \lambda)}{kT^f(\mu_1, \mu, \phi, \lambda)} \tag{9}$$

In this way the knowledge on ground reflectance is included in the k-ratio.

3.2 Computational aspects of ADV

Before retrieval, a look-up-table (LUT) including AOD, reflectance, single scattering albedo and transmittance among other information is computed for each aerosol type. The size distribution of an aerosol type is described by log-normal number size distributions of the form:

$$\frac{dN}{d\ln r} = \frac{N_o}{\ln\sigma\sqrt{2\pi}} \exp\left(-\frac{\ln^2(r/r_g)}{2\ln^2\sigma}\right) \tag{10}$$

where r is the ambient particle radius. The size distribution of an aerosol type is defined by the geometric mean radius r_g and standard deviation σ [Heitzenberg, 1994]. The total number of aerosol particles N_0 depends on the aerosol load. Aerosol optical properties are computed by applying Mie calculations [Mie, 1908]. These calculations require the knowledge of the aerosol size distribution and refractive index. The aerosol types used are described in Section 4.2. An aerosol model consisting of the two aerosol types must be chosen before the retrieval.

The LUTs are computed for discrete sun zenith, viewing zenith and relative azimuth angles, for each AATSR wavelength, and for a number of reference AOD levels. There are typically ten AOD levels ranging from 0.05 to 4.0 at $\lambda = 500$ nm. Transmittance and reflectance are computed also for Rayleigh scattering. LUTs are used to save computation time as the radiative transfer equation would have to be solved numerous times in the retrieval process. Therefore, all radiative transfer computation is done beforehand during the LUT determination with the DAK (Doubling Adding KNMI) algorithm [de Haan et al., 1987]. In the retrieval process needed values are linearly interpolated from the LUTs. Figure 1 shows an example of an AOD LUT.

Equation (9) shows that the computational task is to find the aerosol-type mixture and reference AOD level that solve the equation for all three AATSR wavelengths simultaneously. Due to measurement and modeling errors this task is impossible in practice. Instead, the task can be converted to a least-squares type of problem

$$\arg_{b_1,L}\min\sum_{i=1}^{N_\lambda}\left[\frac{\rho^n(\lambda_i)-\rho_a^n(b_1,b_2,L,\lambda_i)}{T^n(b_1,b_2,L,\lambda_i)}-\frac{\rho^f(\lambda_i)-\rho_a^f(b_1,b_2,L,\lambda_i)}{kT^f(b_1,b_2,L,\lambda_i)}\right]^2 \tag{11}$$

with the fraction of the first aerosol type $b_1 \in (0,1)$ and the reference AOD level $L \in (1,10)$. The mixture of second aerosol type $b_2 = 1 - b_1$. The angle arguments (μ_1, μ, φ) have been omitted for brevity. The number of wavelengths $N_\lambda = 3$. The problem also shows that the modeled atmospheric reflectance and transmittance are functions of the decision arguments b_1 for aerosol type mixture and L for the reference AOD level. The task is now to find the decision arguments (b_1, L) that minimize the least-squares sum (11).

The minimization problem (11) can be optimized by applying mathematical optimization methods. Here the chosen method is Levenberg-Marquardt [Gill et al., 1999]. It is a trust-region type method well suited for least-squares problems, and is meant for unconstrained optimization. The latter feature causes additional considerations as the decision arguments are all box-constrained. This is handled in the evaluation of the least-squares sum where the decision arguments are forced to have values within their box-constrained domains.

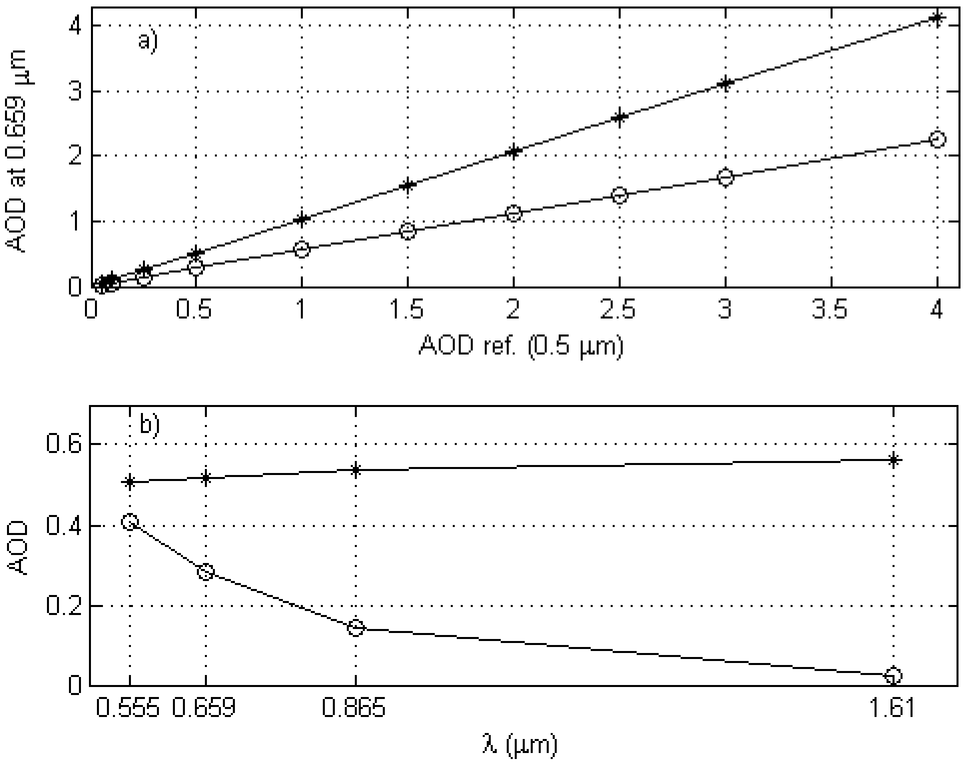

Figure 1: Example of the AOD at 0.659 µm for two aerosol types as a function of (a) AOD reference levels and (b) for the AATSR wavelengths.

Another feature of the Levenberg-Marquardt method is that it is a local optimizer. It will converge efficiently to the nearest local minimum. To increase the probability of finding the globally best solution an initial search is done in a limited discrete set of decision parameters: ten mixtures b_l and ten AOD levels L. The results of the search are then used as the initial guess for the Levenberg-Marquardt method.

3.3 Cloud Screening

Clouded pixels have to be excluded from retrieval as they mask the other contributions of atmosphere to the measured TOA reflectance. The tests that are described here were designed for the ATSR-2 data. For AATSR cloud flags are included in the reflectance data [AATSR Product Handbook, 2007].

Presently, three separate cloud screening tests are used. These tests are based on the work of Koelemeijer et al. [2001] and Saunders and Kriebel [1988]. To automate the cloud screening AATSR orbits are divided into scenes. These scenes are 512×512 pixels in size. Reflectance is histogrammed and thresholds or rejection values for the tests are determined from the histograms. The automation of the tests is described by Robles-

Gonzales [2003]. Brief description of the tests:

1. The gross cloud test. At the AATSR 12 μm brightness temperature channel clouds appear cooler. If the brightness temperature for a pixel is below threshold, the pixel is flagged as cloudy.

2. Generally, clouds are brighter than the underlying surface. If the reflectance of the channel for a pixel is higher than threshold, the pixel is flagged as cloudy.

3. Ratio of the 870 nm and 659 nm reflectance. If the ratio is around one for a pixel, the pixel is flagged as cloudy. The distance from unity that governs cloud flagging is determined by the automation.

These tests are applied for both AATSR views. If any of the tests indicates that a pixel is clouded, it will be excluded from the retrieval.

4. Adaptation of ADV for global multi-year retrievals

The ADV algorithm is suitable for retrieval of optical properties of aerosols over land. It became evident in the initial testing, however, that the time needed for retrieval computations was far too long. The main reason behind the time consumption is the fact that there are two parameters that need to be optimized during the retrieval process: the AOD reference level as well the mixture of the two aerosol types. In addition, some statistical measures indicating the reliability of the retrieval can be computed using the ensemble of measured TOA reflectance values over a larger area. It was decided that for large retrieval tasks a larger result pixel size must be used. In this section the methods for averaging the AATSR measured TOA reflectance over the larger pixel are described. Also the choice of aerosol models is discussed.

4.1 Averaging of measured reflectance for ADV

The natural assumption when averaging the TOA measured reflectance is that atmospheric reflectance is fairly uniform over the averaged area, i.e. that there are no strong spatial gradients in aerosol conditions across the area. Reflectance due to atmospheric gases is assumed to be constant.

The complications in the averaging of the measured TOA reflectance are caused by the k-ratio approach of the ADV. The k-ratio is determined by applying equation (7) and using nadir and forward view ground reflectance at 1.6 μm. It would be unrealistic to assume that ground reflectance is constant over the larger pixel area. In order see how the k-ratio affects the retrieval process, equation (9) can be reformulated as

$$\frac{\left[\rho^f(\mu_1,\mu,\phi,\lambda)-\rho_a^f(\mu_1,\mu,\phi,\lambda)\right]/T^f(\mu_1,\mu,\phi,\lambda)}{\left[\rho^n(\mu_1,\mu,\phi,\lambda)-\rho_a^n(\mu_1,\mu,\phi,\lambda)\right]/T^n(\mu_1,\mu,\phi,\lambda)}=k \tag{12}$$

It is evident that the value of k strongly affects the results of a retrieval. If the k-ratio is computed using values that are simply averaged, values that are not representative for the pixels in the larger area could be encountered especially in areas with variable surface reflectance, pixels influences by strongly reflecting surfaces, glint, etc. For example, consider an area where half of the larger area is covered with pixels having a high and the other half having a low k-ratio. When the k-ratios are averaged the end result would be wrong for the whole area. Furthermore, as both of the AATSR views are employed, in simple averaging of reflectance one cannot be certain that corresponding nadir/forward pixels are used when the k-ratio is determined. This could lead into situations where, in principle, nadir and forward view reflectance come from different pixels.

The chosen approach to average measured reflectance is to find pixels that are the most representative for an area, and at the same time are seen in both the nadir and forward views. The description of the method:

1. At least 50% of pixels belonging to an area must pass the cloud screening tests. This step ensures that enough information is present for the following steps.

2. Make a histogram of the measured reflectance at the 1.61 μm channel separately for nadir and forward reflectance. Typically seven bins are used ranging from zero to the maximum of the measured reflectance. The infrared channel is used here because the effect of aerosols is small. That is, the measured reflectance is considered to have only contributions from the surface.

3. Choose the nadir/forward bins that have the maximum number of reflectance values.

4. Find out which pixels that are in the chosen bins are mutual to nadir and forward views.

5. If there are more than ten values left, average the chosen reflectance values and use them in retrieval. If less than ten values are left, the surface reflectance in the area is considered to vary too much and for that area no retrieval is made.

The number of bins in the histogram determination is a compromise between loss of data and degeneration towards simple averaging. If too many bins would be used, there would be too few pixels for the averaging of the reflectance. This situation would be poor in a statistical sense. If too few bins were used, too wide range of reflectance values would be accepted. This would allow pixels that could lead to situations where the whole representative search k-ratio approach would become meaningless.

Another test for the averaged reflectance measures whether the atmospheric conditions are sufficiently uniform. The standard deviation of reflectance at 555 nm is used as a measure for the uniformity. The 555 nm channel was utilized here as it is sensitive to aerosol and cloud conditions. If the standard deviation is too large for an area, retrieval is not done as the area could be cloud contaminated. Figure 2 shows how the standard deviation of an area sub-pixels is affected by the cloud fraction of the area. Data for this figure was obtained using the AATSR cloud mask and measured TOA reflectance at 555 nm. The current standard deviation threshold for excluding an area based on the 555 nm uniformity test is 0.009. Figure 3 shows an example of the use of the test.

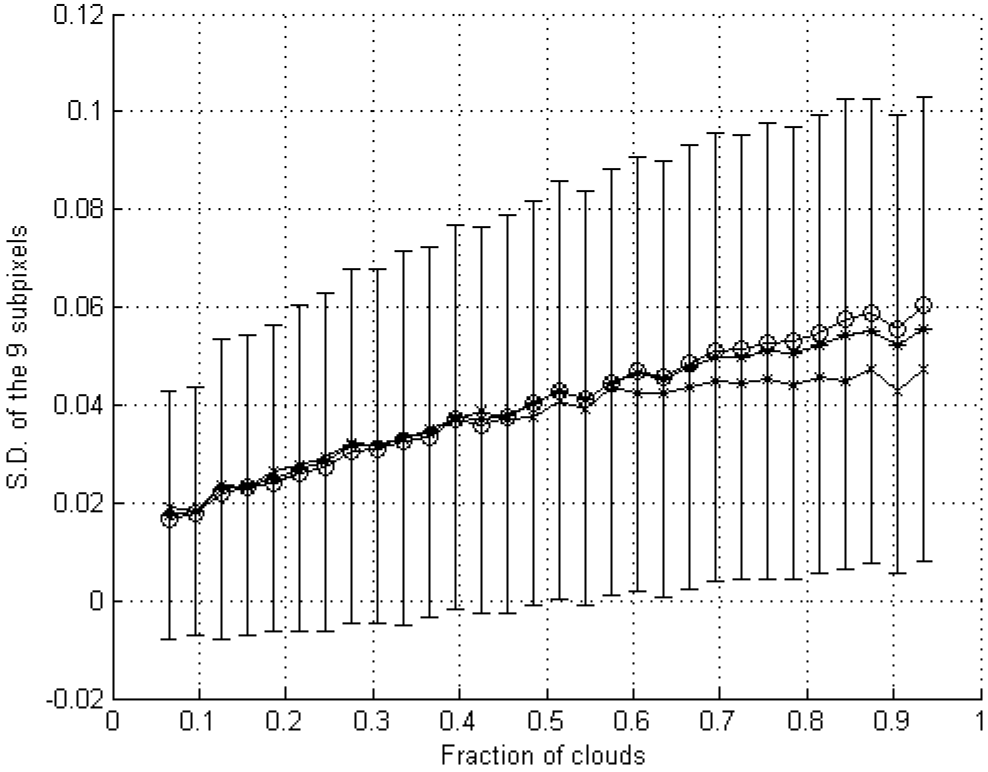

Figure 2: The standard deviation of sub-pixels in an area as a function of the cloud fraction of the area. 144701 areas are included. Results are averaged over 30 cloud fraction bins.

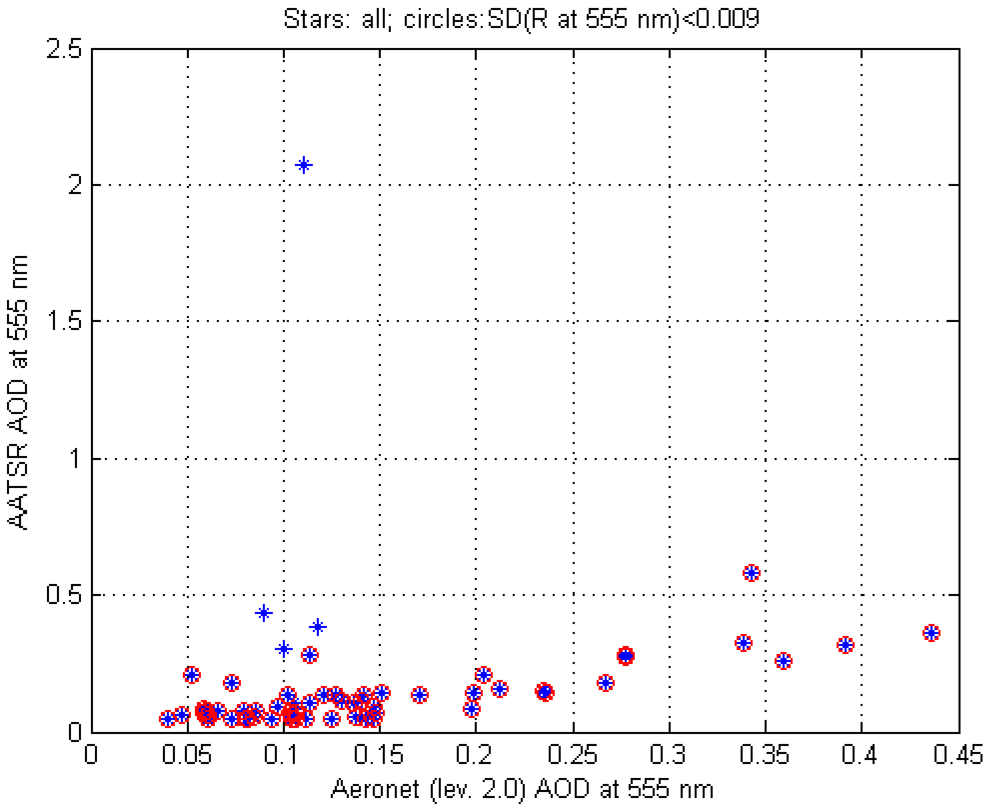

Figure 3: An example of the 0.555 µm reflectance rule. The comparison between AATSR retrieved and AERONET AOD results at 0.555 µm is shown. Excluded results are marked with red circles.

4.2 Regional aerosol models

Aerosol models are based on the AERONET cluster analysis by Omar et al. [2005]. MODIS collection 5 aerosol models are also utilized [MODIS ATBD]. The MODIS models are largely based on the AERONET analysis. Currently the general model used for global retrievals is the background one by Omar et al. [2005] or non-absorbing model from MODIS. These models have quite similar features and lead to almost identical retrieval results. The values of the log-normal parameterization of the general models are:

Model	r_g (µm)	σ	*n*
Background fine	0.0810	1.502	1.4494 – 0.0092i
Background coarse	0.6827	2.104	1.4494 – 0.0092i
Non-absorbing fine	0.1059	1.4841	1.4200 – 0.0073i
Non-absorbing coarse	0.5101	2.2085	1.4200 – 0.0073i

Note: refractive index n is used for all wavelengths unless specifically mentioned.

Particular regional studies have been conducted over China, India and the African continent. From these studies the China/India analysis has been incorporated in global retrievals over land. A special aerosol model is used over South-East Asia (Longitude 65° − 140° East, Latitude 15° − 50° North). This aerosol model is composed of dirty pollution fine type (from Omar et al. [2005]) and neutral coarse type (from MODIS). The features of the SE Asia model:

Model	r_g (μm)	σ	*n*
Dirty pollution fine	0.0800	1.5400	1.4104 – 0.0337i
Neutral coarse	0.5892	2.1145	1.4300 – 0.0084i

During heavy smog conditions in China only a mixture of two fine type aerosols produced credible results. The mixture consists of the above mentioned dirty pollution type and pure sulphate type from d'Almeida et al. [1991]. This model is currently not used in the global retrievals.

Dust detection and dust retrieval methods over land are presently under development. In addition, bright surfaces are excluded from retrievals at the moment as the ADV method does not seem to do well when the ground reflectance is much higher than the atmospheric one.

5 Validation and examples of retrieval results

For the validation global AOD was retrieved for two years, 2006 and 2008. The chosen years were 2006 and 2008. The validation data came from the AERONET (AErosol RObotic NETwork). AERONET is a network of ground-based sun photometers that measure atmospheric aerosol properties [Holben et al., 1998].

The overall performance of ADV was studied by applying a cluster analysis of the comparison between retrieved and AERONET AOD at 555 nm. The choice of the wavelength is somewhat arbitrary and similar results were obtained for the 659 nm channel. In the cluster analysis retrieval and AERONET coincident results were first averaged by AERONET station for the whole time period, years 2006 and 2008. Coincidence was decided by limiting AERONET station and retrieval result coordinates to maximum of five kilometer difference spatially and to maximum of plus/minus 30 minutes difference temporally. An AERONET site was included in the analysis if there where at least five retrieval/AERONET coincidences. This limit was assigned to gain some statistical confidence in the analysis. The purpose of this analysis is to determine where the ADV algorithm is performing well, and where more development or using different aerosol models will be needed.

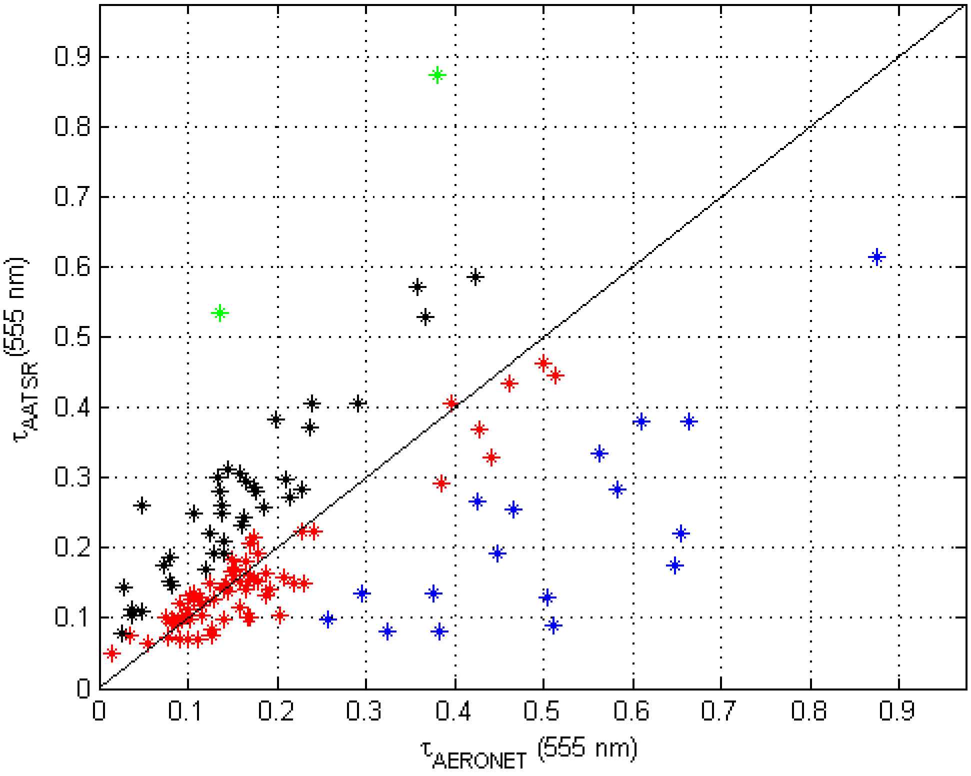

Figure 4: The result of the cluster analysis for the comparison between ADV retrieved and AERONETAOD at 555 nm. See text for explanations.

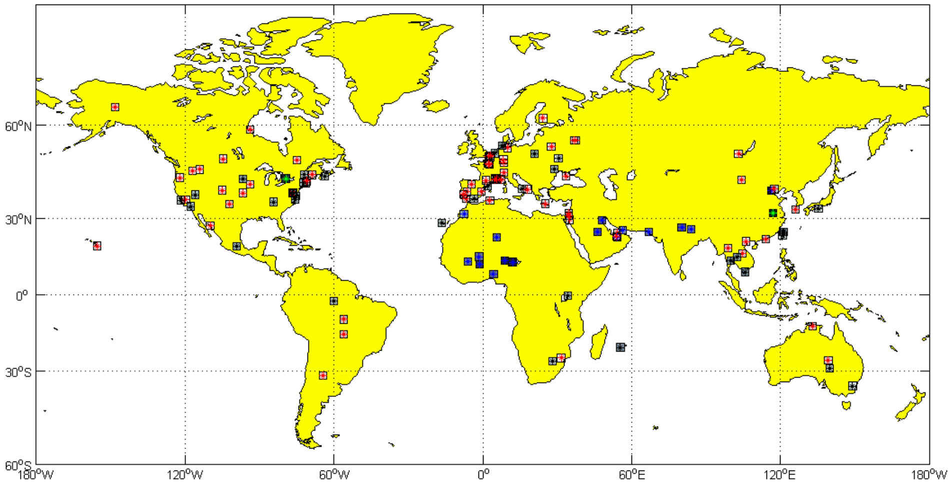

Figure 5: The localization of the AERONET sites that were included in the cluster analysis. The color of the stars indicates in which cluster a site belongs. The darkness of the boxes indicate discrepancy between the ADV retrieved and AERONET AOD at 555 nm.

In the cluster analysis the number of clusters was four. This number was decided by trying different numbers of clusters and then looking at the results. With four clusters understandable explanation was found for each of the clusters. The results of the cluster analysis are presented in figure 4. The AERONET sites that were included in the analysis can be seen in figure 5. The four clusters can be explained as follows:

-Red cluster. These are the AERONET sites where the ADV algorithm is showing acceptable performance.

- Blackcluster. AOD is high at these AERONET stations. The optical properties of the used aerosol model are most probably not suitable. A model that has stronger scattering and/or absorbing characteristics is needed.

- Green cluster. Severe overestimation of AOD at these stations. Again, the applied aerosol model may not be suitable. The aerosol conditions are extraordinary in this cluster as there are only two AERONET stations included.

- Blue cluster. Underestimation of AOD. To understand this other characteristics of the clusters must be employed. Figure 5 shows that the AERONET sites belonging to the blue cluster are located at desert or arid environments. The surface reflectane for these kinds of ground areas is particularly high. To prove this it was assumed that for the 1.6 μm channel the contribution of aerosols to the TOA reflectance is small when compared to the surface reflectance contribution. The average TOA reflectance for the clusters: red - 0.20, black -0.17, green -0.17, and blue -0.37. Thus, it can be verified that the AERONET sites belonging to the blue cluster have considerably high approximated surface reflectance. For high surface reflectance it is difficult to have reliable retrieval results of the aerosol optical properties since the atmospheric reflectance signal is very small when compared to the ground reflectance signal. As to why the ADV algorithm underestimates AOD in these kinds of situations there is no clear answer yet. It was, however, decided that all ADV retrieval results where TOA reflectance is higher than 0.35 at 1.6 μm will be discarded because of high surface reflectance.

Figure 6 shows the AOD comparison at 0.555 μm between ADV and AERONET when the 0.555 μm uniformity test and the 1.6 μm ground reflectance tests are applied.

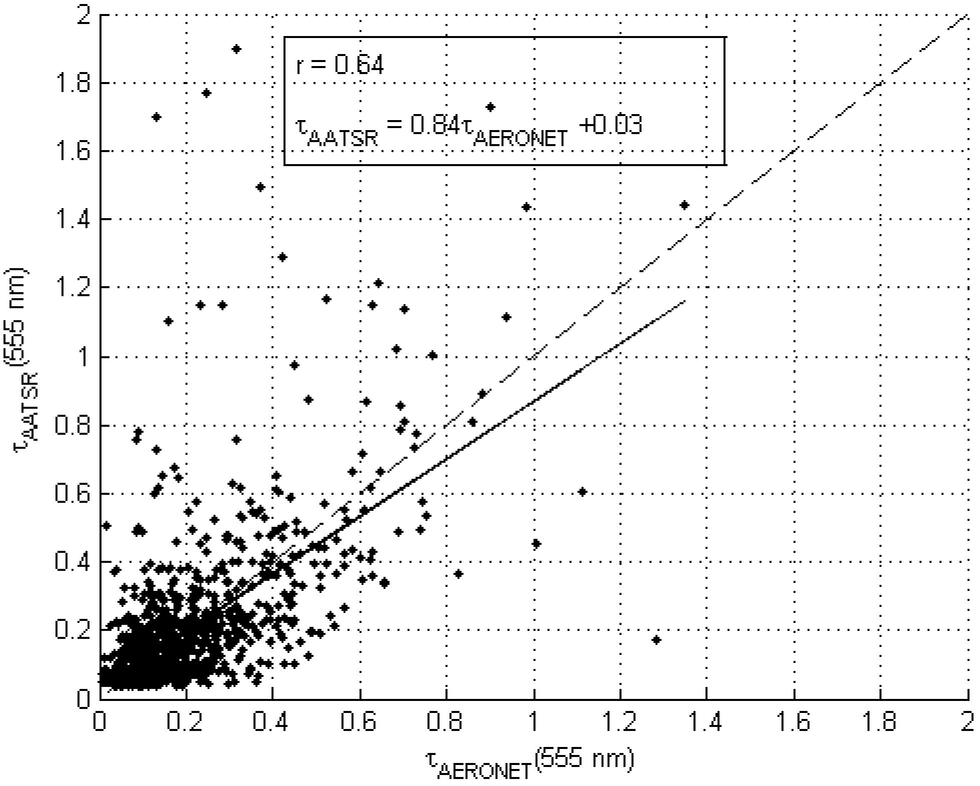

Figure 6: the Comparison of AOD at 0.555 μm between ADV retrieved and AERONET.

6 ADV Discussion

The ADV algorithm has been applied over a wide variety of regions with different surfaces and different aerosol properties, usually on campaign or case studies where the aerosol models used in the retrieval can be adjusted for the particular situation. To retrieve aerosol properties over larger areas this is not possible and choices have to be for aerosol models that provide overall reasonable performance. The results in Figures 4 and 5 illustrate how well the AOD can be retrieved across the globe, with AERONET as reference. Overall AOD provides reasonable results over Europe, North America and some other regions. The results in Figures 4 and 5 also show where ADV needs improvement and the current focus of our research is on these areas. In particular we focus on areas where additional information on the aerosol properties is available, in particular from campaigns or extended intensive monitoring such as the EUCAARI development countries observations in China, India and South Africa or the Megapoli campaigns focusing on very large cities.

ADV does currently not yet include proper dust models that take into the account the non-sphericity of the particles. The implementation of dust models is among the future goals. An associated problem is the detection of dust and the discrimination between dust and water / ice clouds. The AATSR thermal infrared channels offer an opportunity to do this, but over very bight surfaces at high temperatures there channels may be saturated and cannot be used.

In general, the retrieval over bright surfaces is a problem discussed by many teams using different satellites and a point of further investigation is how well ADV works over bright surfaces. These include deserts with the additional problem of TIR channel saturation as indicated above, and snow and ice. The latter is of particular concern for the Nordic countries and activities are planned as part of the Nordic Network on cryosphere.

The ESA ECV Aerosol-cci project is a common effort of prominent retrieval groups in Europe in cooperation with US colleagues to compare and improve aerosol retrieval algorithms with current emphasis on aerosol models, treatment of the surface and cloud detection. Results from this project are expected to contribute to further improvement of ADV.

The results form these research projects will implemented in ADV when appropriate.

7. Data availability

The task in MACC is to provide AATSR data in near real time (NRT). To this end a website has been constructed (http://aatsraerosol.fmi.fi/) with links to 'Globe' and to 'Europe' where the data can be found in the 'data' link. Data are publicly available but we ask for a password to monitor the use of the data. Also there is a disclaimer that the data are research products. They are aimed to be according to the current state-of-the-art of the retrieval algorithm and may be subject to change when improvements are made. The use of the data and checking of their quality is the responsibility of the user and the users are encouraged to contact the AATSR ADV team for more information on the quality and the use of the data.

For testing the NRT data provision a smaller region was selected 'Po Valley' which has been tested since 17 August 2010. The Po Valley data seems scattered which can be explained by the limited coverage due to the relatively small AATSR swath of 512 km, i.e. an overpass of roughly every third day at mid-latitudes and 5-6 days near the equator.

Uploading of larger data sets was a problem that was solved on 13 October 2010 and the proper functioning of the website is now being tested.

8. Next steps

Further improvement of the ADV algorithm and resulting aerosol products will be done in the framework of research projects. The results will be implemented in the NRT algorithm when appropriate, i.e. when satisfactory results are obtained as judged from validation and comparison with independent data sets such as sun photometers, lidar data, other satellite instruments and models.

Validation is not part of the NRT product and will be done by comparison with representative AERONET Level 2.0 data at least once per year. The results will be made available in yearly reports.

The data are currently uploaded as text files. The next step will be to change this to NetCDF to comply to standards selected for the Aerosol-cci and wishes expressed by the Aerosol-cci users , in particular the modeling community.

Currently the data are only provided as data files. To facilitate the selection and use of the data, we aim to plot them on a map which will be provided on the website as a quick-look tool.

The current algorithm provides some information on the data quality. The quality control and flagging aspects needs to be further developed to provide guidance on the confidence that the data provider has in the data.

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The ADV algorithm development has been started with the work of Veefkind started in 1995 and was continued as part of many EU, ESA and National projects, the more recent of which are the ESA projects TEMIS (DUE), PROMOTE (GMES), AMARSI, Aerosol-cci and ALANIS-aerosols (STSE), the EU projects EUCAARI, Megapoli, GEOmon and MACC and a large number of national projects. ESA is acknowledged for provision of the ATSR data since many years with progressive improvement and ease of data access. The AATSR GBT data used in MACC were made available through an agreement between MACC and ESA. The AERONET team and site PI's are acknowledged for their continuous efforts to maintain their instruments in good condition and making data available through the AERONET website.

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