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Abstract

Aerosol remote sensing is very much dependent on the quite accurate knowledge of the top-of-atmosphere (TOA) reflectance retrieved by a particular instrument. The status of the calibration of such an instrument thus is reflected in the quality of the aerosol retrieval. Currently the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) instrument gives too low values of the TOA reflectance, compared e.g. to data from MERIS (Medium Resolution Imaging Spectrometer), both operating on ENVISAT (ENVIronmental SATellite), but the calibration of the operational L1 product of SCIAMACHY is not yet finished.

From an inter-comparison of MERIS and SCIAMACHY TOA reflectance, for collocated scenes correction factors are derived to improve the current SCIAMACHY L1 data for the purpose of aerosol remote sensing. The corrected reflectance has been used for a first remote sensing of the aerosol optical thickness by the BAER (Bremen AErosol Retrieval) approach using SCIAMACHY data.

1. Introduction

In recent time several approaches for the retrieval of the aerosol optical thickness (AOT) over land and ocean from nadir scanning satellite radiometers have been developed. For MODIS over land the cross-correlation approach, c.f. Kaufman et al. (1997) is used. For SeaWiFS (Sea viewing Wide Field Sensor) and MERIS (Medium Resolution Imaging Spectrometer, c.f. MERIS SAG, 1995; Bezy et al., 2000) the BAER approach (Bremen AErosol Retrieval), c.f. von Hoyningen-Huene et al. (2003) has been tested successfully, using 8 visible and NIR channels of the instruments. SCIAMACHY and MERIS are operated by ESA onboard of ENVISAT. Since SCIAMACHY, c.f. Bovensmann et al. (1999) is providing high spectral resolution and a much extended spectral range, comparable spectral information as used in the BAER approach is available in the bands 3, 4 and 5. Therefore an attempt was made to adapt the BAER approach to

SCIAMACHY data too. However the formal use of the BAER approach leads to physically not meaningful negative AOT, if one uses SCIAMACHY top-of-atmosphere (TOA) reflectance directly. This is due to the fact, that the measured TOA reflectance, using data of the present processor version (4.02b) within the required spectral bands can be below the value for the Rayleigh path reflectance, which should be never the case. These findings are also reported by De Graaf and Stammes (2003).

Therefore the application of any retrieval procedure for the determination of aerosol parameters, as AOT or absorbing aerosol index (AAI) in a quite accurate, physically correct range requires the improvement of the values of the TOA reflectance for the SCIAMACHY bands, used for the aerosol retrieval.

Since the BAER approach has been applied successfully with MERIS L1 data, these MERIS data will be used for the derivation of correction factors to improve the SCIAMACHY TOA reflectance for the purpose of aerosol remote sensing. Applying these corrections a first attempt is made to retrieve AOT for 0.442 μm from SCIAMACHY data.

2. SCIAMACHY data preparation and reflectance correction

For the purpose of correcting the TOA reflectance, obtained with SCIAMACHY L1b data, coinciding SCIAMACHY and MERIS scenes are used. Since both instruments are on board of ENVISAT and scanning in nearly the same swath, a comparison of the TOA reflectance for the bands 3, 4 and 5 of SCIAMACHY could improve the TOA reflectance for the purpose of the retrieval of the AOT by the BAER approach.

Therefore, for both instruments the TOA reflectance from the L1 data are derived.

The TOA radiance $L(\lambda)$ from the L1 data is normalized to the solar illumination conditions for each wavelength λ to generate the TOA-reflectance $\rho_{\mathrm{TOA}}(\lambda)$:

$$\rho_{\mathrm{TOA}}(\lambda) = \frac{\pi\, L(\lambda)}{E_0(\lambda)} \cdot M(z_0), \tag{1}$$

where $M(z_0)$ is the airmass factor for the solar zenith distance z_0, $E_0(\lambda)$ is the extraterrestrial irradiance and $L(\lambda)$ is the measured TOA-radiance. The function $E_0(\lambda)$ is provided for MERIS and SCIAMACHY from the L1 data sets. The airmass factors are determined for the given solar zenith distance z_0. Since in high latitudes for large solar zenith distances (z_0>60°) atmospheric curvature gets of increased relevance, therefore $M(z_0)$ is determined by Kasten and Young (1989) and not by $1/\cos(z_0)$.

Since both instruments (SCIAMACHY and MERIS) differ in their spectral and spatial observation parameters, the data must be made comparable. In particular, they must be transferred to comparable spectral bands, band widths and spatial scales. Also we should observe the same uniform target (preferably, for clear sky conditions).

For the comparability of the spectral bands the spectrum of the TOA reflectance of the SCIAMACHY measurement for the spectral regions and band widths of channels of the MERIS instrument has been extracted and integrated over the band width.

Both pixels are selected for the same latitude and longitude, given by the geo-location information of the observation.

Due to the different spatial scales of the TOA reflectance, the data from all MERIS pixels within the 30×60 km pixel area (determined by the edge coordinates of a SCIAMACHY pixel) of SCIAMACHY have been averaged within the area.

The comparison of such different spatial scales also requires to exclude large inhomogeneities, such as clouds and inhomogeneous surface properties within the region of a SCIAMACHY pixel. Therefore, for this comparison homogeneous water surfaces are used. The value of the standard deviation of $\rho_{\mathrm{TOA}}^{\mathrm{MERIS}}$ within one SCIAMACHY pixel should be lower than 10%. In the most selected case it is even lower than 5%. The exclusion of inhomogeneous pixels removes the majority of pixels from the intercomparison, however it reduces the standard deviation and fits the data for one SCIAMACHY band on a linear relation. All other pixels show much higher inhomogeneities in terms of much larger standard deviations of the TOA reflectance of the MERIS pixels within one SCIAMACHY pixel. Such pixels with high standard deviations have been not used for the comparison. Figure 1 shows the TOA reflectance for the wavelength band of 0.865 μm for both instruments. The coinciding area of observations and the selected homogeneous pixels over water surfaces are marked within the MERIS scene.

The selected spectral regions, coinciding with MERIS channels are demonstrated in Fig. 2 and in Table 1. For the comparison only such spectral channels are used, where the spectrum of the TOA reflectance is smooth enough and not disturbed by strong gas absorption. Thus the MERIS channels 11 (O_2A-band) and 15 (H_2O-band) are not used for comparisons. The used MERIS channels are indicated in Table 1.

While MERIS has fixed channels with a defined center wavelength and a fixed band width, SCIAMACHY scans a high resolution spectrum with a pixel resolution of about 0.2 nm within one band region. The bands 3 (0.424–0.565 μm), 4 (0.613–0.775 μm) and 5 (0.798–0.946 μm) are covered by MERIS channels.

The channel 1 of MERIS (see Fig. 2) cannot be used, because of the gap between SCIAMACHY band 2 and band 3. For the determination of a correction factor for band 3 the MERIS channels 2, 3, 4 and 5 could be used.

For the correction factor of SCIAMACHY band 4 only the MERIS channels 7 and 12 are used until now, because they are part of the present BAER approach. Since MERIS provides more spectral information for control and confirmation of the derived correction factor for band 4, the channels 6, 8, 9 and 10 could be added for the comparison. For the comparison with MERIS channel 12 we had to avoid disturbances by the O_2-*A*-band, integrating the corresponding SCIAMACHY data.

For SCIAMACHY band 5 until now only 1 channel of the BAER approach could be used for comparisons. However, also here the MERIS channels 13 and 14 could be added. Especially in the cases of band 5 we avoided to include disturbed spectral regions within the comparisons. Here are several regions affected by stronger narrowband gas absorption and Fraunhofer lines, thus we reduced the selected spectral channel for the purpose of a later aerosol remote sensing.

Examples for SCIAMACHY TOA reflectance spectra from cloudless scenes over the Baltic Sea, which are used within this study, are presented in Fig. 3.

Two different approaches to compare SCIAMACHY and MERIS TOA reflectance are

ACPD
6, 673–699, 2006

W. von Hoyningen-Huene et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Print Version
Interactive Discussion

EGU

used: (a) simple ratio and (b) linear fitting of data. The latter enables also the consideration of a certain offset.

The ratios of the TOA reflectance of both instruments are determined by

$$C = \frac{\rho_{\mathrm{MERIS}}(\lambda)}{\rho_{\mathrm{SCIA}}(\lambda)}. \tag{2}$$

For the different channels of MERIS within one SCIAMACHY band, e.g. band 3, in the most cases the derived values of C are quite stable. Thus we determined for band 3 an average correction factor by fitting a linear function through the corresponding data for one band. The same is made for the other SCIAMACHY bands.

The obtained relationships between the both reflectance for the coinciding pixels is shown in Fig. 4. The slopes are used to derive average correction factors for the SCIAMACHY bands, e.g. band 3 (0.424–0.565 μm), band 4 (0.613–0.775 μm) and band 5 (0.798–946 μm).

The correction of the TOA reflectance to the level of MERIS, which is used within the BAER approach for the retrieval of AOT is achieved by:

$$\rho_{\mathrm{MERIS}}(\lambda) = C_1 \cdot \rho_{\mathrm{SCIA}}(\lambda) + C_0. \tag{3}$$

The correction factors obtained are presented in Table 2.

These factors are very similar with findings of De Graaf and Stammes (2003) on a broader database. Also comparison with AATSR (Advanced Along Track Scanning Radiometer), provided by Kerridge (private communication, 2004)[1], give very similar results.

However the correction factors seem to have also a certain spectral variability within the single bands. The obtained correction factors for the comparison with the single MERIS channels gives their spectral behavior, presented in Fig. 5.

The minimum of the required correction is in band 4 at about 0.65 μm, the largest correction is in band 5 depending on processor version. The standard deviations of

[1] Kerridge, B. J.: private communication, b.j.kerridge@rl.ac.uk, March, 2004.

the results are increasing with the wavelength, because of decreasing TOA reflectance signals.

Presently attempts are undertaken to improve the radiometric calibration by an extensive reanalysis of the on ground calibration measurements of SCIAMACHY. A new procedure has been developed to recalculate some of the radiometric key data from existing end-to-end measurements of the OPTEC 5 period in 1999/2000. The calculations were primarily based on a subset of NASA integrating sphere measurements, performed for SCIAMACHY's radiance and irradiance. The derived new SCIAMACHY key data show a significant difference to the on-ground ambient measured and calculated Bi-directional Reflectance Distribution Function (BRDF) keydata of SCIAMACHY's Elevation Scan Mirror Diffuser (ESM diffuser). Together with a re-determined nadir and limb sensitivity of the instrument, this leads to correction factors for both solar irradiance and reflectance, going into the same directions, like the correction factors derived from the comparison with MERIS TOA reflectance. First tests with in-flight measurements show a significant improvement of the quality of the level-1 data products when using these new key data. This preliminary result of this attempt is shown as black curve in Fig. 5.

After these investigations the derived correction factors will be applied for the SCIAMACHY bands 3, 4 and 5 to improve the TOA reflectance for the purpose of the application of the BAER approach, resulting in the retrieved AOT from cloud free SCIAMACHY data.

3. Short description of the BAER approach

The BAER approach has been developed for the aerosol remote sensing over land surface using SeaWiFS or MERIS L1 data, c.f. von Hoyningen-Huene et al. (2003). The BAER approach separates the aerosol reflectance by subtraction of the contributions of Rayleigh scattering and the surface reflectance for each pixel. For this purpose the approach makes use of the solution of the radiative transfer equation for the TOA reflectance, as described by Kaufman et al. (1997) and derives the aerosol reflectance:

$$\rho_{\text{Aer}}(\lambda) = \rho_{\text{TOA}}(\lambda) - \rho_{\text{Ray}}(\lambda, z_0, z_S, p_{\text{Surf}}(z)) - \frac{T(\lambda, M_S) \cdot T(\lambda, M_0) \cdot A_{\text{Surf}}(\lambda, z_0, z_S)}{1 - A_{\text{Surf}}(\lambda, z_0, z_S) \cdot \rho_{\text{Hem}}(\lambda, z_0)}. \quad (4)$$

Here $\rho_{\text{Aer}}(\lambda)$ and $\rho_{\text{TOA}}(\lambda)$ are the required aerosol reflectance and the TOA reflectance, respectively. $T(\lambda, M)$ is the total atmospheric transmission, containing direct and diffuse transmission for illumination and viewing geometry, composed from $T(\lambda, M){=}T_{\text{Ray}}(\lambda, M){\cdot}T_{\text{Aer}_{\text{Guess}}}(\lambda, M)$, which are the total transmittances including Rayleigh scattering and aerosol extinction. The latter requires a rough estimation of an AOT, which is performed at 0.443 μm using the assumption of a "black" surface. M_O and M_S are the air mass factors for the sun zenith distance z_o and the observer zenith distance z_S. $\rho_{\text{Ray}}(\lambda, z_O, z_S, p_{\text{Surf}}(z))$ is the path reflectance of the Rayleigh scattering. $A_{\text{Surf}}(\lambda, z_O, z_S)$ is the surface albedo and $\rho_{\text{Hem}}(\lambda, z_O)$ is the hemispheric atmospheric reflectance. The influence of the hemispheric reflectance is less important over low reflecting surfaces (ocean and green vegetation in the blue region of the spectrum). A description of the used parameterizations for the total transmittances and the hemispheric reflectance is given in the Appendix.

The BAER approach comprises the following main steps to determine the aerosol reflectance as the basis for the application of look-up-tables (LUT), which relate AOT and aerosol reflectance.

The main steps for the determination of the aerosol reflectance are:

(a) The determination of the spectral TOA reflectance for the selected bands (for SCIAMACHY, in this step the correction factors are used).

(b) The subtraction of the Rayleigh path reflectance for the geometry conditions of illumination and observation within the pixel.

(c) The estimation of the spectral surface reflectance for land and ocean surfaces by mixing of different basic spectra to an apparent surface reflectance over land by equations 5, 7 and 9, respectively over ocean equations 6, 8 and 9.

Over land spectra of a "green vegetation" and "bare soil" type are mixed following Eq. (7), tuned by the NDVI (normalized differential vegetation index),

$$\mathrm{NDVI} = \frac{\rho^*(0.870\,\mu\mathrm{m}) - \rho^*(0.665\,\mu\mathrm{m})}{\rho^*(0.870\,\mu\mathrm{m}) + \rho^*(0.665\,\mu\mathrm{m})}; \tag{5}$$

over ocean "clean ocean water" and "coastal water" type spectra are mixed using the NDPI (normalized differential pigment index),

$$\mathrm{NDPI} = \frac{\rho^*(0.443\,\mu\mathrm{m}) - \rho^*(0.560\,\mu\mathrm{m})}{\rho^*(0.490\,\mu\mathrm{m})}: \tag{6}$$

over land with $C_{\mathrm{Veg}} = f(\mathrm{NDVI})$, the vegetation fraction,

$$\rho_{\mathrm{Surf}}(\lambda) = F \cdot [C_{\mathrm{Veg}} \cdot \rho_{\mathrm{Veg}}(\lambda) + (1 - C_{\mathrm{Veg}}) \cdot \rho_{\mathrm{Soil}}(\lambda)] \tag{7}$$

and over ocean with $C_{\mathrm{Clear}} = f(\mathrm{NDPI})$, the clear water fraction,

$$\rho_{\mathrm{Surf}}(\lambda) = F \cdot [C_{\mathrm{Clear}} \cdot \rho_{\mathrm{Clear}}(\lambda) + (1 - C_{\mathrm{Clear}}) \cdot \rho_{\mathrm{Coastal}}(\lambda)]. \tag{8}$$

The basic surface type spectra $\rho_{\mathrm{Veg}}(\lambda)$, $\rho_{\mathrm{Soil}}(\lambda)$, $\rho_{\mathrm{Clear}}(\lambda)$ and $\rho_{\mathrm{Coastal}}(\lambda)$ for "green vegetation", "bare soil", "clean ocean water" and "coastal water" are given by von Hoyningen-Huene et al. (2003). F is a scaling factor for the level of the surface reflectance determined at 0.665 μm:

$$F = \frac{\rho_{\mathrm{TOA}} - \rho_{\mathrm{Ray}} - \rho_{\mathrm{Aer}}}{C_{\mathrm{Veg}} \cdot \rho_{\mathrm{Veg}}(\lambda) + (1 - C_{\mathrm{Veg}}) \cdot \rho_{\mathrm{Soil}}(\lambda)} \tag{9}$$

over land or the corresponding expression for the ocean.

(d) Smoothing the spectral AOT, using an Angström power law, by the iterative modification of the apparent surface reflectance:

$$\rho_{\mathrm{Surf},i}(\lambda) = \rho_{\mathrm{Surf},i-1}(\lambda) \cdot w(\lambda) \cdot (1 - \Delta_i(\lambda)), \tag{10}$$

with

$$\Delta_i(\lambda) = \frac{\delta_A(\lambda) - \bar{\delta}_A(\lambda)}{\delta_A(\lambda)}. \tag{11}$$

$\bar{\delta}_A(\lambda)=\beta\cdot\lambda^{-\alpha}$ is obtained from the fit of an Angtröm power law through the retrieved spectral AOT $\delta_A(\lambda)$ of the different channels. A sufficient smoothness of the spectrum of the AOT is reached at a minimal RMSD

$$\mathrm{RMSD} = \frac{1}{N}\sqrt{\sum_N (\delta_A(\lambda) - \bar{\delta}_A(\lambda))^2}. \tag{12}$$

The aerosol reflectance $\rho_{\mathrm{Aer}}(\lambda)$ is then used to derive the AOT applying LUT: $\delta_A(\lambda) = f(\rho_{\mathrm{Aer}}(\lambda))$. The LUT is obtained by radiative transfer modelling (RTM). In this case for the LUT aerosol parameters, mainly aerosol phase functions with increased lateral scattering, obtained in the LACE-98 experiment (Ansmann et al., 2001; von Hoyningen-Huene et al., 2003) are used. These parameters have shown to be very robust in a lot of other applications as for the determination of the AOT close to ground-based data, c.f. Kokhanovsky et al. (2004), Lee et al. (2004), von Hoyningen-Huene et al. (2004).

4. First results with the BAER approach using SCIAMACHY L1b data

For a first test of the possibility to retrieve AOT with SCIAMACHY, the BAER approach in the same way is used, like it is developed for the application with MERIS or SeaWiFS data, von Hoyningen-Huene et al. (2003, 2004), but using the correction factors from the analysis above.

Specific problems, connected with the larger pixel scale of SCIAMACHY ($30\times60\,\mathrm{km}^2$) compared with that of MERIS RR (reduced resolution) ($1.1\times1.1\,\mathrm{km}^2$), are not yet considered.

The result for the channel 2 (0.443 μm) is compared (a) with ground-based AERONET measurements, c.f. Holben et al. (1998), presented in Fig. 6 and (b) with the retrievals, made with MERIS data, presented in Fig. 7.

With the correction factors for SCIAMACHY, the AOT in a physically meaningful range can be obtained. For cloud free sections even comparable AOT with two AERONET instruments in the scene could be obtained. However, if one compare the retrieved values within the whole scene, c.f. Fig. 7, one must recognize, that they deviate in particular significantly from the results obtained by MERIS.

The reasons might by very different: (a) insufficient corrections of biasses within the scan line, caused by mirror and polarization corrections applied during the L1c data processing, (b) insufficient cloud screening for the SCIAMACHY pixels, (c) different mixing of the land surface and ocean surface properties, to be adequate for the spatial scale of SCIAMACHY pixels, (d) use of an inadequate digital elevation model (GTOPO30) for the scale of SCIAMACHY pixels. Therefore in the present status of the adaptation of the aerosol remote sensing to the SCIAMACHY data a comparison must be restricted to simple cases, e.g. no mountain regions with significant surface elevations, scenes with no or very few clouds.

For the comparability of the results we integrated the MERIS results over the size of the SCIAMACHY pixels. The standard deviation and the fully cloudy MERIS pixels are used to reject pixels as cloud contaminated. Further, we excluded all pixels, with surface elevations >250 m. Thus the most pixels over Sweden, which had strong positive deviations in AOT, have been removed. The result for the channel at 0.443 μm is presented in 8. This selection reduces the number of comparable pixels. However, the remaining part is very comparable with the results of MERIS. The fit between both results gives $AOT_{SCIA}=0.778 \cdot AOT_{MERIS}-0.01235$. This result shows that principally the AOT can be derived by BAER using SCIAMACHY measurements and the instrument is sensitive enough to observe aerosol properties, if an adequate calibration is available. The present approach with SCIAMACHY data underestimates for cloud free scenes the AOT, compared with the results of MERIS. For a better comparability and the application also for elevated terrains there is a need to adapt the approach to the specific scale of the SCIAMACHY observations.

5. Conclusions

This study showed, that principally SCIAMACHY measurements are sensitive enough for a remote sensing of aerosol properties, if one applies correction factors to the TOA reflectance. Since the remote sensing of the AOT as well also of the AAI is very sensitive to the exact level of TOA reflectance, the present L1c calibration (processor version v4.02b) is not sufficient to this task and needs to be improved.

Correction factors could be derived from comparisons of coinciding SCIAMACHY and MERIS scenes.

Performing this study, we realized, that the selection of useful coinciding data of both instruments, MERIS and SCIAMACHY, is sometimes difficult, because of problems with the availability of both information for the suitable observation situation (limb-nadir matching, cloud disturbances, missing data, different processing levels etc.)

The different processing levels until version 4.02b, do not improve the reflectance level at all in the required way. They give improvements for the consideration of polarization effects and reduce the bias within one scan line, however not the general level of the reflectance. However, the bias within the scan line (from W to E) seems to be not fully compensated. Concluding from this first results of AOT retrievals, a remaining bias within the scan line can be observed, giving higher AOT at the left side and lower at the right side of the scan line.

The finding for the correction factors are consistent with findings of De Graaf and Stammes (2003) and Acarreta and Stammes (2005), providing similar investigations over bright desert surface, using MERIS and GOME. The same is found by Kerridge (private communication, 2004)[1] comparing SCIAMACHY reflectance with AATSR.

Kokhanovsky et al. (2004)[2] came from investigations of cloud retrieval techniques and their comparison with MERIS results to very comparable results with this study. And, finally, the recalculation of the calibration key data, using the on ground measurements of the SCIAMACHY instrument during the OPTEC-5 campaign give very similar results for the considered spectral region. This implements an urgent need to find consolidated results for an improve of the radiometric calibration of the SCIAMACHY instrument and its implementation to the L1 processing.

Promising are also the tests of the new radiometric key data of the spectralon calibration, provided by Acarreta and Stammes (2005) reducing the deviations between MERIS and SCIAMACHY to few percent. Considering the given accuracy of the MERIS reflectance, Delwart et al. (2004), the new radiometric key data eliminate significant radiometric differences between both instruments.

The application of the correction factors obtained within this study enabled us to improve the SCIAMACHY TOA reflectance to a level, that no more the TOA reflectance was below the value of the Rayleigh path reflectance and an aerosol remote sensing by the BAER approach could be tested. Thus, under ideal conditions the AOT in a physically meaningful range could be obtained, comparable also with ground-based AERONET measurements.

A very important step within the application of an aerosol remote sensing algorithm for SCIAMACHY data is a rigorous cloud screening, which is still open for this scale.

The approach for the aerosol remote sensing is still not adapted to the spatial scale of SCIAMACHY. Especially the digital elevation model and the mixing rules for the estimation of the spectral surface properties need to be adapted to the larger spatial scale of SCIAMACHY ($30\times60\,\mathrm{km}^2$).

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Appendix

Total transmission and hemispheric reflectance

In Eq. (4) total atmospheric transmissions and hemispheric reflectance are used, containing the effect of multiple scattering. The total transmittance and hemispheric reflectance are determined using the SCIATRAN radiative transfer model (RTM), Rozanov et al. (2001) and the results are applied in a parameterized form for a fast processing within the retrieval procedure. Here we separate the total atmospheric transmission into their fractions for Rayleigh and aerosol scattering:

$$T(\lambda, M(z)) = T_{\mathrm{Ray}}(\lambda, M(z)) \cdot T_{\mathrm{Aer}}(\lambda, M(z)), \tag{13}$$

with the total transmission for the Rayleigh and aerosol scattering, respectively

$$\begin{aligned} T_{\mathrm{Ray}}(\lambda, M(z)) &= \exp\left(-\beta_{\mathrm{Ray}} \cdot \delta_{\mathrm{Ray}}(\lambda) \cdot M(z)\right) \\ T_{\mathrm{Aer}}(\lambda, M(z)) &= \exp\left(-\beta_{\mathrm{Aer}} \cdot \delta_{\mathrm{Aer}}(\lambda) \cdot M(z)\right), \end{aligned} \tag{14}$$

where $M(z)$ is the airmass factor for the zenith distance z, $\delta_X(\lambda)$ – the optical thickness for Rayleigh or aerosol scattering and β_X ($X \equiv$Ray, Aer) a weighting factor for the combined effect of multiple and single scattering of molecules and aerosols, depending on $M(z)$. For the aerosol an asymmetry parameter g=0.7 is assumed. The weighting factors β_X are obtained as polynomials of $M(z)$.

$$\beta_{\mathrm{Ray}} = \sum_{i=1}^{5} b_i^{\mathrm{Ray}} \cdot M(z)^{-(i-1))} \tag{15}$$

$$\beta_{\mathrm{Aer}} = \sum_{i=1}^{5} b_i^{\mathrm{Aer}} \cdot M(z)^{-(i-1))} \tag{16}$$

ACPD

6, 673–699, 2006

SCIAMACHY aerosol remote sensing

W. von Hoyningen-Huene et al.

The coefficients of the polynomials are given in Table 3. For the hemispheric reflectance the following parametrization is obtained:

$$\rho_{\mathrm{Hem}}(\lambda, z_O) = \sum_{i=1}^{4} a_i \cdot \delta^i(\lambda) \tag{17}$$

For the cases of aerosol remote sensing over Europe the error of the parametrization is below 5% compared with the results of the RTM.

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Table 1. SCIAMACHY bands and MERIS channels with their channel characteristics and the used integration range for the SCIAMACHY spectrum.

SCIAMACHY band	MERIS channel	Center wavelength μm	Band width μm	SCIAMACHY integration range, μm	Remarks
3	1	0.4125	10	0.424–0.428	incomparable λ
3	2	0.4425	10	0.435–0.445	used
3	3	0.4900	10	0.485–0.495	used
3	4	0.5100	10	0.505–0.515	used
3	5	0.5600	10	0.550–0.560	used
4	6	0.6200	10	–	
4	7	0.6650	10	0.660–0.670	used
4	8	0.6813	7.5	–	
4	9	0.7088	10	–	
4	10	0.7538	7.5	0.754–0.758	used without
4	11	0.7606	3.8	–	O_2A-Band
4	12	0.7783	15	0.772–0.776	used without O_2A-Band
5	13	0.8650	20	0.868–0.875	used, avoid disturbances
5	14	0.8850	10	–	
5	15	0.9000	10	–	H_2O vapor

[1)] in this particular case MERIS reflectance of channel 12 is compared with the SCIAMACHY range 0.754–758 μm.

Table 2. Derived average correction factors for the SCIAMACHY TOA reflectance for band 3, 4 and 5.

SCIAMACHY	Correction factor C_1	Offset C_0	Correlation coefficient
band 3	1.0991	+0.000009	0.9982
band 4	1.1215	−0.000013	0.9955
band 5	1.2109	+0.000140	0.9613

Table 3. Polynomial coefficients for the determination of the total transmissions and hemispheric reflectance

	Rayleigh	Aerosol		ρ_{Hem}
b_1	−0.44408	+0.01176		
b_2	+4.49481	+1.01682	a_1	+0.33185
b_3	−9.71368	−2.32949	a_2	−0.19653
b_4	+9.49795	+2.11831	a_3	+0.08935
b_5	−3.42016	−0.71737	a_4	−0.01675

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6, 673–699, 2006

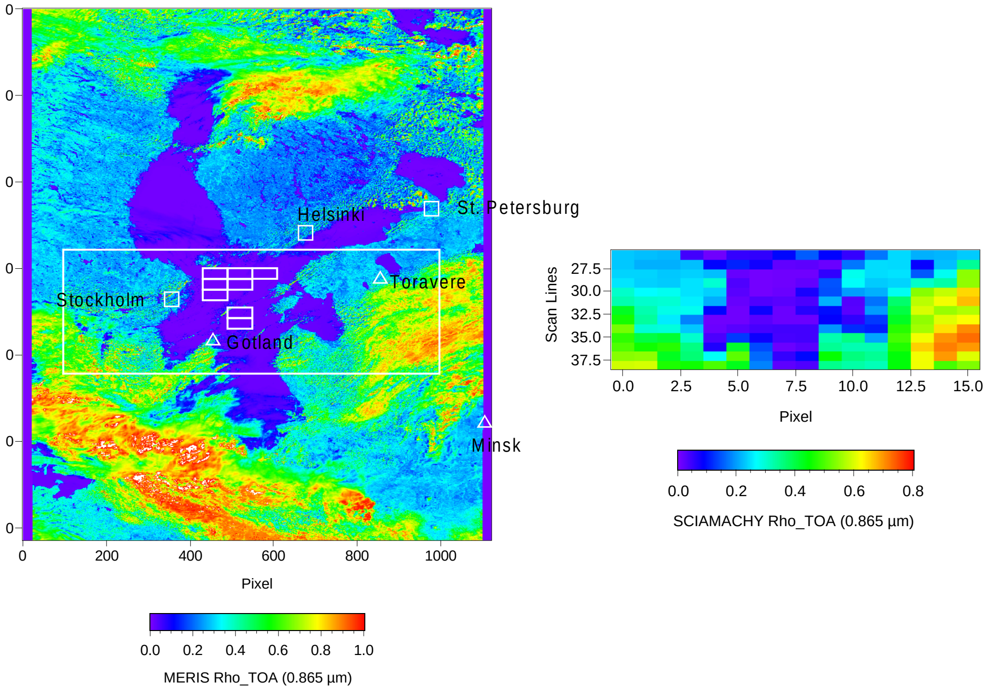

Fig. 1. Coinciding MERIS (left) and SCIAMACHY (right) scenes of the 3 August 2002, used for the comparisons. The scenes present the TOA reflectance for the spectral band 0.865 μm. The SCIAMACHY scene and the selected pixels over water of the Baltic Sea without any cloud disturbance are marked by rectangles. The center of the SCIAMACHY scene is located at 58.85° N and 22.03° E. The AERONET sites Gotland, Minsk and Toravere are marked as triangles.

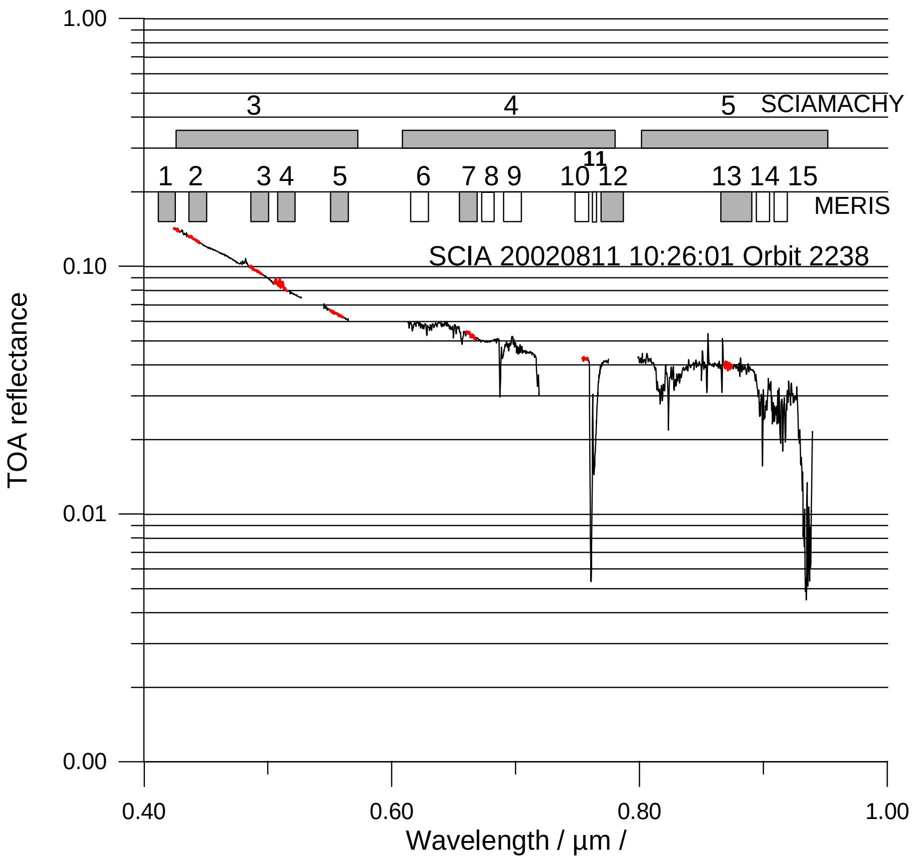

Fig. 2. Example of a SCIAMACHY TOA-reflectance spectrum for the bands 3, 4 and 5 and the position of the comparable MERIS channels. The MERIS channels used within the BAER approach are indicate in grey. The available channels of MERIS are indicated in white. The integration regions for the comparisons are shown in red.

ACPD
6, 673–699, 2006

SCIAMACHY aerosol remote sensing

W. von Hoyningen-Huene et al.

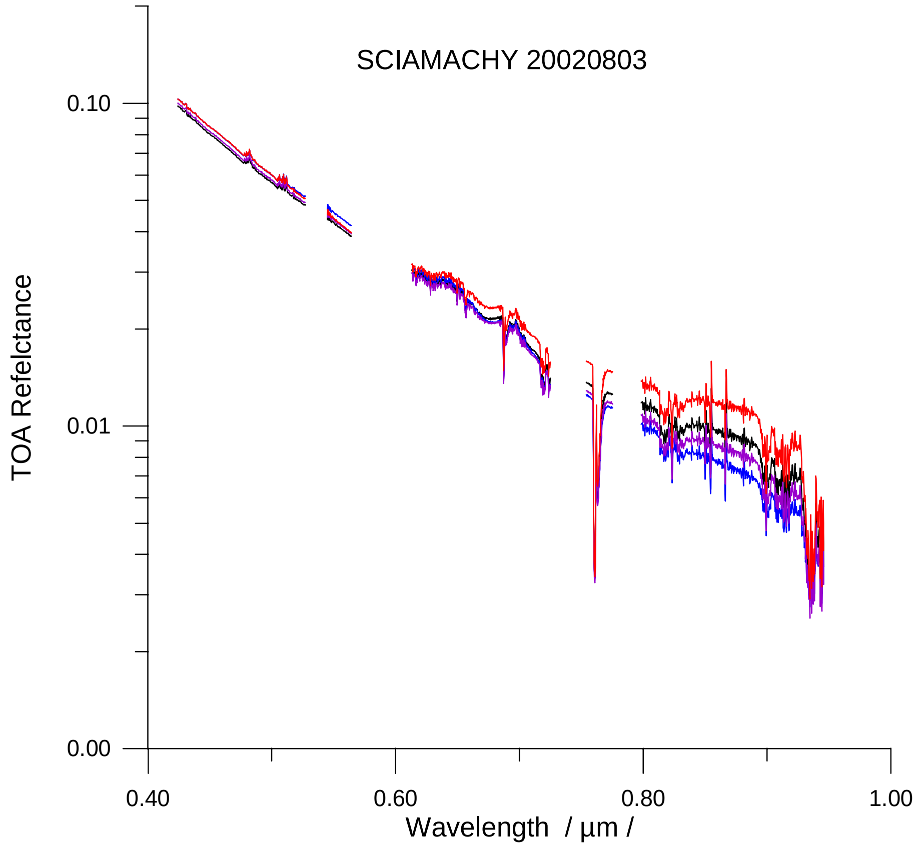

Fig. 3. Examples of SCIAMACHY spectra of the TOA-reflectance for the selected cloud free pixels over the Baltic Sea area at 3 August 2002.

ACPD
6, 673–699, 2006

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W. von Hoyningen-Huene et al.

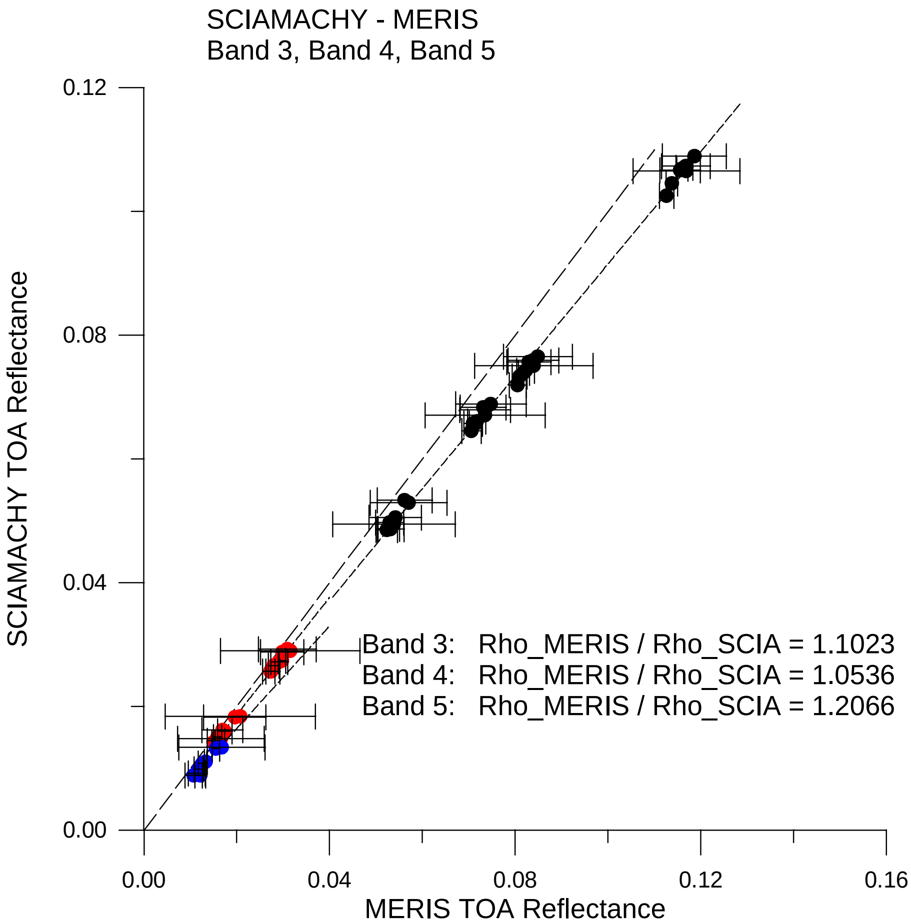

Fig. 4. Comparison of TOA reflectance of SCIAMACHY band 3 and band 4 with the MERIS channels 2, 3, 4, 5, 7, 12. The error bars give the standard deviation of the TOA reflectance of the MERIS pixels within one SCIAMACHY pixel.

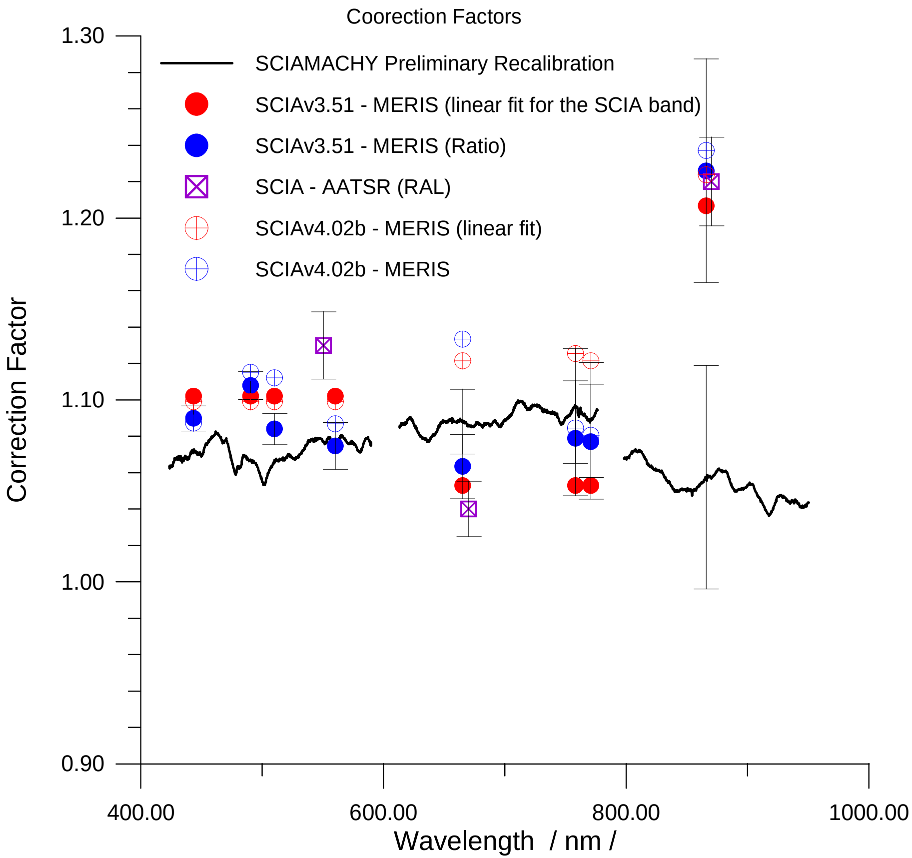

Fig. 5. Spectral behavior of the correction factors within the range of SCIAMACHY band 3, 4 and 5. For comparison of correction factors from different approaches the preliminary recalibration of SCIAMACHY and a comparison with AATSR reflectance is combined.

ACPD
6, 673–699, 2006

SCIAMACHY aerosol remote sensing

W. von Hoyningen-Huene et al.

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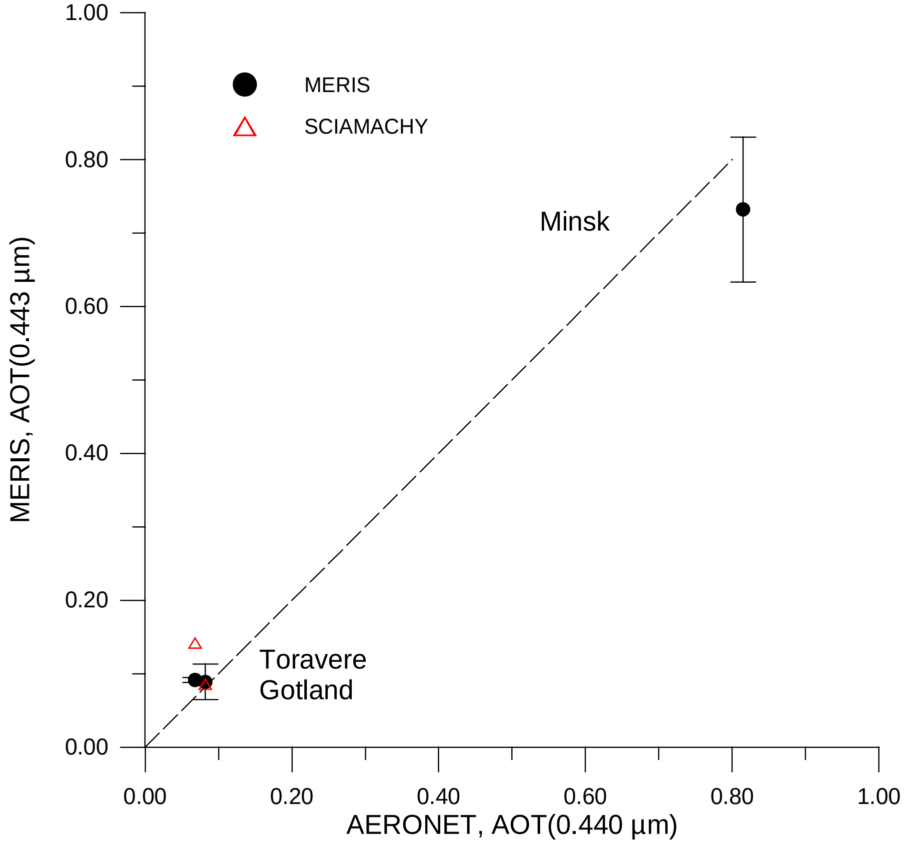

Fig. 6. Comparison of AOT for 0.443 μm channel, retrieved from MERIS (black dots) and SCIAMACHY (red triangles) with ground based measurements by the AERONET instruments in Gotland, Toravere and Minsk.

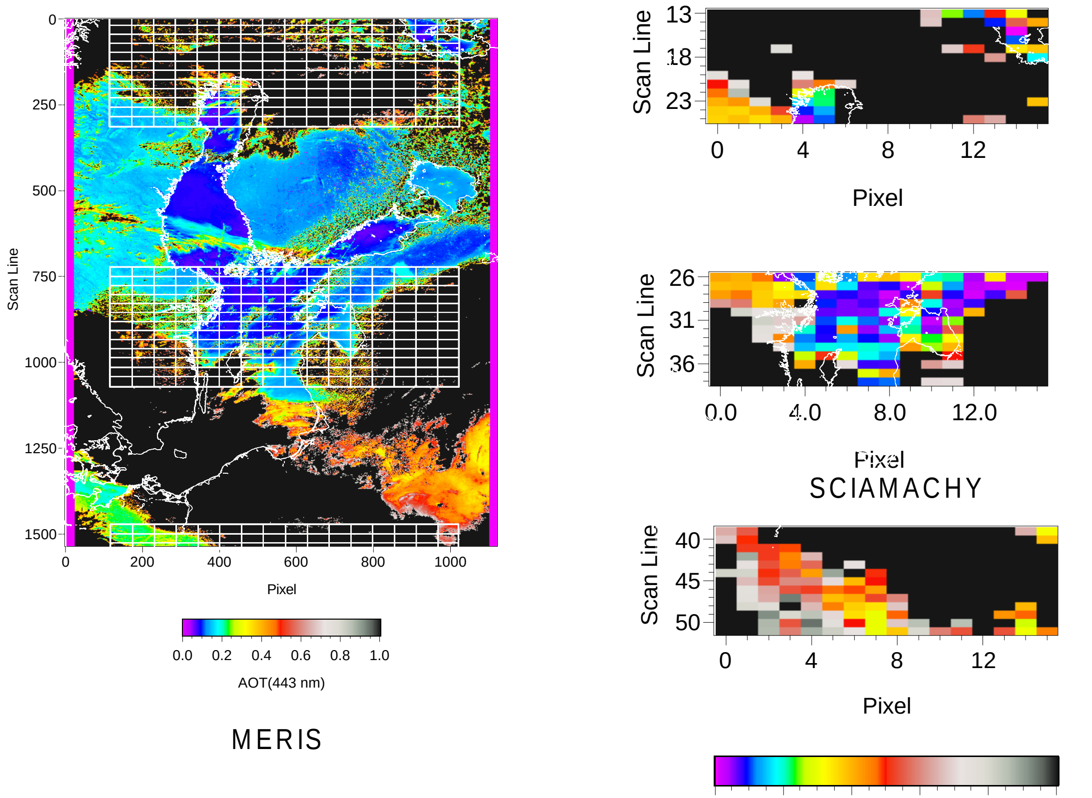

Fig. 7. The aerosol optical thickness for 0.443 μm channel, retrieved from MERIS (left) and SCIAMACHY (right). The color scale is the same for both cases. AOT>1 (disturbed by clouds) is coded in black.

ACPD
6, 673–699, 2006

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◂
▸
Back
Close
Full Screen / Esc
Print Version
Interactive Discussion

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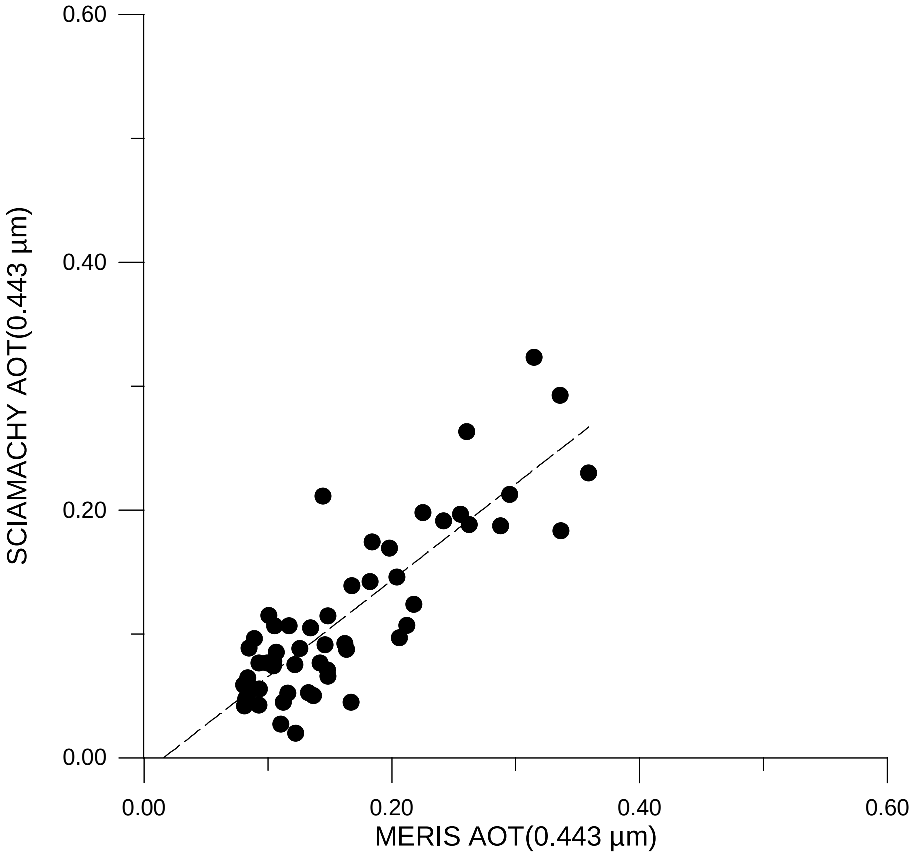

Fig. 8. The aerosol optical thickness for 0.443 μm channel, retrieved from MERIS and SCIAMACHY for the selected pixels.

ACPD

6, 673–699, 2006

SCIAMACHY aerosol remote sensing

W. von Hoyningen-Huene et al.

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