Polar Multi-Sensor Aerosol Product: ATBD

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Document Change Record

Issue / Revision	*Date*	*DCN. No*	*Summary of Changes*
V1 draft	26 September 2011		First draft, for internal review of intermediate prototype in development
V2 draft	28 March 2013		Update to current prototype
V2A	29 November 2013		Update to release candidate prototype
V2B	12 January 2014		Reviewed before product release to test sites.
V2C	27 March 2014		Description of quality flags added in Section 3.7. Minor corrections.
V2D	21 May 2014		Description of error calculation added. Motivation, benefits and problems of the multi-sensor approach are discussed in additional subsections. The structure of the document is improved. Minor corrections in the text.
V2E	10 Dec 2014		Update to prototype 1.0.10
V3	28 Aug 2015		New version for PMAp version 2. Added retrieval over land.
V3A	28 Aug 2015		Revised signature list.
V3B	01 Dec 2015		Revised signature list & product update
V3D Draft	31 July 2018		Update to PMAp v2.2 release
V3E Draft	06 June 2019		Update with final version 2.2. of PMAp
V3F	28 April 2021		Review and update before PMAp 2.2.4 release

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1 INTRODUCTION

1.1 Purpose of this document

This document describes the algorithm theoretical basis of the **P**olar **M**ulti-sensor **A**erosol **P**roduct (PMAp) for remote sensing of Aerosol properties from METOP. The algorithm uses the Polarization Monitoring Devices (PMD) of GOME-2 in combination with data from other METOP instruments, in particular AVHRR and IASI.

1.2 Applicable Documents

The following internal documents have been used to composite this document. Further references are found in the reference Section at the end of this document.

Doc ID	*Title*	*Reference*
AD 1	Review of aerosol optical properties retrieval algorithms for Metop	EUM/MET/TEN/09/0797
AD 2	AVHRR Level 1b Product Guide	EUM/OPS-EPS/MAN/04/0029
AD 3	GOME-2 Product Guide	EUM/OPS-EPS/MAN/07/0445
AD 4	GOME-2 PMD Band Definitions 3.0 and PMD Calibration	EUM/OPS-EPS/DOC/07/0601
AD 5	IASI Level 1 Product Guide	EUM/OPS-EPS/MAN/04/0032
AD 6	Vector Radiative Transfer Model PSTAR, User manual	EUM/MET/TEN/11/0624
AD 7	Sensitivity Study: Retrieval of aerosol optical properties using GOME-2 PMD	EUM/MET/TEN/12/0136
AD 8	Polar Multi-Sensor Aerosol Product Format Specification - Annex (436226)	EUM/OPS-EPS/DOC/12/0639
AD 9	Polar Multi-Sensor Aerosol Product Generation Specification	EUM/TSS/SPE/13/728558
AD10	Quantification of Potential Metop-A and Metop-B AVHRR/3 IR Channel Radiance Biases Using Co-located IASI spectra	EUM/RSP/DOC/14/780835

1.3 Acronyms Used in this Document

The following table contains definitions for all acronyms used in this document.

Acronym	*Full Name*
AER	Aerosol Product
AOD	Aerosol Optical Depth
ARA	Aerosol Retrieval Algorithm
ATBD	Algorithm Theoretical Basis
BT	Brightness Temperature
BTD	Brightness Temperature Difference
CMa	Cloud Mask
CFR	Cloud fraction ratio
COD	Cloud optical depth
IR	Infrared
LUT	Look-Up Table
NIR	Near Infrared
PMAp	Polar Multi-sensor Aerosol Product
RAZI	Relative Azimuth Angle
RTM	Radiative Transfer Model
PMD	Polarization Monitoring Device
SAF	Satellite Application Facility
SZA	Solar Zenith Angle
TIR	Thermal Infrared
TOA	Top Of Atmosphere
VIS	Visible (solar)
VZA	Viewing Zenith Angle

2 THE MULTI-SENSOR APPROACH IN AEROSOL RETRIEVAL

The **P**olar **M**ulti-**S**ensor **A**erosol product **(PMAp)** is dedicated to retrieve aerosol optical depth (AOD, aerosol total load in the vertical column) at 550nm and further aerosol parameters e.g. aerosol type. The algorithm uses a multi-sensor approach combining GOME-2, AVHRR and IASI. The product is delivered as a GOME-2 product with the (spatial) target resolution of the GOME-2 PMDs (see Section 2.2.1).

This section briefly describes the physical background, the available instruments and the benefit of a multi-sensor approach. The multi-sensor approach also introduces specific problems which are not present in single-sensor problems. The major important problems are summarized and the requirements for the design of multi-sensor retrievals are discussed.

2.1 Motivation for a multi-sensor approach

Aerosols are suspended particulate matter in the atmosphere carried by air masses. Aerosol particles can be solid or liquid and can cover a wide range of particle sizes (0.005 µm – 100 µm, depending on aerosol type). This leads to a large variation in scattering and absorption characteristics.

- In many cases, the presence of aerosols over ocean increases the measured TOA reflectance. This signal is correlated with the aerosol optical depth. There are some situations where this assumption does not hold (absorbing aerosols in the UV, sun glint conditions).
- The reflectance of the ocean surface is very low in the near-infrared (PMDs from 640 nm to 790 nm) which allows the retrieval with a small impact of surface reflectance, except for sun glint conditions.
- The measured reflectance over ocean also depends on wind speed and chlorophyll load. Channels with a very strong sensitivity to chlorophyll are not a good choice for AOD retrievals over ocean.
- Over land, the presence of aerosols can increase the measured TOA reflectance if the surface albedo is low. There is often no significant contrast between aerosol and surface for scenes with high surface albedo. For lots of surfaces types the surface albedo increase with wavelengths. VIS/NIR reflectances for wavelengths higher than 700 nm are usually not usable for aerosol retrievals over land. Between 600-650nm, AOD can be retrieved for specific, dark areas over land only (e.g. dense vegetation).

If only the points listed above would be taken into account, a single-band retrieval would already give the AOD in clear-sky cases–if a band with a low surface reflectance is selected. But the measured signal is not only determined by the AOD of the aerosol. The measured radiance is sensitive to various aerosol optical properties like phase function and single scattering albedo. These parameters are connected to aerosol microphysics characterized–by particle size distribution, particle shape and refractive index. In addition, usually more than one aerosol type is present in an individual scene. A bimodal aerosol distribution is usually assumed. To address this problem, as much independent information as possible from different bands and instruments should be used, but the system is still not fully defined.

We can use several kinds of information to retrieve the aerosol type: The wavelength dependency of the GOME-2 reflectance, the stokes fractions measured by GOME-2, the UV absorbing index of GOME-2, the wavelength dependency between VIS channels and the NIR channels of AVHRR, the split window technique of the thermal infrared channels of AVHRR, the SO_2 absorption measured by IASI and the fine structure of the IASI spectra.

However, the combination of different instruments introduces new error sources which can be caused by calibration problems of the instruments (which may change in time), collocation problems (different size and shape of footprints), different windows (wavelength range of the channel, spectral response function) etc. The measured signals of aerosols are usually very small, in particular one order of magnitude smaller compared to clouds. This leads to the problem that the errors introduced by a combination of different instruments can easily be larger than the contrast between aerosol and surface. The combination of different instruments needs to take into account these problems.

2.2 METOP instruments used within PMAp

This section briefly describes the METOP instruments used within PMAp.

2.2.1 The GOME-2 instrument

GOME-2 is a medium-resolution double UV-VIS spectrometer, fed by a scan mirror which enables across-track scanning in nadir, as well as sideways viewing for polar coverage and instrument characterisation measurements using the moon. The scan mirror directs light into a telescope, designed to match the field of view of the instrument to the dimensions of the entrance slit. This scan mirror can also be directed towards internal calibration sources or towards a diffuser plate for calibration measurements using the sun.

GOME-2 comprises four main optical channels which focus the spectrum onto linear silicon photodiode detector arrays of 1024 pixels each, and two Polarisation Measurement Devices (PMDs) containing the same type of arrays for measurement of linearly polarised intensity in two perpendicular directions.

The PMDs are required because GOME-2 is a polarisation-sensitive instrument and therefore the intensity calibration must take account of the polarisation state of the incoming light. This is achieved using Stokes-fraction information from the PMDs.

For PMAp retrieval algorithm the radiances and stokes fractions measured by the PMD-P are used to retrieve aerosol optical properties directly. PMDs are available for the following wavelength ranges:

Table 1: Table: GOME-2 PMD band definitions (v 3.1) as adapted by EUMETSAT based on level 1B spectral calibration of PMD data from PPF version 3.8 from orbit 3372 (14 June 2007). This set of definitions has been uploaded for orbit on 11 March 2008.

Band-S					**Band-P**				
No.	**pix1**	**pixw.**	**wav1**	**wav2**	**No.**	**pix1**	**pixw.**	**wav1**	**wav2**
0	22	5	311.709	314.207	0	20	5	311.537	313.960
1	30	4	316.762	318.720	1	29	4	317.068	318.983
2	37	12	321.389	329.139	2	36	12	321.603	329.267
3	50	6	330.622	334.443	3	49	6	330.744	334.560
4	57	6	336.037	340.161	4	56	6	336.157	340.302
5	84	17	360.703	377.873	5	83	17	361.054	378.204
6	102	4	380.186	383.753	6	101	4	380.502	384.049
7	117	19	399.581	428.585	7	116	19	399.921	429.239
8	138	27	434.083	492.066	8	137	27	434.779	492.569
9	165	18	494.780	548.756	9	164	18	495.272	549.237
10	183	2	552.474	556.262	10	182	2	552.967	556.769
11	187	11	568.070	612.869	11	186	11	568.628	613.680
12	198	9	617.867	661.893	12	197	9	618.711	662.990
13	218	4	744.112	768.269	13	217	4	745.379	769.553
14	224	2	794.080	803.072	14	223	2	795.364	804.351

2.2.1.1 Degradation correction in GOME2

A continuous signal degradation is observed in GOME-2 due to the ageing of the instrument. This causes a spectral degradation in reflectance (resulting from the combination of differential radiance and irradiance signal degradations) which could impact the retrieval of L2 products.
A list of contributors to the observed signal degradation of GOME-2 has been identified as thermal instability of the optical bench, internal contamination of the optical path, degradation of the scan mirror with viewing angle dependent response and solar optical path degradation. The signal degradation in time is considered as an essential 'feature' of the instrument performance, it will very likely continue to be so and it is routinely monitored [RD 13].
Being spectrally non-homogeneous this degradation could impact significantly aerosol optical properties retrieval especially over land. The degradation effect is actually largest in blue part of the spectrum range mostly used by PMAp for the retrieval of AOD over land. A degradation model – based on a statistical approach - has been developed to compensate for this degradation providing a set of platform dependent correction coefficients allowing correction of GOME-2 radiances separately for the solar and the earthshine data (reference will be added later, under preparation).
This radiometric correction is now in use in PMAp for Metop-A, B and C with the possibility for update of the correction coefficients used in the calculation.
The degradation correction of GOME2 L1B has two modes:

1) Forecast mode (for NRT use, provides coefficients to extrapolate the current state of the instrument at the end of the historically available correction data (~ 2years) into the future)
2) Historical mode (derived from actual measurements in the past, correcting for the degradation at each time step).

PMAp (as an NRT aerosol product) uses degradation correction in Forecast mode. The historical mode is useful for other purposes e.g. producing Climate Data Record (CDR) for which we need to reprocess PMAp in early time of mission as well (when degradation of instrument was the fastest).
The degradation correction coefficients currently in use in PMAp have been recently updated to ensure that the forecast time range is compatible with the processing time.
Note: Part of the text in this Section is taken from [AD 3]. The table is taken from [AD 4]. See Section 1.2 for a complete document description

2.2.1.2 Radiometric adjustment of GOME2 PMD-P radiance

The need for an additional radiometric adjustment of GOME2 L1b data (after degradation correction) for PMD bands was recognized when significant number of pixels with AOD=0 was found in PMAp over land, and it was identified to be an anomaly on the TOA reflectance before the aerosol retrieval itself (too low reflectance).

To evaluate the anomaly on GOME2 PMD-P reflectance and estimate the needed adjustment, we use 6S Radiative Transfer Model to calculate the reference reflectance for clear sky (including the surface contribution from LER) and compare it with GOME2 PMD-P reflectance measurements. For this purpose, we collect reflectance measurement at channel 7 and 8 from multiple days (1-7) from recent years (2020) and also older ones (e.g. 2015). We select observation for which surface contribution is minimum (surface reflectance < 0.03). We also selected observation for which the atmospheric reflectance is dominated by Rayleigh scattering by screening the turbid situations for which the polarization reflectance measured from GOME2 differs from the Rayleigh calculated one by more than 0.01).

From the comparison of 6S and GOME2 reflectance, we found that simulated TOA reflectance is higher than observation from GOME2 and this is the reason for having negative AOD retrieval.
Through this statistical approach, the relative difference between clear sky reflectances from GOME2 and 6S is calculated. After filtering of atmospheric turbidity and selection of darkest surfaces (both seen as dispersion and noise on the matchups), a minimum curve is observed corresponding to the Rayleigh asymptote. The final radiometric adjustment is based on this filtered population of data.

The difference in reflectance is converted to photon radiance to be applied on GOME2 PMD L1B radiance inside the PMAp processor. The additional radiometric adjustment is calculated for the three Metops.

2.2.2 The AVHRR instrument

The AVHRR/3 is a six-channel scanning radiometer providing three solar channels in the visible/near-infrared region and three thermal infrared channels. The AVHRR/3 has two one-micrometre wide channels between 10.3 and 12.5 micrometres. The instrument utilises a 20.32 cm (8-inch) diameter collecting telescope of the reflective Cassegrain type. Cross-track scanning is accomplished by a continuously rotating mirror directly driven by a motor. The three thermal infrared detectors are cooled to 105 °K by a two-stage passive radiant cooler. A line synchronisation signal from the scanner is sent to the spacecraft MIRP processor which in turn sends data sample pulses back to the AVHRR.

Although AVHRR/3 is a six-channel radiometer, only five channels are transmitted to the ground at any given time. Channels 3a and 3b cannot operate simultaneously. The transition from channel 3a to 3b (and vice-versa) is done by telecommand and reflected in the science data. For Metop-A, channel 3a is operated during the daytime portion of the orbit and channel 3b during the night-time portion.

Note: The text of this section is from [AD 2].

The following table summarises the spectral characteristics of AVHRR/3:

Table 2: Spectral Characteristics of AVHRR/3

Channel	***Central wavelength (µm)***	***Half power points (µm)***	***Channel noise specifications***	
S/N @ 0.5% reflectance			NEdT @ 300K	
1	0.630	0.580 - 0.680	9:1	-
2	0.865	0.725 - 1.000	9:1	-
3a	1.610	1.580 - 1.640	20:1	-
3b	3.740	3.550 - 3.930	-	<0.12K,0.0031 mW/(m^2 sr cm^{-1})
4	10.800	10.300- 11.300	-	<0.12 K, 0.20 mW/(m^2 sr cm^{-1})
5	12.000	11.500- 12.500	-	<0.12 K, 0.21 mW/(m^2 sr cm^{-1})

2.2.3 The IASI instrument

The Infrared Atmospheric Sounding Interferometer is composed of a Fourier transform spectrometer (IASI) and an associated Integrated Imaging Subsystem (IIS). The Fourier transform spectrometer provides infrared spectra with high resolution between 645 and 2760cm^{-1} (3.6 µm to 15.5 µm). The IIS consists of a broad band radiometer with a high spatial resolution. However, the IIS information is only used for co-registration with the Advanced Very High Resolution Radiometer (AVHRR).
The main goal of the IASI mission is to provide atmospheric emission spectra to derive temperature and humidity profiles with high vertical resolution and accuracy. Additionally it is used for the determination of trace gases such as ozone, nitrous oxide, carbon dioxide and methane, as well as land- and sea surface temperature and emissivity and cloud properties.

IASI has 8461 spectral samples, aligned in three bands between 645.0 cm^{-1} and 2760 cm^{-1} (15.5µm and 3.63 µm), with a spectral resolution of 0.5 cm^{-1} (FWMH) after apodisation (L1c spectra). The spectral sampling interval is 0.25 cm^{-1}. The IASI sounder is coupled with the IIS, which consists of a broad band radiometer measuring between 833 cm^{-1} and 1000 cm^{-1} (12µm and 10µm) with a high spectral resolution.
The following table summarises the spectral characteristics of IASI:

Table 3: Special Characteristics of IASI.

Band	***wavelength (µm)***	***wave number (cm^{-1})***
1	8.26 – 15.50	645.0 – 1210.0
2	5.00 – 8.26	1210.0 – 2000.0
3	3.62 – 5.00	2000.0 – 2760.0

Note: Information in this section is taken from [AD 5]. See Section 1.2 for the full document name and ID number.

2.3 Benefits of a GOME-2 / AVHRR combination

The combination of GOME-2 and AVHRR is useful if the improvement of the retrieval due to the additional channels is larger than the errors introduced by problems due to calibration and collocation. An alternate option would be an implementation bases on either GOME-2 or AVHRR alone.
An implementation based on GOME-2 only would introduce these major shortcomings compared to an AVHRR/GOME-2 combination:

- GOME-2 has a relatively coarse spatial resolution which is a clear disadvantage in cloud detection. This leads to two problems:
  1.) it limits the accuracy of the cloud detection significantly and
  2.) a lot of pixels are partly cloudy and a cloud correction of the GOME-2 reflectance is not possible without an instrument with higher spatial resolution. Our studies prove the reliability of a cloud correction of GOME-2 reflectance based on the heterogeneity of AVHRR radiances within the GOME-2 pixels.

- GOME-2 does not have thermal infrared channels. This is a strong disadvantage in cloud detection, in particular in discriminating aerosols and clouds. It is also a strong disadvantage in the detection of volcanic ash and desert dust (split window technique). The split window technique gives complementary information to the GOME-2 UV index. The split window technique is also more stable than the UV index because of the degradation in the GOME-2 UV channels.
- GOME-2 does not have a channel in the near infrared. The combination of VIS and NIR reflectance allow

  1.) the discrimination of coarse mode / dust dominated aerosols from fine mode aerosols for clear sky scenes over ocean and

  2.) the detection of mismatches of the split window technique over ocean.

An implementation based on AVHRR only would also introduce a lot of shortcomings compared to an AVHRR/GOME-2 combination:

- The calibration of the AVHRR VIS channels is currently not good enough for aerosol retrievals. An option is the calibration of AVHRR channel 1 by GOME-2 and AVHRR channel 4 and 5 by IASI. However, this would already be a step to a multi-sensor approach and such a inter-satellite calibration approach is planned to be used in the future.
- The AVHRR instrument is a very bad option for AOD retrievals over land, because the lowest wavelength is AVHRR channel 1 (580nm –680nm). The contrast between aerosol and surface is too bad to retrieve aerosol optical properties from AVHRR over land in the visual spectral range. Exception: In some dark areas, in particular pixels with dense vegetation, AVHRR would potentially allow a one-channel retrieval at 630nm.n
- The split window technique to detect volcanic ash and dust retrieves a lot of mismatches, but the detection of mismatches using VIS/NIR channels does not work well over land due to the high surface albedo. A good replacement is the UV absorbing index provided by GOME-2.
- The GOME-2 instrument provides additional information on the aerosol type providing stokes fractions and reflectances between 311nm –805nm.
- GOME-2 provides channels sensitive to the chlorophyll pigment concentration in the ocean. The wavelength range of AVHRR channel 1 still shows some influence of the ocean colour characteristic.

In addition, our tests indicate that the combination of the Aerosol Absorbing Index of GOME-2, the split-window technique of AVHRR and the wavelengths dependency of AVHRR channel 1, 2 and 3A may allow the detection of strong biomass burning events over ocean (discriminating from other kinds of aerosols and clouds).

2.4 Benefits of IASI as a third PMAp instrument

The monitoring of volcanic eruptions is an important requirement of the PMAp aerosol product due to the strong impact of ash clouds on air traffic. Therefore an infrared instrument with high spectral resolution is included to the PMAp retrievals.

The collocation process between IASI and GOME-2 is more complicated, because the spatial resolution of IASI has the same order of magnitude than GOME-2 (12 km), but the shape of the footprint is different and the scan lines do not match each other exactly. In the worst case, six different PMD pixels can be partly covered by one IASI pixel. The collocation problem and the implementation within PMAp is described in [AD 9]. The combination of IASI and GOME-2 needs an analysis of the scene homogeneity.

IASI is currently used to flag dust presence and ash events using flags based on a composite of limited amount of channels. These channels provide additional information (e.g. sulfour dixide, dust detection) and a better radiometric accuracy compared to AVHRR. The disadvantage of IASI compared to AVHRR is the lower spatial resolution and the complicated collocation to GOME-2. The results of the IASI retrievals are delivered as an input to the GOME-2 part of the retrieval. This improves distinguishing clouds and aerosols, dust classification with an indirect improvement of the AOD and volcanic ash detection.

In the future, IASI could further improve the volcanic ash retrieval using the following features:

- The hyperfine structure of the IASI spectra include information on the chemical composition of volcanic ash
- The CO_2 absorption measured by IASI may be used to retrieve ash plume heights.

IASI has an indirect contribution to the AOD retrieval, because it improves the characterization of coarse mode aerosols. The reflectance in the VIS is a function of the AOD and several further aerosol parameters.

2.5 Co-location of Radiance and cloud-fraction -

The radiance and cloud fraction co-location is carried out by the PMAp co-registration and co-location framework [reference to PMAp PGS]. The co-location of AVHRR pixels to GOME can be treated as points within a polygon because the spatial resolution of AVHRR is much higher than the footprint of the GOME PMD. The collocation of IASI and GOME PMD is more difficult because the spatial resolutions are more close to each other, but the shape of the footprints are largely different. Thresholds in the overlap percentage are used to establish a suitable collocation.

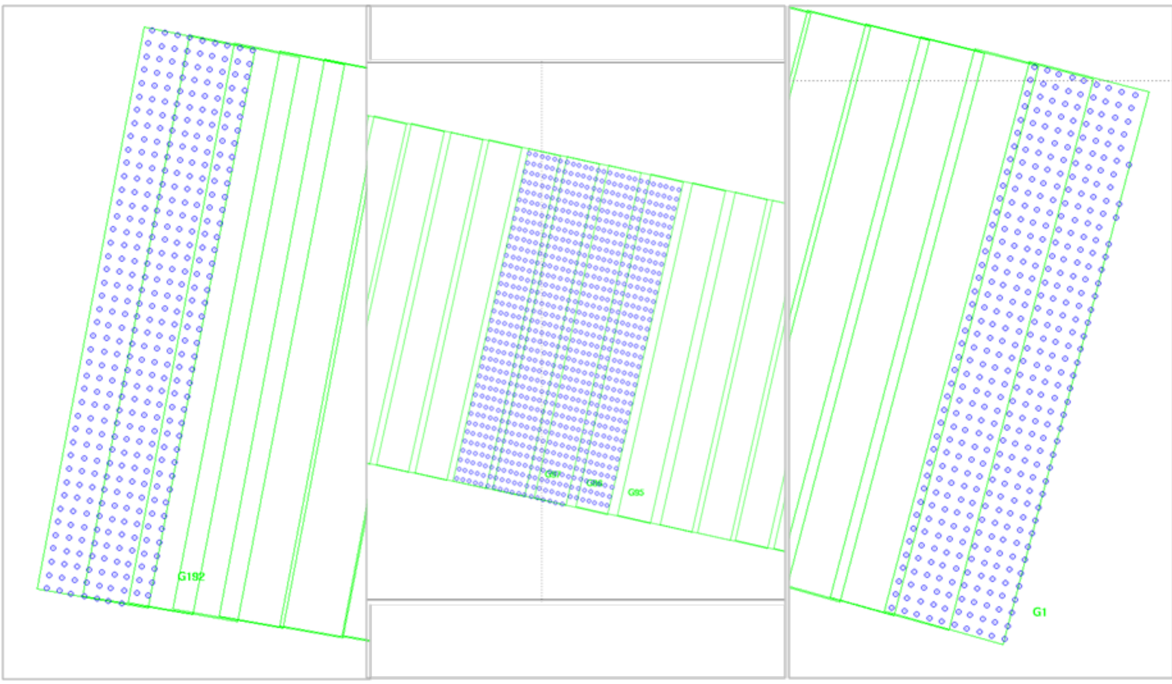

Figure 1: Schematic example for co-location of a "point-in-polygon" problem as used for the co-location of Metop AVHRR ground pixels (blue) to GOME-2 PMD ground-pixels (green).

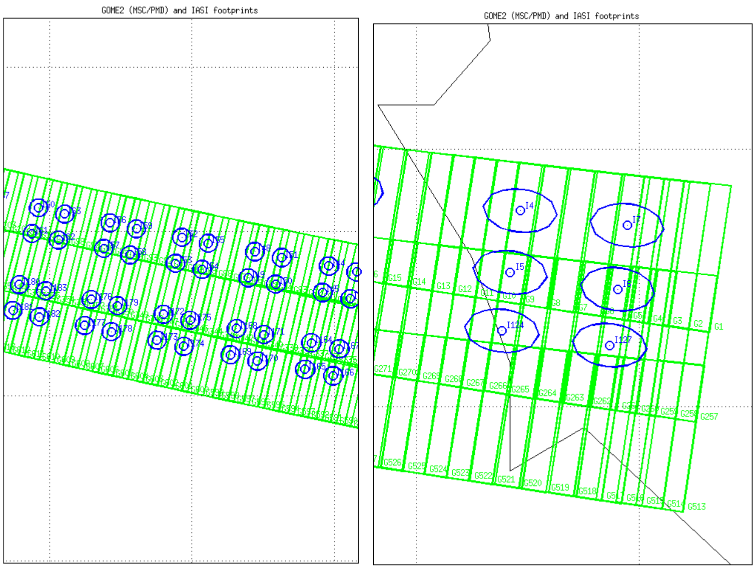

Figure 2: Schematic example for co-location of a "polygon-in-polygon" problem as used for the co-location of Metop IASIground pixels (blue) to GOME-2 PMD ground-pixels (green).

2.6 Strategy for a multi-sensor retrieval

A multi-sensor retrieval has to evaluate the benefits of adding an instrument against the errors introduced to the retrieval.

Figure 3 shows the correlation of PMD 12 with the collocated reflectance of AVHRR channel 1 for one orbit (16/10/2017) without radiometric correction (L1b) and with radiometric correction applied to GOME-2 signals (L1c), as introduced in the above section (2.2.1). The collocation algorithm is described in [AD 9].

However, the plots show the following aspects which are also confirmed by further comparisons between GOME-2 science channels, AVHRR and the GOME-2 PMD:

- The correlation show a significant slope, which is basically caused by a calibration error of AVHRR. The GOME-2 PMD band also show a calibration error, but this error is much smaller than for AVHRR.
- The scatter is mainly caused by the uncertainty of the collocation. Shortcomings in spectral convolution also contribute to the scatter.
- The offset between the different instruments is currently very small. A careful implementation takes into account that this is not necessarily the case in all relevant situations (e.g. day-0 implementation of PMAp on METOP-C).
- The L1b to L1c correction is significant confirming the impact on the Level2 products retrieval of the GOME-2 instrument degradation.

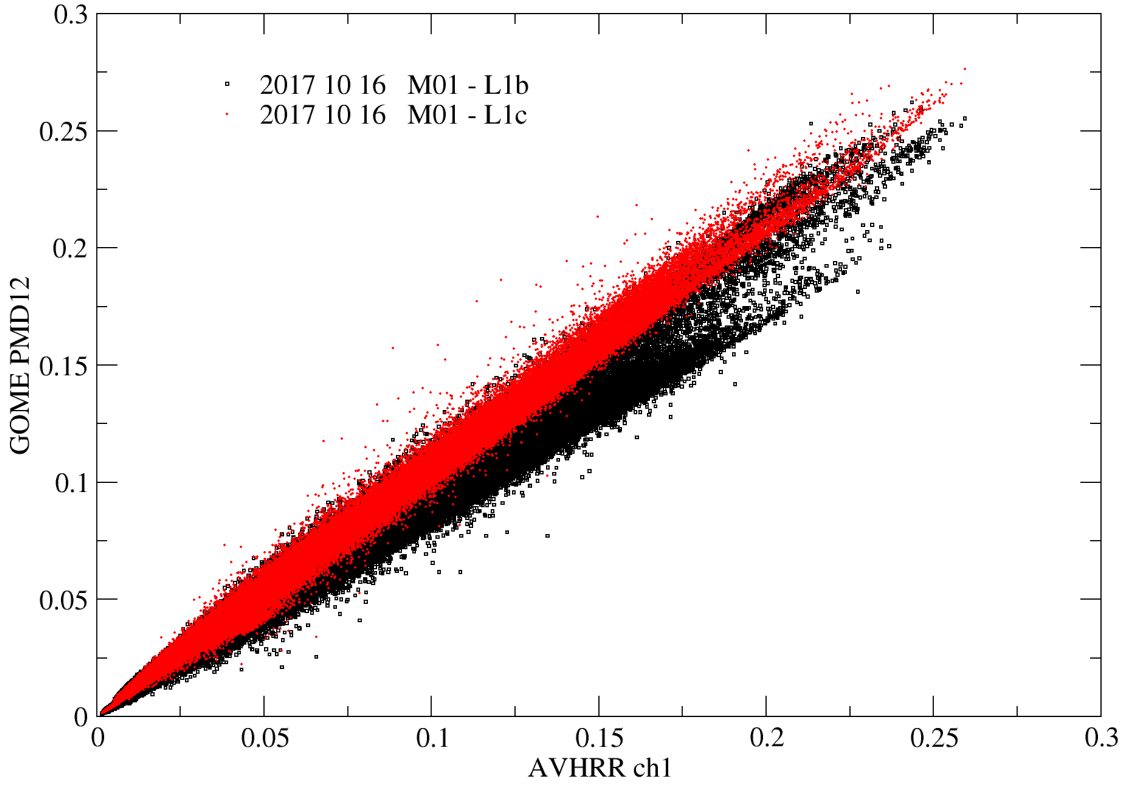

Figure 3: Reflectances of PMD12 without radiometric correction (L1b) and with radiometric correction (L1c) compared to co-located AVHRR reflectances (channel 1) to PMD12.

In particular, a scatter caused by different sizes and shapes of the footprint cannot be corrected accurately. It is also expected that differences between the instruments will change in time, e.g. because of different degradation effects. The following approach is used to combine GOME-2 PMD reflectances with AVHRR and IASI measurements used to combine the two instruments:

- PMAp avoids quantitative fits combining two instruments. If a problem is detected for one instrument, the impact on the retrieval should be as clear as possible and should not lead to unforeseen effects by a mathematical optimization over channels of different instruments. Subretrievals are implemented on single instrument bases and the points of combination are defined as clearly as possible.

- A quantitative retrieval on AVHRR is currently of limited use only because of uncertainties in calibration. PMAp does not use RTM data on AVHRR.
- The quantitative base retrieval is implemented on GOME-2, because the radiometric calibration is better than AVHRR. Collocation aspects also support this decision.
- First-guess cloud screening is based on AVHRR using a threshold method. This technique is already well established in different kind of applications. PMAp improves this approach using a more sophisticated analysis (sect.3.1.2.2)
- Dust/ash detection is implemented using the split window technique in the thermal infrared combined with VIS/NIR tests on AVHRR over ocean. Over land, the VIS/NIR test will be replaced by the UV absorbing index of GOME-2. This detection is based on thresholds. The output is an aerosol type pre-classification which is delivered as an input to the base retrieval on GOME-2.
- Volcanic ash clouds which contain sulphur dioxide are identified using IASI
- Thick aerosols are distinguished from clouds using a combination of IASI thermal channels, AVHRR thermal channels (with higher spatial resolution), UV absorbing index, the wavelength dependency of the stokes fraction and the wavelength dependence between AVHRR ch1,2 and 3A. The results are transmitted as an input to the GOME-2 part of the retrieval.
- The cloud correction for partly cloudy GOME-2 pixels is implemented based on the heterogeneity of the AVHRR reflectance within the GOME-2 pixel in order to ensure the following:
  1.) the correction is mainly insensitive to the slope between the GOME-2 PMD and the collocated AVHRR reflectances. This makes the correction stable to a lot of systematic degradation effects.
  2.) offsets between AVHRR and GOME-2 reflectances are transferred to a slope error in the corrected GOME-2 reflectance, because the AOD retrieval is more sensitive to offsets than to slopes.
  3.) The scatter between AVHRR and GOME-2 is included to the error estimation but the impact of this effect to the retrieval results is not avoided. The cloud correction scheme is described in Section 3.1.7 and 3.1.7.2.

3 AEROSOL RETRIEVAL ALGORITHM OVER LAND AND OCEAN

The PMAp aerosol algorithm consists of three parts:

- **Step 1**: At the beginning, a pre-classification is applied based on AVHRR, IASI both co-located in this phase to the GOME-2 pixel used as a pivot. This includes the detection of clouds, calculation of cloud correction factors (for subpixel-cloud decontamination), the detection of strong aerosol events (in particular volcanic ash and dust) and a pre-classification of possible aerosol types.
- **Step 2:** A set of AODs at 550nm are retrieved using one GOME-2 PMD-P band. The selected band depends on the condition (dark ocean, ocean with slight glint effects, dense vegetation, bright surfaces/deserts or continents with moderate albedo). Each of these AODs is retrieved with respect to different aerosol types and microphysical properties. At this point it is not known which selection of aerosol type and microphysical properties is the best representation of the given scene. For clear sky pixels over ocean, the chlorophyll pigment concentration is fitted in addition.
- **Step 3:** In a third step, one of the AODs from step 2 is selected which fits best to the GOME-2 PMD-P measurements (reflectances and stokes fractions from several bands) which are usable for the given scene. The included bands may depend e.g. on the surface albedo, the predicted clear-sky top of atmosphere stokes fraction and the cloud coverage.

PMAp retrieval algorithm design. Version 2.2. (next release)

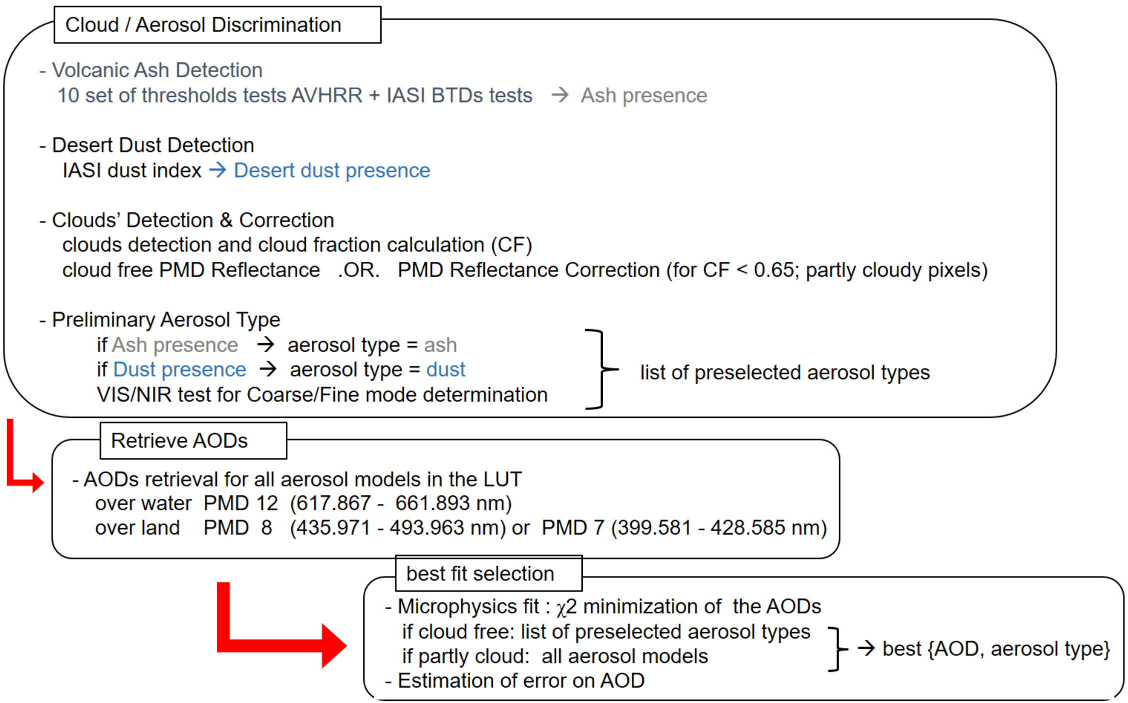

Figure 4. Flowchart of PMAp retrieval algorithm.

Remarks:

- The aerosol cases included to the retrieval within step 2 can be defined by external parameters (usually a subset of the 28 cases over ocean and 6 cases over land. The radiative transfer data for these cases is provided by a Look up table.
- It should be stated that most of the information available in the GOME-2 data is already used by retrieving one AOD-related parameter. Most information is obtained for clear sky pixels over ocean far from sun glint conditions because both clouds and bright surfaces are avoided for all bands. However, a lot of this additional information is needed to fit the chlorophyll pigment concentration. It is impossible to distinguish all cases provided by the LUT, because the remaining independent information is usually equal or lower than the noise of the measured signal. Nevertheless, some information remains dependent on the observation geometry. The algorithms use this information to improve the retrieved AOD. The information on the aerosol type and additional microphysical parameters available in addition to the AVHRR pre-classification should be considered as quite limited.

3.1 Step 1: Cloud/aerosol discrimination

The first step is to discriminate aerosol and cloud using pre-classification and cloud tests based on AVHRR, IASI, the UV absorbing index and the GOME-2 stokes fractions. This step results in:

- Exclusion of pixels which are too cloudy for an AOD retrieval. The GOME-2 pixels suitable for AOD retrieval can be clear sky or partly cloudy.
- A determination of an aerosol class. The aerosol classes are Volcanic ash with SO_2, Volcanic ash/thick dust, biomass burning, coarse mode, fine mode and no classification as listed in Table 4. The classification coarse mode/fine mode only indicates which mode results the larger contribution to the measured signal. The AOD retrieval always uses a bimodal approach including both fine mode and coarse mode. Each aerosol class may contain different aerosol models which differ from each other in their microphysical properties like refractive index. The correct model within the aerosol class is selected at a later stage of the retrieval (see sect. 3.4).
- The selection of the optimal cloud free reflectance representing the actual measurement. For this step, one of different options described in sect. 3.1.2.2 is selected. The clear-sky selection is dependent on the aerosol class (Section 3.1.1 to 3.1.5), because the estimation of clear-sky reflectance is different for each of aerosol classes (sect. 3.1.2.2).
- The geometric cloud fraction of the involved GOME-2 PMD pixel.
- A cloud correction factor for selected GOME-2 PMD bands. The correction factor is used to calculate cloud-corrected PMD reflectance for all bands used within the retrieval for partly cloudy pixels (see sect. 3.1.7)

Note: The cloud fraction and the pre-classified aerosol type are also stored into the output product of PMAp.

The aerosol pre-classification for land and ocean selects one out of three cases using a top-down approach. In the following sections, the applied tests for each case is explained:

- **Case 1**: The GOME-2 footprint is tested for volcanic ash, extreme dust events and extreme biomass burning events independent of the AVHRR cloud filter. This case is explained in detail in sect. 3.1.1 that includes:
    - The detection of volcanic ash - over land and ocean - using IASI. If the IASI test indicate volcanic ash (including sulphur dioxide) the aerosol class is set to Volcanic

ash with SO_2. If volcanic ash is detected tentatively only, additional tests on GOME-2 and AVHRR are included (see sect. 3.1.1.1).
  - The detection of desert dust - over land and ocean - using IASI. A desert dust index is calculated making use of one hundred channels selected in the infrared thermal spectra provided by IASI. When desert dust is detected the whole cloud masking phase is skipped leading straightforward to the retrieval in Step2. In this case the AOD retrieval is constrained to use the desert dust aerosol type. (see 3.1.1.2)
  - Over ocean, a thick dust/ash event detection is performed based on all bands of AVHRR. If thick dust/ash is detected tentatively only, the GOME-2 UV index is used in addition (see sect. 3.1.1.1).
  - A thick aerosol event detection is performed based on BTD from IASI/AVHRR and the GOME-2 UV absorbing index. Over ocean, AVHRR VIS/NIR is used in addition (see sect. 3.1.1.3)
  - Over ocean, a combination of the GOME-2 UV index and AVHRR VIS/NIR bands is used to detect thick biomass burning events (see sect. 3.1.1.3)
  - Over land, a combination of the wavelength dependency of the GOME PMD stokes fractions and the UV absorbing index is used to detect biomass burning events (see 3.1.1.4).

- **Case 2:** If the the thick aerosol event tests are negative, it is tested if there are enough clear-sky pixels to obtain a clear-sky AVHRR reflectance using pixels classified as cloud free by all AVHRR cloud tests. For details about this case see sect 0
  - **Over Ocean:** The cloud fraction (composite of all tests, see sect. 3.1.2.1) needs to be below *maxCloudFractOcean* and the cloud fractions of the individual tests need to be below *maxCloudGOMEOcean.* The aerosol class and clear-sky reflectance is not yet finally determined at this point. The preliminary aerosol class is No classification. Possible clear-sky reflectances are *cloud free coarse mode aerosols, cloud free fine mode aerosols* and *cloud free unclassified aerosols* (sect. 3.1.2.2).
  - **Over land:** The cloud fraction (composite of all tests, see sect. 3.1.2.1) needs to be below *maxCloudFractLand* and the cloud fractions of the individual tests need to be below *maxCloudGOMELand.* The preliminary aerosol class is No classification. The clear-sky reflectance is *cloud free unclassified aerosols.*

- **Case 3:** If case 1 and 2 fail, the pixel is skipped as cloudy. No AOD is retrieved, the aerosol class is set to *No Classification*.

3.1.1 Determination of extreme dust, ash and biomass burning events

3.1.1.1 Volcanic ash/thick dust test

i) Volcanic ash/thick dust test over ocean

The algorithm selects one AVHRR pixel within the PMD footprint characterized by the lowest (highest negative) brightness temperature difference T4-T5 using channel 4 and channel 5 of AVHRR. For this AVHRR pixel, the radiances of all AVHRR channels are read. The algorithms apply a set of ten test settings to detect volcanic ash. If one of the test settings is passed, the presence of volcanic ash is assumed by the algorithm independent of the cloud flags for the AVHRR pixel. Each test setting contains a combination of six thresholds. All threshold tests have to be passed to give a positive ash result.

Each test setting contains the following thresholds:

1.) The brightness temperature difference between AVHRR channel 4 and AVHRR channel 5 is below a threshold. Ash and thick dust events usually give a negative brightness temperature difference while cirrus clouds show a positive BTD. Nevertheless, this test also lead to a lot of false alarms as long as no further criteria are applied.
2.) The ratio of the reflectance from AVHRR channel 3A and AVHRR channel 2 is above a threshold.
3.) The ratio of the reflectance from AVHRR channel 3A and AVHRR channel 1 is above a threshold.
4.) The ratio of the reflectance from AVHRR channel 2 and AVHRR channel 1 is above a threshold. The tests 2.)-4.) select pixel with a relatively flat dependence of the reflectance in wavelength which is typical for ash and dust and can be used to discriminate these aerosols from clouds and aerosols with a strong fine mode component.
5.) The AVHRR homogeneity cloud test fraction (at 11 µm) for the whole GOME-2 pixel is above a threshold. This threshold should be 0 for some of the tests, but we accept weaker thresholds in 1)-4) if this threshold is passed, because we have a heterogeneous scene which may contain a mixture of ash and clouds. This is important to detect ash more far from source.
6.) The AVHRR cirrus cloud test fraction for the whole GOME-2 pixel is above a threshold. This threshold should also be 0 for some of the tests, but we accept weaker thresholds in 1.)-4.) if this threshold is passed, because we may have a mixture of cirrus clouds and ash. Cirrus clouds lead to positive BTDs in test 1.).
7.) The GOME-2 UV absorbing index for the whole PMD footprint is above a threshold. A positive UV index is not mandatory for a positive volcanic ash test, but we accept weaker thresholds in 1.) -4.) if the UV index test is positive.

A set of combinations for these thresholds is defined by the parameter *ashThresholdsOcean*. If a pixel is classified as volcanic ash, this classification is considered as a final decision if one of the first *numStrictAshTestOceans* is positive. These tests require a particular strong ash signal in the TIR. Otherwise the decision is revisited within the GOME-2 retrieval. A mismatch is assumed, if problems with the surface are expected or a high uncertainty is expected for the observation geometry of the scene. For quite a large amount of observation geometries the surface of the ocean can introduce a wavelength dependency of the measured signal similar to dust and ash type aerosols. For these pixels the result of the ash detection algorithm is considered as not meaningful and a retrieval failure is reported.

If a pixel is finally classified as volcanic ash, the PMD footprint is approximately splitted into an ash-dominated and weaker-ash-dominated part using a PMD reflectance correction factor. This correction factor is provided the same PMD bands and is used in the same way as the cloud correction for the other aerosol classes (see Section 3.1.7):

$$R_{corrected}(ash) = R_{PMD}\frac{R_{AVHRR}(\min(T4-T5))}{\overline{R_{AVHRR}}(all)}$$

Equation 3

where $R_{AVHRR}(\min(T4-T5))$ denotes the reflectance of the AVHRR pixel within the GOME-2 PMD which has the largest negative brightness temperature difference between AVHRR channel 4 and 5.

ii) Strong brightness temperature test over land

If a negative brightness temperature difference between 10.8µm and 12µm is very strong for at least one AVHRR pixel within the PMD footprint over land, the pixel is classified as volcanic ash. This classification is independent from the other tests used for the detection. The reflectance used as input for the AOD retrieval is calculated as described in (i).

iii) Volcanic ash detection with SO_2 over land and ocean

PMAp retrieves a volcanic ash index based on IASI channels at 8.7µm, 10.8µm and 12µm. This discriminates the PMD pixels in volcanic ash, no volcanic ash and unclear situation.

If the classification is "unclear situation" the pixel is classified as ash if one of the following criteria is fulfilled:

- The UV absorbing index is above a threshold
- The pixel is over ocean and the coarse mode test as described in sect. 3.1.2.2 is true.

3.1.1.2 Desert dust detection using IASI channels

In order to better identify desert dust aerosol over sea and land surfaces, even over bright surfaces, a detection scheme based on the unified approach to aerosol remote sensing in the infrared spectral range developed by Clarisse [RD12].
A desert dust index is calculated making use of one hundred channels selected in the infrared thermal spectra provided by IASI, a previously collected mean clear sky and polluted spectra (i.e. spectra affected by the presence of a selected aerosol type, which is represented in our case by desert dust). The index consists thus in comparing the distance between polluted and clear sky spectra to the distance between measured and clear sky spectra. A threshold is set for the comparison of these distances which has been manually set by looking at a large number of assumed clear and polluted observations.
IASI to GOME-2 collocated data are used for computing the desert dust index
In case desert dust is detected the whole cloud masking phase is skipped leading straightforward to the retrieval in Step2. In this case the AOD retrieval is forced to the use of the desert dust aerosol type. If no dust aerosol is detected in the currently analyzed GOME-2 pixel, PMAp cloud screening procedure takes place.

The aforementioned approach works in most cases, cloudy or not, because the PMAp algorithm is able to derive the optical depth of aerosols even if the pixel is partly cloudy. Additionally, it solves the problem of a misclassification of a thick aerosol event as "cloud". However, it is possible that a given pixel contains both dust and a large cloud coverage. In other words, a pixel for which no AOD retrieval is possible on the grounds of high cloud coverage and that should have been discarded. The IASI desert dust detection combined with the skipping of the cloud filtering would cause in the end a retrieval of a wrong optical depth. This optical depth would be that of the cloud and aerosol combined. To prevent these situations, a post processing test has been included: pixels labelled as desert dust by IASI for which an AOD retrieval has been possible undergo a cloud fraction check. If the cloud coverage is higher than 90% of the pixel, then the pixel is labelled as *aerosol contaminated cloud* and the retrieval is sent back to the cloud screening. The retrieved AOD is discarded for the corresponding pixel, but the pixel has the added value of having been identified as a joint cloud and aerosol event instead of being discarde for being cloudy in an earlier step.

3.1.1.3 Thick aerosol event detection using UV absorbing index

If the tests described in sect. 3.1.1.1 are negative the UV index is used to classify the PMD pixel into the cases thick aerosol, potentially thick aerosol or no thick aerosol.

In addition to the UV index test, a set of further tests are applied. Pixels classified as "potentially thick aerosols" are considered as cloud if all additional tests fail. These tests are:

- The minimum brightness temperature difference between 10.8µm and 12µm of an AVHRR pixel within the GOME-2 PMD footprint is below a threshold.
- The pixel is over ocean and the coarse mode test as described in sect. 3.1.2.2 is true.

If the thick aerosol test is positive, a further classification of the aerosol class is sometimes possible.

- If the pixel is over ocean and the pixel fulfils the criteria as fine mode aerosol using the tests described in sect.3.1.3, the pixel is classified as biomass burning aerosol.
- If the pixel is over ocean and the pixel fulfils the criteria as coarse mode aerosol using the tests described in sect.3.1.3, the pixel is classified as thick dust
- If the brightness temperature difference between 10.8µm and 12µm of at least one AVHRR pixel is below a threshold, the pixel is classified as thick dust.
- If the AVHRR dust test over ocean is positive, the pixel is classified as thick dust.

Note: this detection scheme is currently under development

3.1.1.4 Biomass burning test over land based on PMD stokes fractions

The Stokes fraction test looks for a local maximum around the red spectral range (PMD 11 and 12) showing a larger polarization at the top of atmosphere compared to both higher and lower wavelengths. Over land, the polarization usually decreases with wavelength as most of the wavelength-dependency is caused by the decrease of Rayleigh scattering with wavelength. The polarization of the surface show a weak wavelength dependency only. A fine mode aerosol with very small particles can cause a Rayleigh scatter event which lead to a peak in the measured stokes fraction around 600-650nm. This is in particular the case for biomass burning type aerosols.

The Stokes fraction test classifies a pixel as biomass burning, no biomass burning and unclear. If the classification is unclear, the presence of biomass burning aerosols is assumed if the UV index tests indicate absorbing aerosols and all dust tests described above are negative.

Note: this detection scheme is currently under development

3.1.1.5 Selection of the aerosol class using the AVHRR dust test over ocean

The AVHRR dust test is used to identify dust-type aerosols for parts of the footprint, which are already classified as cloud free by other parts of the retrieval. This is in particular important for observation geometries where the wavelength dependency between the VIS and NIR cannot be used to classify the aerosol because the surface reflectance of the ocean shows similar wavelength dependence as the dust aerosol.

The dust test is similar to the widely used visualization of dust RGB images. Similar to the volcanic ash detection, the split window method is used for dust detection. But different to the thick event detection described in sect. 3.1.1.1, a wider range of the brightness temperature difference T4-T5 is considered dependent on the absolute value of the BT at 11µm. This is not accurate enough to distinguish aerosols from clouds.

The combination of the T4-T5 and T4 is based on a sector selection in red-green (RG) color space where red describes the BTD and green the absolute value of the BT at 11µm (T4). The constants which described the exact area of the sector are determined in the auxiliary file. Dust show up magenta in the dust RGB.

The color red is calculated by:

$$R = \frac{T5 - T4 + dustTestT5T4Offset}{dustTestT5T4Length}$$

The color blue is calculated by

$$B = \frac{T4 - dustTestT4min}{dustTestT4max - dustTestT4min}$$

R and B are limited to the range between 0 and 1. If the range is exceeded for measurements the values are set to 0 or 1 respectively.

In the RG space the color is defined using the angle while the brightness is described by the distance from the origin. The color is given by

$$color = \frac{\alpha - \frac{\pi}{dustTestColorAngleConst1}}{\frac{\pi}{dustTestColorAngleConst2}}$$

where $\alpha = \tan^{-1} B/R$ if $\frac{R}{B} > 1$ and $\alpha = \tan^{-1} R/B$ otherwise.

The brightness is given by

$$brightness = \frac{\sqrt{R^2 + B^2}}{\sqrt{2}}$$

The PMAp dust index – dedicated as a qualitative index to detect dust – is then calculated as the product of brightness and color. The dust test is positive if

$$if\ color * brightness > 0, then\ dust\ test\ positive$$

Note: Over land, the pre-classification is completed with the procedure described so far. But over ocean, an extended pre-classification is applied. *For optimization of the retrieval performance, the pre-classifications and the detection of thick events over ocean are split into two parts. The first part is described in this section and similar to the classification over land. The second part can skip the results of the first part and provide the determination of additional aerosol classes. The first part described here only uses methods which do not (directly or indirectly) rely on the LUT for the retrieval of the AOD (sect. 3.2). The second part of the pre-classification also makes use of the LUT. The interpolation of the LUT to the observation geometry of an individual measurement is relatively time consuming. If we split the pre-classifications into two parts, we can avoid these time consuming calculations for those pixels which are already detected as cloudy in the first part of the classifications. The LUT for the UV absorbing index is already used in the first part.*

Table 4: Aerosol classes, PMAp algorithm

Nr	***Class***	***Characterization***	***Fitted aerosol models (Section. 3.4)***	***Default aerosol model***
0	No dust/fine mode (ocean only)	BTD ash tests negative and strong wavelength dependency of the measured signal between 0.6µm and 1.6 µm.	*noDustModelOcean*	*defAerModelOcean*
1	coarse mode (ocean only)	Desert dust, ash or coarse mode sea-salt without significant BTD signal but weak wavelength dependency in VIS/NIR	*dustModeOceanl*	*defDustModelOcean*
2	Thick biomass burning	Over ocean: UV index indicate UV absorbing aerosol, coarse mode tests negative, TIR dust/ash tests negative. Over land: Stokes fraction and UV index tests positive.	*biomassModelOcean* *biomassModelLand*	*defBioModelOcean* *defBioModelLand*
3	Thick dust/volcanic ash	Volcanic ash or thick dust, BTD in TIR indicate dust/ash, weak wavelength dependency in VIS/NIR (ocean) or UV index indicate absorbing aerosol Calculation of the dust index from IASI channel detecting dust presence – over land and ocean.	*dustModelOcean* *dustModelLand*	*defDustModelOcean* *defDustModelLand*

4	Volcanic ash with SO_2	Volcanic ash, IASI ash test positive (including tests with SO2 TIR channels), confirmation by AVHRR VIS/NIR or GOME-2 UV tests	*ashModelOcean* *ashModelLand*	*defAshModelOcean* *defAshModelLand*
5	volcanic ash with SO_2			
10	Aerosol contaminated cloud			
11	Ash contaminated cloud			
15	No classification		*Ocean:* *allModelOcean* if surface shows similar characterization as dust: *noDustModelOcean, if AVHRR thermal dust test negative* *dustModelOcean, if AVHRR thermal dust test positive* *Land:* *allModelLand*	*defAerModelOcean* *defAerModelLand*

3.1.2 Cloud fraction and clear-sky reflectance selection

3.1.2.1 First guess cloud fraction

The preliminary, first guess cloud fraction is based on the cloud product distributed by the AVHRR Level-1 product [AD2]. The geometric cloud fraction is given by collocation of the AVHRR pixels to GOME-2-PMD:

$$CF(GOME) = \frac{n_{cloudy}(AVHRR)}{n_{colocated}(AVHRR)}$$

There are four cloud tests provided for AVHRR [L1AVH]:

- T11 test (brightness temperature of AVHRR channel 4) to reveal low temperature to medium or high clouds
- T11-T12 test (difference in brightness temperature of channel 4 and 5) to detect cirrus clouds
- Albedo test (reflectances in the two VIS channels to detect bright clouds)
- T4 spatial coherence test over sea to detect cloud edges, thin cirrus and small cumulus over sea

The thresholds for the different tests depend on season, geographical location, satellite viewing angle and availability of distinct data sets (e.g. forecast data and/or climatological data).

In the calculation of the preliminary cloud fraction, an AVHRR pixel is counted as cloudy, if one of the four tests indicates a cloud.

Note 1: For every AVHRR cloud test two flags are delivered:
1.) "cloudy or fail" is true, if the threshold for a cloudy pixels is passed or if the test fails at all for a given scene
2.) "clear or fail" is true if the threshold for a clear pixel is passed or if the test fails at all for a given scene.
In the PMAp interpretation, an AVHRR test indicates a cloud free pixel if the "cloud or fail" test is false and the "clear or fail" test is true.

Note 2: The AVHRR cloud fraction distributed within the EUMETSAT GOME-2 Level-1 product is different from the cloud fraction retrieved within the aerosol product PMAp.

3.1.2.2 Candidate clear-sky AVHRR reflectances in dependence of the aerosol class

The AOD will be retrieved for a GOME-2 PMD footprint. Each footprint contains various collocated AVHRR pixels because the spatial resolution of AVHRR is higher than the spatial resolution of GOME-2 (see sect. 2.5). The easiest and most common approach to select clear-sky pixels would be the application of a cloud filter. If all AVHRR pixels are cloud free, the GOME-2 pixel is cloud free. If a part of the AVHRR pixels are cloudy, the GOME-2 pixel is partly cloudy. However, this approach is not used by PMAp that way. The AVHRR cloud fraction is used as one out of several criteria only.

1.) The PMAp approach determines the clear-sky reflectance dependent on the aerosol type. Each clear-sky reflectance is based on a composite of different AVHRR measurements within the GOME-2 footprint, but the AVHRR pixels selected depend on the aerosol classification. The AVHRR cloud filter is a good first guess, but not good enough to discriminate aerosols and clouds. Thick dust events may be labelled as cloudy, in particular by the albedo test in the AVHHR cloud filter (sect. 3.1.2.1) and additional tests are needed to detect these pixels. But also some clouds may be undetected by the filter. PMAp indentifies some of the undetected clouds using homogeneity analysis dependent on the aerosol class: Inhomogeneity in the long wavelengths can be caused by aerosols with large particle radius, but not by the fine mode component of the aerosol.
2.) Inhomogeneities in the NIR are interpreted as remaining cloud contributions or other non-aerosol artefacts if there are no large aerosol particles and the pixel is over ocean.
3.) An outlier correction is used to detect remaining clouds both over land and ocean.
4.) The AVHRR cloud fraction is ignored in case of positive tests for thick aerosols both over land and ocean.

PMAp calculates and stores a set of different clear-sky AVHRR reflectances in advance. Each of the reflectances is optimized for different aerosol classifications. The clear-sky reflectance taken by the retrieval was not unknown at that point but is determined when the aerosol class is retrieved. The algorithm stores the reflectances of AVHRR CH 1,2,3A and the brightness temperatures of CH 4 and CH 5.

The different options for clear-sky reflectances are

1.) **Cloud Free Volcanic ash (incl. extreme dust events):**
The AVHRR pixel with the lowest (highest negative) brightness temperature difference is the best representation of pixels identified as volcanic ash or extreme dust events over ocean and land.
2.) **Cloud Free Coarse mode aerosols:**
Clear-sky pixels are determined using the cloud fraction from 0. In addition a *VIS/IR homogenization* and *an outlier correction* is used to skip additional pixels. This is used for aerosols over ocean with a strong coarse mode component and dust aerosols with reasonable signal in the TIR bands over land.
3.) **Cloud Free Unclassified aerosols:**
like 2.), but *R4 homogenization* is applied in addition. This is used for aerosols with unclassified type over ocean and land.
4.) **Cloud Free Fine mode aerosol:**
like 3.), but *R3 homogenization* is applied in addition. This is used for aerosols over ocean without a strong coarse mode component (most of measured signal is supposed to be from the fine mode). Over land, this selection is used to test for inhomogeneities of the surface.
5.) **IR clear:**
Pixels classified as cloud free by the T4 test, the T4T5 test and the uniformity test of AVHRR (albedo test ignored). This is used in some cases for thicker aerosols or partly cloudy pixels.
6.) **Cloud Free Unfiltered clear sky:**
Average of all pixels which are classified as clear-sky by the AVHRR cloud tests (combination of all tests) but no additional filter is applied. This is currently not used, but may be used in the future to analyse scene homogeneity over deserts.

For the calculation of these clear-sky reflectances a set of tests and selection criteria (labelled in italic letters in the description above) are used:

a.) **Outlier correction**:
If a set of AVHRR pixels is preclassified as clear-sky, an outlier correction is applied to exclude remaining cloud contributions or artefacts.
The median of the pixels is in general a better representation of a scene than the arithmetic average. Potential cloudy outliers may have a strong contribution to the average because the reflectance of clouds can exceed the reflectance of the aerosol by one order of magnitude. On the other hand, the selection of a single AVHRR pixel may be not a good representation of the scene if multi-wavelengths analysis is applied because the channels cover VIS, NIR and TIR bands.
As a compromise, we introduce the **median-corrected average** which is defined by the arithmetic average of a subset defined by the following criteria
- The arithmetic average of the subset reflectance is equal or lower than median of the original data set for channel 1,2,3A (brightest pixels may be skipped)

- The arithmetic average of the subset radiance is equal or higher than the median of the original data set for channel 4 (coolest pixels may be skipped)
- The brightest (coolest) pixels are skipped step by step on a single-channel base. The order of the channels is predefined by *avhrrSortChannel*. Pixels skipped for one channel are automatically skipped for the channels considered afterwards. However, the median used for comparison is always the median of all pixels from the initial dataset.

b.) VIS/IR homogenization

Extended aerosol layers may result in a homogeneous scene. The footprint of GOME-2 is quite large and aerosol layers may also cause inhomogeneities. In case of fine mode aerosols, inhomogeneities should appear in the visual wavelength only. Dust aerosols with a strong coarse mode component may introduce inhomogeneities both in visual and the thermal bands. On the other hand, it is not expected that aerosols introduce inhomogeneities in the thermal bands only. If a footprint is heterogeneous in AVHRR CH4 (variance threshold: *varianceIRHomoVisIR*) but homogeneous in AVHRR CH1 (variance threshold: *varianceVisHomoVisIR*) the coolest pixels in AVHRR CH4 are skipped until the threshold criteria is fulfilled. The measurement is evaluated only if the remaining amount of AVHRR pixels within the GOME-2 footprint is above *minAmountMeasHomo*.

c.) R4 homogenization

This procedure removes the coolest AVHRR pixels until the variance of the radiances in AVHRR Channel 4 is below *maxR4CleanedVariance*

d.) R3 homogenization

This procedure removes the brightest AVHRR pixels in channel 3A (1.6µm) until the variance is below *maxR3CleanedVariance.*

e.) AVHRR dust test

IR dust test as described in sect.3.1.1.5.

f.) Coarse mode test

The coarse mode test is positive for AVHRR pixels which show only a week dependency of the reflectance on the wavelength for AVHRR Ch1 (R1), AVHRR channel 2 (R2) and AVHRR channel 3A (R3A). The test is based on the combination of two thresholds

$$\frac{R3A}{R1} > R3R1CloudFreeDust$$

$$\frac{R2}{R1} > R2R1CloudFreeDust$$

3.1.3 Second part of pre-classification step (only for ocean) to determine the clear-sky reflectance and aerosol classification over ocean

Over ocean, a second part of the pre-classification is applied after the LUT is interpolated to the individual measurements.

General idea: The pre-classification provided in sect. 3.1 can be wrong if the surface reflectance has a strong impact on the measured reflectance. Glint on the ocean show weak wavelength dependence between 600 nm and 1600 nm and lead to mismatched dust. The UV absorbing index leads to false positives for sun glint conditions as well. For pixels over ocean far from glint conditions, additional information on the aerosol type can be retrieved from the combination of the UV absorbing index and the wavelength dependency between 600 nm and 1600 nm.

A selection of the aerosol class is applied dependent on the impact of the surface on the measured signal in AVHRR channel 1, 2 and 3A. Three cases are distinguished over ocean:

- Case S1: The impact of the surface uncertainties to the measured signal is very small. The surface and consistency tests as described in sect. 3.3.1 are passed. In addition, a stricter threshold for the wind speed impact on the AOD retrieval is passed (*maxWindSensThre* is replaced by *windLimitVisNirTests*, equations in sect. 3.3.1.)
- Case S2: like case 1, but the stricter test on the wind speed impact on the AOD retrieval fails
- Case S3: The surface and consistency tests described in sect. 3.3.1 fail.

If the pixel is already classified as thick dust/volcanic ash based on a test including VIS/NIR channels the result is considered as correct only for case S1 and S2. In case S3, the positive volcanic ash test is considered as a false positive. Exception: If a very strict volcanic ash test is passed so that the final decision is already taken at the beginning (see sect.3.1.1.1), the volcanic ash classification is kept. *Note:* If volcanic ash is detected based on IASI (including SO_2) the classification is considered correct in all cases because the false positive is caused by reflectances in the VIS/NIR bands.

If the thick aerosol tests were negative or they are cancelled as described above, an infrared test for dust is applied in case S2 and S3. The dust test is explained in sect. 3.1.1.5. If the dust test is positive, PMAp selects the aerosol class *coarse mode*. Otherwise the aerosol class is set to *No classification.*

If the thick aerosol tests are negative the wavelength dependency of the signal in AVHRR channel 1, 2 and 3A is used to select the aerosol class for case S1. Threshold tests are used to determine the aerosol classes 0 (*No dust/fine mode*) and 1 (*Coarse mode*). The algorithm distinguishes pixels showing a strong or weak wavelength dependency between 0.6 µm and 1.6 µm. Two thresholds are used respectively:

1.) the measured reflectance ratio between channel 2 and 1 divided by the modelled clear-sky reflectance from a LUT: $(R_2(\text{meas})/R_1(\text{meas}))/(R_2(\text{clear})/R_1(\text{clear}))$

    Note: For AVHRR Channel 1 and Channel 2, clear-sky model data is taken from the GOME-2 LUT for PMD 12 and PMD 14. In principle, this is not correct (particularly for AVHRR Channel 2) but it is sufficient for a threshold approach.

2.) the measured reflectance of channel 3A divided by the measured reflectance of channel 2.

In the auxiliary dataset several combination of the two thresholds are defined which indicate the presence of one of the two aerosol classes:

- For the coarse mode class detection: lower thresholds are set for test 2.) and 1.) in *dustThresholds*.
- For the no dust/fine mode class detection: upper thresholds are set for test 1.) and 2.) in *fineThresholds*.

If no aerosol class is found based on the conditions described above, the aerosol class is set to No classification.

Within the least square fit over several aerosol models described in Section. 3.4, usually not all aerosol models (*useModel*) are included to the retrieval, but a subset depended on the aerosol class only. The clear-sky reflectance is also selected dependent on the aerosol class (sect. 3.1.2.2). ***Note:*** Each aerosol class may contain different aerosol models. Example: The aerosol class *Coarse mode* may contain different dust-type aerosols which differ in their microphysical properties like refractive index.

3.1.4 Removal of inhomogeneous pixels over land

Over land, all GOME PMD pixels are tested for homogeneity using the collocated AVHRR reflectances in AVHRR channel 1. It is assumed that inhomogeneous footprints are either cloud contaminated or suffers from a variability of the surface reflectance on spatial scale which is not well represented by the (relatively coarse) spatial resolution of the surface albedo databases. For partly cloudy pixels, only the cloud free part is considered.

PMAp considers three different subsets of AVHRR pixels as potentially good representation of cloud free AVHRR pixels within the GOME pixels. These subsets are retrieved according to sect. 3.1.2.2: the subsets described in the bullets 2.) 3.) and 4.). The subset 5.) is considered in addition if the first guess cloud fraction is 0 (sect. 3.1.2.1) and the subset 5.) considering IR cloud tests only has a lower reflectance than the other three subsets in AVHRR channel 1.

For the three (or four) AVHRR sunsets homogeneity tests are applied. The difference in reflectance needs to be below *maxCFOptDiffCh1Land* for all cross-combinations. If this test fails, the GOME PMD pixel is skipped for the AOD processing. If the test is passed, the subset with the lowest reflectance in AVHRR channel 1 is chosen as the best representation of the cloud free reflectance except of thick aerosol cases.

3.1.5 Determination of the default model

In case the retrieval of the aerosol type as described in Section 3.1.1 and 3.1.3 is unclear or impossible, a default model is selected based on the initial AVHRR analysis.

If the detection of thick aerosol events is negative, the default model is:

- A sea salt model is used for pixels over ocean classified as no dust/fine mode or without classification. The aerosol type is defined by *defAerModelIndOcean*.

- A dust model is used for pixels over ocean classified as coarse mode. The aerosol type is defined by *defDustModelOcean*.
- A dust model is also used for pixels over land with a brightness temperature difference between 10.8µm and 12µm below *minBTDForDustDefaultLand*. The aerosol type is defined by *defDustModIndLand*.
- For all other pixels over land a continental aerosol is used. The aerosol type is defined by *defAerModIndLand*.

If the thick aerosol event is positive, the default model is selected according to Table 4.

3.1.6 Determination of clear-sky pixels and cloud fraction

A GOME-2 pixel is classified as cloud free, if the averaged reflectance of all AVHRR pixels within the GOME-2 footprint is close to clear-sky AVHRR reflectance calculated by the algorithm described in sect. 3.1.2.2. The clear-sky classification is dependent on the aerosol class (Section 3.1.10 to 3.1.5), because the estimation of clear-sky reflectance is different for the aerosol classes.

A GOME-2 PMD footprint is cloud free if one out of two criteria is fulfilled.

1.) The absolute difference between clear-sky and average AVHRR reflectance is below a threshold (separated for land and ocean):

$$\left|R_{AVHRR}(cloudfree) - R_{AVHRR}(average)\right| \leq clearSkyMaxAbsDiffOcean$$

$$\left|R_{AVHRR}(cloudfree) - R_{AVHRR}(average)\right| \leq clearSkyMaxAbsDiffLand$$

2.) The pixel is over ocean and the relative difference between clear-sky and average AVHRR reflectance is below a threshold:

$$\frac{\left|R_{AVHRR}(cloudfree) - R_{AVHRR}(average)\right|}{R_{AVHRR}(average)} \leq clearSkyMaxRelDiffOcean$$

where R_{AVHRR}(cloudfree) is the selected clear-sky reflectance from sect. 3.1.2.2 and R_{AVHRR}(average) is the average reflectance of all AVHRR pixels within the GOME-2 footprint.

The final *cloud fraction* is fiven by cf = 1-clearSkyRatio, where clearSkyRatio is the relative amount of AVHRR pixels finally classified as clear sky using the procedure described in sect. 3.1.1 to 3.1.5

3.1.7 Cloud correction factors for GOME-2

3.1.7.1 PMD bands with spectral overlap to AVHRR channel 1

A pixel is partly cloudy, if the pixel is not skipped as too cloudy, but the clear-sky classification from sect. 3.1.3 fails. For these pixels a cloud correction factor is calculated for the PMD band to allow a simplified AOD retrieval. The most accurate correction factors are provided for PMD bands overlapping with the AVHRR channels. The best spectral overlap between the two instruments is currently provided by PMD12 and AVHRR channel 1. The idea is to estimate the relative amount of the signal caused by the cloud. The method does not require a correct slope of the AVHRR/3 data to the calibrated radiance, but an accurate collocation of the AVHRR pixels to GOME-2. GOME-2 reflectances are corrected for clouds using the formula:

$$R_{corrected}(cloudfree) = R_{PMD}\frac{R_{AVHRR}(cloudfree)}{\overline{R_{AVHRR}}(all)}$$

The cloud free reflectance R_{AVHRR}(*cloudfree*) is taken from sect. 3.1.2.2 dependent on the aerosol class and is divided by the reflectance average of all AVHRR pixels $\overline{R_{AVHRR}(all)}$ within the GOME-2 PMD ground scene. The PMD reflectance from the input is then multiplied by this factor within the AOD retrieval. The collocation introduces an error to the correction factor because the footprints of the two instruments have different shapes (see Section 2.6). But it should be noted that these errors are always present as relative errors on GOME-2, because the uncertainties introduce an error in a correction factor. A relative error is significantly better than a small offset (even if the relative error is relatively large) because the reflectance of a cloud-free aerosol loaded pixel is often very small. Note, that the approach is mainly insensitive to the slope found in Section 2.6, because a ratio of two AVHRR reflectances is used.

3.1.7.2 PMD bands with no spectral overlap to AVHRR channel 1

Over ocean and selected areas over land (dense vegetation) an AOD can be interpolated using PMD bands overlapping AVHRR channel 1 if the aerosol type is given. For most areas over land the surface is too bright to interpolate an AOD at this band. For these areas cloud corrected reflectances are required at lower wavelengths, preferable between 400nm and 500nm.

PMAp uses a simple correction of the Rayleigh scattering by describing the cloud reflectance as a lambertian layer at a pre defined pressure leverl (*defCloudCorrPress*) the surface with very high albedo (*defCloudAlbedoLand*). One should keep in mind that:

1.) Some of the reflectance attributed to the cloud is coming from the surface. Only small cloud contributions can be corrected. The correction introduces a surface-related error.
2.) The reflectance of the cloud should not be too large compared to the reflectance of the aerosol. This is usually the case for cloud edges and clouds with small optical depth only (1-3). Cloud correction is possible only if the reflectance is comparable to the signal of the aerosol (signal to noise limit). For these cases it is expected to be difficult to retrieve cloud optical properties like cloud height, cloud type, cloud optical depth or cloud phase.
3.) The correction basically corrects Rayleigh scattering effects within the wavelength shift.
4.) It is important to take the spatial aliasing into account. The AVHRR radiances are collocated to the PMD band with spectral overlap to AVHRR as well as to the PMD band which the correction is calculated for.
5.) It is planned to test corrections using realistic cloud models within the upcoming releases of PMAp. The simple correction may be replaced by a better one if these tests are successful.

The GOME-2 L1b product provides PMD radiances at a given wavelength together with a reference geo-location footprint from which PMAp determines the corresponding footprint of the used PMD band taking spatial aliasing into account (see GOME-2 factsheet, Section 6.3). The wavelength of any used PMD band *i* (*PMDi*) can therefore be different to the wavelength of the PMD band defining the footprint. This is needed as an intermediate step to correct for spatial aliasing and the shift in wavelength simultaneously.

The cloud correction of PMD band *PMDi* is calculated by the following procedure:

In a first step, the clear-sky reflectance at the wavelength of the AVHRR band, but within the footprint of the *PMDi* band is calculated by:

$$R_{corrected}(PMDi, AVHRRch1) = R_{PMD}(PMD_{AVHRROverlap})\frac{R_{AVHRR}(cloudfree_{PMDi})}{\overline{R_{AVHRR}}(all, PMD_{AVHRROverlap})}$$

The average reflectance of *PMDi* at the wavelength of the AVHRR band taking spatial aliasing into account is approximated by

$$R_{average}(PMDi, AVHRRch1) = R_{PMD}(PMD_{AVHRROverlap})\frac{\overline{R_{AVHRR}}(all, PMD_i)}{\overline{R_{AVHRR}}(all, PMD_{AVHRROverlap})}$$

The reflectance of the bright cloud reflector is taken from the LUT. The top of atmosphere reflectance of the cloud layer is calculated for the wavelength of PMDi ($Rcloud_{PMDi}$) and the wavelength of band overlapping with AVHRR ch 1 ($Rcloud_{PMDAVHRROverlap}$).

The effective cloud fraction is then given by:

$$CF = \frac{R_{average}(PMDi, AVHRRch1) - R_{corrected}(PMDi, AVHRRch1)}{R_{PMDAVHRROverlap}(cloud, theoretical) - R_{corrected}(PMDi, AVHRRch1)}$$

The clear-sky reflectance is then given by:

$$R_{clear,PMDi} = \frac{R_{PMD}(PMDi) - CF * R_{PMDi}(cloud, theoretical)}{1 - CF}$$

3.2 Radiative transfer data for the aerosol retrieval

The radiative transfer calculations are stored in a look-up table.

3.2.1 Look up table for the aerosol retrieval over ocean

In step 2 and step 3 of the retrieval, we apply a look-up-table (LUT) from [Hasekamp et al., 2008]. The LUT contains reflectances and stokes fractions for ten PMD bands (PMD5 – PMD14, cp. Section. 2.1) and 28 aerosol models. The reflectances are modelled dependent on observation geometry (solar zenith angle (SZA), relative azimuth angle (RAZI), viewing zenith angle (VZA), wind speed and the amount of chlorophyll. The models are characterized by [Hasekamp et. al., 2008] and are dependent on microphysical properties of the aerosols: effective radius and the variance of the effective radius for small and coarse mode respectively, the real and the imaginary part of the refractive index (m_r and m_i), and the fraction of the aerosol coarse mode f_l.

Aerosol model	*Eff. Radius liquid*	*Eff. Radius solid*	*Eff. Variance small*	*Eff. Variance large*	f_l	m_r	m_i	*Aerosol type*
1	0.11	0.84	0.65	0.65	1.53e-2	1.40	-4.0e-3	oceanic
2	0.12	2.19	0.18	0.81	4.36e-4	1.40	-4.0e-3	industrial
3	0.13	2.24	0.50	0.81	4.04e-4	1.40	-4.0e-3	industrial
4	0.21	2.50	0.18	0.81	8.10e-4	1.45	-4.0e-3	industrial
5	0.14	2.15	0.22	0.62	7.00e-4	1.45	-1.2e-2	industrial
6	0.15	2.26	0.22	0.62	6.84e-4	1.45	-1.2e-2	industrial
7	0.18	2.69	0.22	0.62	6.84e-4	1.45	-1.2e-2	industrial
8	0.12	2.43	0.20	0.87	1.70e-4	1.50	-1.0e-2	biomass
9	0.15	2.70	0.20	0.87	2.06e-4	1.50	-1.0e-2	biomass
10	0.20	3.42	0.20	0.87	2.94e-4	1.50	-1.0e-2	biomass
11	0.11	2.52	0.17	0.70	2.07e-4	1.50	-2.0e-2	biomass
12	0.12	2.67	0.17	0.70	2.05e-4	1.50	-2.0e-2	biomass
13	0.14	3.28	0.17	0.70	1.99e-4	1.50	-2.0e-2	biomass
14-18	0.10	1.60	0.32	0.42	4.35e-3	1.53	See Figure 5	dust
19-28	Same as model 7-16 with altitude 3-4km (model 0-18: altitude 1-2km)							

Table 5: Radiative Transfer - Look up Table from [Hasekamp et al, 2008]

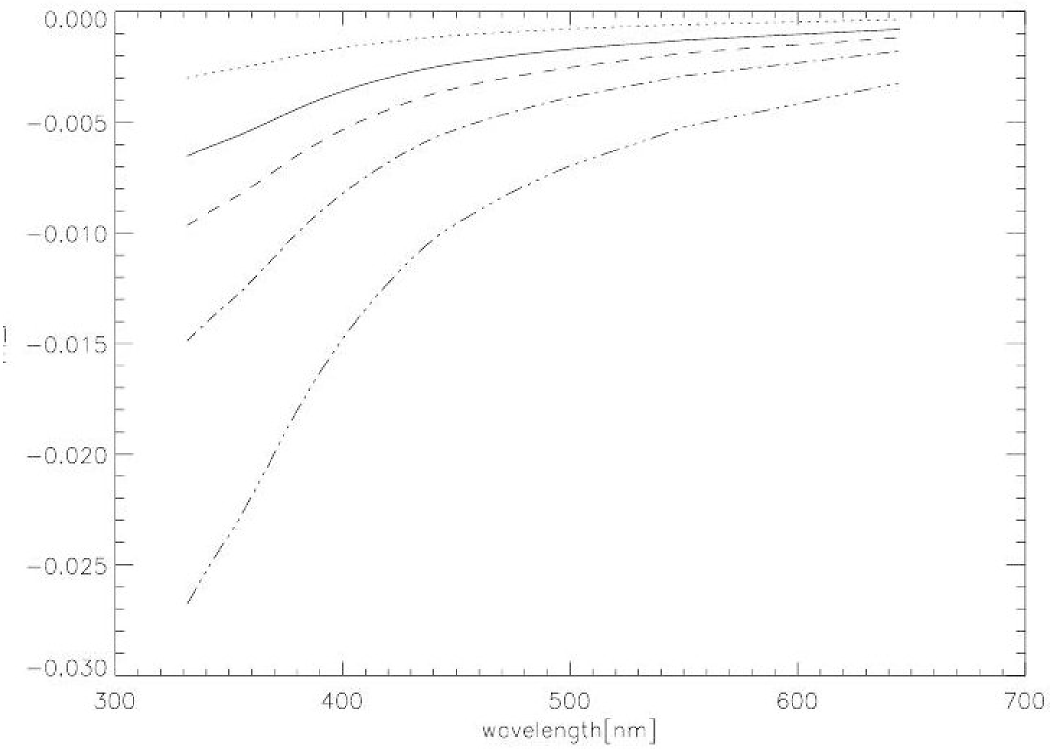

Figure 5: Schematic of the refractive index for five dust models. Models 14-18 are shown from top to bottom.

3.2.2 Look up table for the aerosol retrieval over land

The LUT for the AOD retrieval over land contain a subset of the cases available over ocean. The aerosol LUT over land contains 5 models (aerosol nr. 1-5). The microphysical properties of these cases are identical to the aerosol models 2,5,8,12,16 over ocean. The reflectance and stokes fractions are stored dependent on solar zenith angle, viewing zenith angle, relative azimuth angle, surface albedo and surface pressure.

3.2.3 Interpolation to actual geometry

PMAp interpolates the LUT to the actual geometry (SZA, VZA and RAZI) for each individual GOME-2 footprint. Over ocean, this interpolation is applied for all aerosol models and all grid points available for AOD, wind speed and chlorophyll load respectively. Over land, this interpolation is applied for 5 aerosol models and all grid points available for AOD, surface albedo and surface pressure.

A step-by-step spline interpolation turned out to be too slow for the operational retrieval. A two step scheme is used instead. The first step is a selection of eight nearest neighbours from the LUT (two nearest neighbours for SZA, VZA and RAZI respectively). From this set, a linear interpolation in scattering angle between the two nearest neighbours is performed. This approach implies that multiple scattering is taken into account for reflectance and stokes fractions at the grid points, while the

interpolation between the grid points assumes single scattering approximation and linearity in scattering angle–only reliable for small distances between grid points.
The result of this procedure is an interpolated LUT for a given observation geometry which is used as input for the retrievals on the pixel level.

3.2.4 UV absorbing aerosol index

The LUT for the Aerosol Absorbing Index contains modelled reflectances for a Rayleigh only atmosphere (without clouds and aerosols). The LUT is provided dependent on solar zenith angle, satellite viewing angle and relative azimuth angle for *uvAAIBd1* (default: PMD4, around 340nm) and *uvAAIBd2* (default: PMD6, around 380nm). The LUT is interpolated to the actual observation geometry in the same way as described in sect. 3.2.3.

The aerosol absorbing index is defined in the same way as for the existing products for TOMS, GOME-2 and SCIAMACHY (see e.g. http://o3msaf.fmi.fi for documentation the GOME-2 AAI product). Basic idea: The presence of absorbing aerosols increases the wavelength dependency of the reflectance in the UV: the reflectance at the lower wavelengths is lower for an atmosphere with absorbing aerosols compared to a pure Rayleigh atmosphere. The reasons are increasing multiple-scattering events at the lower wavelength bands which increase the light pass within the absorbing aerosol layer. On the other hand, non-absorbing aerosols and clouds increase the measured reflectance compared to the Rayleigh case because more pixels are backscattered to the top of atmosphere while less photons are absorbed at the surface. The absorption effect of the aerosols increases when the light pass within the aerosol layer increases. This result in the effect, that the presence of a small cloud amount close to the aerosol layer may increase the aerosol index, because the enhancement of the lightpath within the aerosol layer is the stronger effect compared to the scattering effect of the cloud. The aerosol index avoids relying on the absolute value of measured reflectances, but making use of the relative change between two bands, but is very sensitive to changes in the difference between the chosen wavelength tuples (e.g. due to instrument degradation).

A detailed discussion of the AAI applied to GOME-2-type instruments can be found in [RD11].

In a first step the effective albedo *effalbedo* for the PMD band *uvAAIBd2* is calculated by PMAp. The effective albedo is the lambertian surface albedo which results in a calculated top-of-atmosphere reflectance (cloud and aerosol free atmosphere) identical to the measured reflectance. In a second step, the top of atmosphere reflectance for PMD *uvAAIBd1* R_{calc}(uvAAIBd1, effalbedo) is calculated for an cloud and aerosol free atmosphere using the effective albedo *effalbedo* calculated for the other channel. The aerosol absorbing index is then given by:

$$AAI = -100 * \log_{10} \frac{R_{PMD}(uvAAIBd1)}{R_{calc}(uvAAIBd1, effalbedo)}$$

3.3 Step 2A: Retrieval of the AOD set over ocean

In the second step a set of (at maximum) 28 AODs at 550nm are retrieved over ocean. The differences between the values are related to the assumption of different aerosol models. External parameters are used to exclude a part of the models provided by the LUT database. Only 5-10 models are included to the retrieval and from these models a subset may be selected based on the AVHRR aerosol type pre-classification. For each model, the AOD is retrieved using the scheme shown in Figure 6. The retrieval is designed as followed: The LUT is interpolated to the actual observation geometry. One out of three retrieval schemes is selected dependent on a surface test (which estimates the relative contribution of the surface reflectance to the total signal) and the AVHRR cloud retrievals described in Section 0.

There are three retrieval schemes:

- Retrieval scheme 1 (main retrieval) is applied if the surface test is passed and the GOME-2 pixel is classified as cloud free
- Retrieval scheme 2 (simplified retrieval for cloudy pixels) is applied if the surface test is passed and the pixel is partly cloudy.
- Retrieval scheme 3 (alternate retrieval) is applied if the surface test failed and the GOME-2 pixel is classified as cloud free
- If none of the three cases is valid, no AOD retrieval is performed.

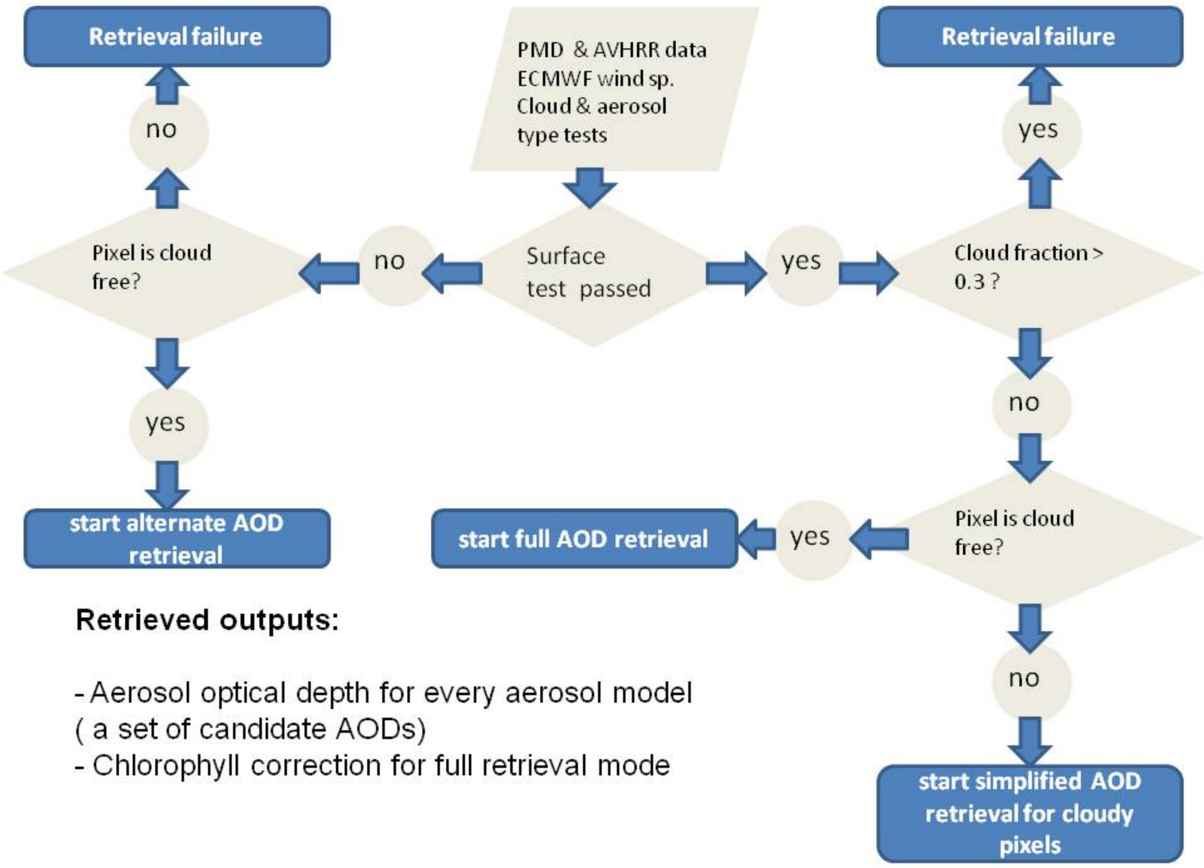

Figure 6: Retrieval algorithm selection for AOD retrieval from GOME-2. This algorithm is applied to all aerosol models provided by the LUT separately.

3.3.1 Surface and consistency test

The AOD inversion applies different algorithms dependent on the expected impact of the surface to the measured signal. The surface test is a threshold test applied to theoretical reflectance obtained by radiative transfer calculation (LUT from Section 0). The surface test is passed if

a.) the impact of the clear sky top of atmosphere reflectance is not too large (the difference between the reflectance of an aerosol loaded scene and a clear sky scene should be not to small compared to the total clear-sky signal) :

$$\frac{R_{aerosol}(v_{wind}[meas.]) - R_{clear}(v_{wind}[meas])}{R_{clear}(v_{wind}[meas])} > minAerSurRatMain$$

Equation 4

b.) the impact of the wind speed to the clear sky top of atmosphere reflectance is not too large compared to contrast between the aerosol and the surface:

$$\frac{\left| R_{clear}(v_{wind}[\max]) - R_{clear}(v_{wind}[\min]) \right|}{R_{aerosol}(v_{wind}[meas.]) - R_{clear}(v_{wind}[meas])} < maxWindSensThre$$

Equation 5

c.) the AOD describes a partly monotonic function in reflectance of the main retrieval channel *aodMainChOcean* as predicted by the RTM LUT. The function is defined as partly monotonic if a minimum AOD “minAOD” can be found so that the AOD is described by a monotonic function of the reflectance in the range [minAOD, 4] and the AOD retrieved for the given scene is higher than minAOD.

For the tests a.) and b.) a sea-salt aerosol (model 1 of Table 5) with an AOD of 0.3 is assumed.

3.3.2 Retrieval scheme 1: Pixel is clear sky and surface test passed

The **full AOD retrieval** retrieves a set of AOD at 550nm and chlorophyll load values under assumption of different aerosol models. Three channels in reflectance are used, which are configurable by the parameter file.

- The main retrieval band (*aodMainChOcean,* usually around the red edge / NIR) should be sensitive to all aerosol types and the signal should have a weak dependence on the chlorophyll load.
- The UV chlorophyll band (*chlUvRefChOcean* in the deep blue or UV) should measure chlorophyll absorption.
- The green chlorophyll band (*chlVISRefChOcean*, VIS) should measure an enhancement of the ocean reflectance if chlorophyll is present.

Chlorophyll pigment concentration and AOD is estimated by a χ^2-minimazation of the reflectance in these three bands. Afterwards, the final AOD is retrieved using a spline interpolation for the main retrieval band. The chlorophyll load is taken from the previous retrieval step.

3.3.3 Retrieval scheme 2: Partly cloudy pixels and surface test passed

In the case of moderate cloud contamination, the simplified AOD retrieval for partly cloudy scenes is used, if the surface test is passed. The measured signals have to be corrected for the cloud contribution.

In the retrieval for partly cloudy pixels, no chlorophyll pigment concentration is calculated. The default chlorophyll load (taken from the input parameters) is used instead. The AOD is then calculated using a spline interpolation in the same way as for the clear-sky retrieval, but using the *aodMainCh* only. This channel needs to have a spectral overlap with AVHRR/3. The reflectance is corrected for clouds using the cloud correction factor calculated in step 1 of the retrieval. See Section 3.1.7.

3.3.4 Retrieval scheme 3: Clear sky pixels and surface test fails

If a pixel does not pass the surface test, the **alternate aerosol retrieval** is applied if the scene is cloud free. In most of the cases it has to be expected that measurements suffer from the impact of the surface if these algorithms are selected. The retrieval uses both stokes fractions and reflectances. Both quantities are sensitive to aerosols and the surface, but the type of impact is different. Nevertheless, it turned out to be difficult to estimate the surface properties and the AOD at the same time due to the huge amount of parameters affecting the result. The algorithm "guesses" an appropriate surface (described by the ocean model used for creation of the LUT dependent on SZA, VZA, RAZI and the input wind speed). The AOD is retrieved under these assumptions and the results are checked for consistency using further bands. The result is added to the output in case of a passed consistency check only.

First, a retrieval of the AOD is attempted using the reflectance of one band defined in the parameter settings. The chlorophyll load is not retrieved and a default value is used instead. The algorithm uses lower wavelengths than the main retrieval, because this reduces the dependence of the clear-sky reflectance and stokes fraction on a priori assumptions compared to retrievals using the red edge/NIR. The calculation of the AOD is based on a spline interpolation implemented in the same way as for the main retrieval, but for a different band. Afterwards the χ^2-differences for PMD reflectance and stokes fractions (R_{PMD} and q_{PMD}) in several bands are calculated:

$$\chi^2 = \sum_N \frac{(R_{PMD} - R_{modelled})^2}{R_{modelled}} + \sum_M \frac{(q_{PMD} - q_{modelled})^2}{q_{modelled}} < chi2RelTestThre \quad \text{Equation 6}$$

The set of *N* bands used in reflectance and *M* bands used in stokes fraction is pre-defined in the configuration file. If this difference is below an upper threshold and, in addition, the two partial sums are below pre-defined thresholds, the result is considered as consistent and included to the results.

In the case of a retrieval failure, a further method is tried. The AOD is retrieved using a one-band retrieval in the Stokes fractions using the same algorithm as in the previous step. The χ^2- test is the same, but bands and thresholds are selected differently. If this retrieval fails too, no result is given and the retrieval failure flag is set to true.

3.4 Step 2B: Retrieval of the AOD set over land

Over land, the band used for the interpolation of the AOD set is basically selected dependent on the surface albedo. Three channels are considered: *aodMainChLand, aodBrightChLand and gomeCloudChLand*. The darkest channel is generally the best choice. If the difference in surface albedo between two bands is small, the following two criteria are considered in addition:

- PMD at lower wavelengths may introduce a larger error on the retrieved AOD. Reasons are lower radiometric accuracy, stronger instrument degradation and a stronger dependence of the reflectance on the aerosol type due to the variability in absorption for different types of aerosols.
- If the surface albedo is low around 630nm (PMD12), it would be an advantage to use this channel because of the overlap with AVHRR ch1. This allows a more accurate cloud correction for partly cloudy pixels which does not rely on modelled data. The surface albedo at 630nm is significantly higher than at 440nm for most of the areas. The selection of this channel is limited to a few areas only, in particular areas with dense vegetation.

The selection is realized by the following selection using surface albedo from climatology [RD7]:

- If the surface albedo at *gomeCloudChLand* exceeds the surface albedo in *aodMainChLand* by not more than *maxAlbDiffMainCloud* and the surface albedo at *gomeCloudChLand* is below *maxAlbedoAodLand*, PMAp selects *gomeCloudChLand*.
- If *gomeCloudChLand* is not selected, the surface albedo at *aodMainChLand* exceeds the surface albedo in *aodBrightChLand* by not more than *maxAlbDiffMainBright* and the surface albedo in *aodMainChLand* is below *maxAlbedoAodLand*, PMAp selects *aodMainChLand*
- If *aodMainChLand* and *gomeCloudChLand* is not selected and the surface albedo at *aodBrightChLand* is below *maxAlbedoAodLand*, PMAp selects *aodBrightChLand.*
- If no channel could be selected within the previous steps, the algorithms stops with error due to too high surface albedo. This may happen for some pixels over Sahara and pixels with seasonal snow coverage

3.4.1 Homogeneity test

Different to the retrieval of the ocean, it cannot be assumed that the surface is homogeneous over the whole GOME-2 PMD pixel. It has to be assumed that the surface can show a heterogeneity in the albedo which is not reflected by the surface albedo database. As inhomogeneity has also to be assumed for the cloud, a reasonable homogeneity is required for the aerosol.

PMAp limits the retrieval to pixels which show a reasonable homogeneity for the cloud free part in at least one VIS/NIR AVHRR channel (channel 1, 2 or 3A). The retrieval compares three potential cloud free reflectances as defined in sect. 3.1.2.2: Cloud Free Unclassified aerosol, Cloud Free Coarse Mode Aerosol and Cloud Free Fine Mode Aerosol. For each AVHRR channel a threshold for the maximum difference between the three clear sky reflectances is defined.

Pixels with heterogeneous aerosol layer may be removed by the retrieval at that point. There are two exceptions: 1.) Pixels with positive detection of thick aerosol events. The homogeneity test is ignored for these cases. 2.) Aerosols with small particles (or weak coarse mode) over a surface with homogeneous albedo. The homogeneity test is passed for AVHRR CH3A for these cases.

3.4.2 Retrieval scheme for the set of AOD over land

The AOD is interpolated in the band selected in step 2B above. For each pixel the LUT is interpolated to the actual observation geometry (see sect. 3.2.3). In addition, the LUT is linear interpolated for the surface albedo taken as an input from climatology. An interpolated LUT for the actual footprint is obtained, which describes the measured reflectance as a function of the AOD only. A spline interpolation is used to retrieve the AOD. For clear-sky pixels this interpolation is applied to the measured PMD reflectance. For partly cloudy pixels, this interpolation is applied to cloud corrected PMD reflectances. The cloud correction of the reflectances is described in sect. 3.1.7 and 3.1.7.2 (dependent on the selected channel)

3.5 Step 3: Improving the AOD using different aerosol models

In step 2 a set of AODs for different microphysical properties is calculated by using one channel only. The final step is to select the most appropriate out of this using a lot of bands in reflectance and stokes fraction.

The fit is performed using the equation:

$$\chi^2 = \frac{\sum_O \frac{(R_{PMD} - R_{modelled})^2}{R_{modelled}} + \sum_P \frac{(q_{PMD} - q_{modelled})^2}{q_{modelled}}}{O + P}$$

where O is a selection of PMD bands in reflectance and P a selection of bands in stokes fraction.

3.5.1 Specific aspects of the fit over ocean

- The fit is performed for the bands defined in *microFitRefChOcean* (reflectances) and *microFitStoChOcean* (stokes fraction). The Stokes fractions are included only if the expected Rayleigh Stokes fraction predicted by the LUT passes a lower threshold.
- The cases included to the fit depends on the aerosol pre-classification using AVHRR (see sect. 3.1, in particular Table 4).
- The best fit is compared to the default model. The best fit is taken as a result only if the fit is signifantly better than the default model. Otherwise the default model is used. The best fit is taken if the χ^2 of the default case exceeds the best case by a pre-defined value.

- This scheme is applied for clear sky pixels only (retrieval scheme 1 & 3 in step 2). For partly cloudy pixels, the fit is not applied. In the latter case the aerosol model depends on the aerosol type retrievals of stage 1. One default model is defined for each aerosol class

3.5.2 Specific aspects of the fit over land

- The fit is performed for the bands defined in *microFitRefChLand* (reflectances) and *microFitStoChLand* (stokes fraction). The Stokes fraction are included only if the expected Rayleigh stokes fraction predicted by the LUT passes a lower threshold.
- For the land retrieval in all cases a fixed set of models is included to the retrieval. The set of models is defined in sect 3.2.2.
- The best fit is compared to the default model. The best fit is taken as a result only if the fit is significantly better than the default model. Otherwise the default model is used. The best fit is taken if the χ^2 of the default case exceeds the best case by a pre-defined value.
- The default model is based on AVHRR TIR measurements (see sect. 3.1.5)
- The full fit is performed for clear sky pixels only. For partly cloudy pixels stokes fractions are excluded and a subset of the bands in reflectances is used only. For partly cloudy pixels, the fit is applied to cloud corrected reflectances (see sect. 3.1.7.2 and 3.1.7).
- If the fit over the reflectances is too bad, the measurement is excluded and no AOD is plotted. This happens for an extremely small amount of measurements only (<0.05%).

3.6 Retrieval flags of the aerosol retrieval

The PMAp aerosol product delivers a set of up to 16 (currently: 7) retrieval flags. A positive retrieval flag does not mean a general bad quality of the retrieval (bad retrievals are filtered out automatically and bad inputs are accessible by the quality flags). The quality flags are delivered as an integer and need to be converted to the binary system by the user.

Example: quality flag 50 = 0110010.

Bit 0	*Large cloud contribution to the signal (correction factor low) over sea*

The cloudy part is much brighter than the clear-sky part which enhances the error caused by the different shape of the footprints:

$$\frac{\tilde{R}_{AVHRR}(cloudfree)}{\overline{R_{AVHRR}}(all)} \leq qualityMinCorrFactor$$

Usually all unusable pixels are filtered out so that the value is not needed to filter bad AODs. However, for bright clouds we currently assume that the AOD error value could be less accurate due to enhanced collocation issues. This flag could be useful to investigate the AOD error value within the product validation. Note: This flag is not raised over land, because values fulfilling the filter criterion are skipped over land because over land cloud correction and AOD are retrieved at different wavelengths.

Bit 1:	*Observation geometry with typically enhanced errors in the retrieval over sea and land*
A set of pixels close to the limits set for observation angles (SZA, VZA, scattering angle). For applications specifically analysing dependencies on observation geometry this flag should be applied together with bit 3 and bit 4. As all these effects are taken into account in the AOD error appropriately and unusable values are thrown away, this flag needs not be applied for stardard-users of AOD or for assimilation.	

Bit 2	*Measured signal exceeds upper or lower limits over sea and land*
AOD is set to *minAod* or *maxAod*, but the mathematically retrieved AOD is lower than *minAod* or higher than *maxAod*. Can be important for comparisons to other retrievals, if there is a systematic bias & slope, as the artificial setting to *minAod* /*maxAod* has an impact on the correlation. AOD values lower than 0 can appear caused by overestimation of the surface reflectance.	

Bit 3	*Limitation in aerosol type preclassification over sea, in particular fine/coarse mode classification.*
The expected clear-sky and aerosol free reflectance is large compared to the total signal for a sea salt aerosol with an optical depth of 0.3 The AVHRR preclassifiation fine/coarse mode is not available and dust detection is limited for small optical depth as well. This is reflected in the AOD error, the flag should not be used for most application of the AOD. The quality flag may be used if 1.) the aerosol class/type is used 2.) if one is looking specifically for volcanic ash because there is a higher risk that ash is undetected (misclassified as cloud).	

Bit 4	*Signal has an enhanced dependence on the actual wind speed*
Uncertainty in wind speed impacts results, to be used together with Bit 1: $\frac{\lvert R_{clear}(v_{wind}[\max]) - R_{clear}(v_{wind}[\min])\rvert}{R_{aerosol}(v_{wind}[meas.]) - R_{clear}(v_{wind}[meas])} > qualityMaxWindSensThre$ The error of this effect is appropriately reflected within the AOD error column, the interesting point of this flag is a known systematic effect dependent on the viewing geometry.	

Bit 5	*Bad fit*
The fit over all PMD bands (stokes fraction & reflectances) are bad. However, as some of the fitted bands - in particular all stokes fraction - are available for clear-sky pixels only, this flag is useful only if one limits the application to completely clear-sky pixels because the fit over partly cloudy pixels is usually good because of the large overestimation of the system. As two third of the pixels are partly cloudy and the AERONET comparisons also don't show a big decrease of the quality for partly cloudy pixels, it is usually not recommended to use this as a filter. One should also be aware, that the limitation to	

completely clear sky pixels could maybe systematically remove thick aerosols (e.g. dust aerosols)

Bit 6	*Thick aerosols*
Pixels are detected as aerosols, but AVHRR sees cloud fraction above limits. Flag regularly raised for thick dust and volcanic ash. Higher risk for AOD overestimation due to undetected cloud. If one is interested in the AOD of an individual measurement, flag should not be used. Could be useful for time series or creation of climatologies to exclude single events with large AOD.	

3.7 Error calculation

The error is calculated as a standard deviation of a set of AODs obtained using the manipulation of inputs or intermediate results. We retrieve a randomized error, which does not include errors which introduce a constant offset or slope to the result. This statistical approach is selected to provide an error suitable for assimilation purposes.

The inputs and intermediate results manipulated to retrieve a set of AODs for the error calculation are different for the retrieval over ocean and land. In both cases the following parameters are varied:

- the cloud correction factor. The maximum and minimum values are obtained from the scatter between averaged AVHRR reflectances and the GOME-2 reflectance (standard deviation of the linear fit).
- The solar zenith angle, the relative azimuth angle, the viewing zenith angle (the two nearest neighbours are used instead of the values of the actual measurements)
- The aerosol model. All models included to the fit (sect. 3.5) are used

Over ocean, variations are included in addition for:

- The wind speed
- The chlorophyll pigment concentration

Over land, variations are included in addition for

- Errors in the surface albedo (the surface albedo is manipulated by a pre-defined offset and/or a pre-defined factor which should be chosen with respect to the expected error in the database.

At least 30 different AODs (under different assumptions) need to be calculated to retrieve an error of the AOD. If this is not possible (e.g. because of retrieval failures), no AOD error is calculated, but the retrieved AOD may not be accurate for these cases.

4 ADDITIONAL PRODUCTS (DEMONSTRATIONAL)

This section describes a set of additional parameters which are added as unofficial products. These products are currently not validated. Verification is based on small datasets and performed using a qualitative approach.

4.1 Cloud optical depth

Cloud optical depth is retrieved using single band retrieval (*codMainCh*). It is assumed that surface and aerosol are homogeneous across the PMD pixel and that the difference between the reflectance of the PMD and the reflectance of the subpixel used in the aerosol retrieval is caused by cloud contamination. This is not always true because inhomogeneities in the surface reflectance or the aerosol load may be interpreted as cloud contamination.

The reflectance of the cloud free part is determined by the reflectance used for the aerosol inversion. This value is taken from the calculations described in sect.3.1.7. The relative amount of AVHRR pixels used for the determination of this clear-sky part is used to determine a geometric cloud fraction discriminating the cloud free and cloud contaminated part of the pixel (PMAp cloud fraction) as described in sect. 3.1.6.

The clear-sky (cloud free) reflectance is used to invert an "effective albedo" using a RTM based LUT dependent on observation geometry. The effective albedo is the albedo of a lambertian reflector at the surface, which gives the same TOA reflectance as the surface together with the aerosol. The albedo inversion from measurements is retrieved for geometric cloud fractions below 0.7 only. For high cloud fractions over ocean, the effective surface albedo is retrieved using modelled reflectances from the LUT of the aerosol retrieval (Section 0). The modelled reflectances are calculated dependent on observation geometry and wind speed from ECMWF forecast. In the case of high cloud fractions over land, the surface albedo is taken from climatology.

The cloudy reflectance is retrieved from the averaged reflectance of the PMD, the PMAp cloud fraction and the retrieved cloud free reflectance using the independent pixel approximation:

$$R_{cloud} = \frac{R_{PMD} - (1 - CF) * R_{clear}}{CF}$$

The COD is retrieved from the calculated cloudy radiance using an inversion algorithm with a similar approach as for aerosols. The LUT is interpolated to the actual geometry for all COD and effective albedos in the database (Section. 3.2.3). The effective albedo is estimated from the clear-sky input reflectance using cubic spline interpolation. Afterwards the LUT is interpolated to the retrieved effective albedo using linear interpolation. The result is a function of the cloudy reflectance dependent on the COD for the observation geometry and effective albedo of the pixel. This is used to invert the cloud optical depth using cubic spline interpolation.

Note: The retrieval is done in *codMainCh*, but the COD is reported at 550nm to be consistent with the AOD retrieval. This does not make much different because the spectral dependence of the measured cloudy reflectance is weak. However, we correct for the different wavelengths using a Henyey-Greenstein phase function.

Cloud optical depth is not retrieved under the following conditions:

1.) if the surface reflectance is large compared to the cloud reflectance
2.) if problems are expected for a given observation geometry
3.) for areas with persistent seasonal snow/ice coverage. Persistent snow/ice coverage is estimated from the surface albedo climatology [Popp et al., 2011] using the following criteria:
    a.) if the surface albedo is high for high wavelengths over ocean, sea ice is assumed
    b.) if the surface albedo is high for low and high wavelengths over land and the wavelength dependency of the albedo is significantly smaller than expected for deserts, persistent seasonal snow/ice coverage is assumed.

The RTM data used for the COD inversion is based on the libRadTran package together with the DISORT solver [RD-1].

The PMAp COD product delivers a set of up to 8 (currently 4) quality flags. The quality flags are a set of bits indicating good quality (0) or reduced quality (1). In netCDF products, an integer value is currently delivered which needs to be converted to the binary system by the user.

Bit 0	*Low accuracy fir actual observation geometry*
An increased error is expected for the observation geometry of the measurement (SZA, VZA, and RAZI). These conditions are defined *by qualityMaxSza, qualityMaxVza and qualityMaxAbsCosRazi*.	

Bit 1	*Albedo retrieval failed, albedo taken from climatology*
The surface albedo is not taken from the individual measurement because the cloud fraction is too large. If this flag is raised, an enhanced error is expected for low COD over bright surfaces.	

Bit 2	*Large error due to a significant impact of the surface on the retrieval*
The expected or retrieved contribution of the surface to the total signal is large: the ratio of the clear-sky AVHRR reflectance and the cloudy AVHRR reflectance is larger than qualityCloudClearImpact. This leads to lower accuracy of the retrieved COD.	

Bit 3	*Sun glint*
Sun glint test positive using the criteria of the GOME-2 Level 1 product.	

4.2 Cloud-top temperature

The cloud top temperature is not considered as a final product, but introduced for validation purposes only. It may nevertheless provide some meaningful data.

The average radiances of the cloudy AVHRR pixels are calculated for AVHRR channel 4 and 5. The brightness temperature calculated from AVHRR channel 4 is given as cloud top temperature if the following criteria are fulfilled:

1.) The brightness temperature difference between channel 4 and channel 5 is lower than 100K (black body test)
2.) The impact of the surface reflectance to the total signal is small in the visual wavelength range. This is assumed to be fulfilled if the surface-related quality flags in the COD retrieval are not raised.

4.3 Radiance inhomogeneity

The standard deviation of all AVHRR channel 1 reflectance within the GOME-2 PMD pixel is calculated and plotted to the output.

This may be useful for the user as indicator of the homogeneity or inhomogeneity of the pixel in the visual spectral range.

4.4 T4-T5 difference

The radiances in AVHRR channel 4 and AVHRR channel 5 within the GOME-2 pixel are averaged. The averaged values are transformed to brightness temperatures using the formulas suggested in [AD2]. The difference between the brightness temperature from AVHRR channel 4 and AVHRR channel 5 are plotted to the output.

This may be useful to interpret specific scenes because the BTD is sensitive to dust/ash (negative values) and cirrus clouds (positive values).

5 I/O DATA OF THE AEROSOL ALGORITHM

5.1 Input Data

This section contains a list of required input data for PMAp.

- Thick and non-italic points are already technically included in PMAp version 1 but not loaded in the ground segment. They will be loaded in PMAp 2.
- Thick, italic and red points are required for PMAp2 but not included to the PPF release1. They are added for PMAp release 2
- The remaining inputs are already used in PMAp1

5.1.1 Setup required at the start of the algorithm (one time):

- LUT database for reflectance and stokes fraction over ocean (PMD6-15).
- LUT database for one PMD band describing reflectances dependent on solar zenith angle, zenith viewing angle, relative azimuth angle, lambertian surface albedo and cloud optical depth.
- LUT database for reflectances and stokes fractions over land (PMD6-15).
- LUT database for the Aerosol Absorbing Index (AAI)
- MERIS Surface albedo database
- GOME-2 LER surface albedo database
- ANGULAR ALBEDO COEFFICIENTS
- Land-sea mask (used as a backup only, if AVHRR information is not available).
- Surface elevation database.
- configuration parameter file.

5.1.2 Inputs required from the GOME-2 level-1 data (on-going):

- Reflectance of 15 PMD bands (currently only a subset is in use, but the input of 15 values is foreseen in the device)
- Solar reference of 15 PMD bands
- Stokes fractions of 15 PMD bands
- Solar zenith angle (SZA)
- Viewing zenith angle (VZA) as defined in GOME-2 Level 1 product
- Satellite azimuth angle as defined in GOME-2 Level 1 product
- Solar azimuth angle as defined in GOME-2 Level 1 product

5.1.3 Inputs required for the collocation algorithm

These parameters are required as input to the collocation algorithm to provide co-located data as described below:

- Land-/sea flags (from AVHRR Level-1)
- Wind speed for the given scene taken from ECMWF forecast
- AVHRR cloud flags (2 x 4 tests from AVHRR Level 1b per AVHRR pixel)
- AVHRR reflectance channel 1, 2, 3A

- AVHRR brightness temperature channel 4 & 5
- IASI Level 1 input (at least 10 channels)
- ETOPO5 surface elevation database

5.2 Co-location and spatial resolution

The spatial resolution of the product is determined by the PMD bands of GOME-2. Input data from other detectors, instruments or datasets have to be collocated to GOME-2 PMD.

The collocation algorithms provide the following information collocated to a GOME-2 PMD pixel:

- Land-/Sea flag
- 10-m-wind speed
- AVHHR cloud albedo test (co-located to GOME-2 PMD as fractional coverage)
- AVHRR T4 test (co-located to GOME-2 PMD as fractional coverage)
- AVHRR T4T5 test (co-located to GOME-2 PMD as fractional coverage)
- AVHRR uniformity test (co-located to GOME-2 PMD as fractional coverage)
- AVHRR average radiance (all channels, brightness temperature for channel 4 and 5)
- AVHRR clear sky radiance: all clear sky radiances dependent on aerosol class described in sect. 3.1.2.2 (all channel, brightness temperature for channel 4 and 5).
- AVHRR radiance: average of the clear-sky pixels within GOME-2 PMD (all channels, brightness temperature for channel 4 and 5)
- AVHRR average cloudy radiance (channel 1 & 2, average of all AVHRR pixels classified as cloudy within the GOME-2 PMD)
- AVHRR average brightness temperature difference (T(channel4) – T(channel5))
- AVHRR radiances/BTD of all channels for the pixel with the highest negative brightness temperature difference within the PMD footprint $(T4\text{-}T5)_{min}$
- IASI radiances & brightness temperatures at up to 10 waveneghths in the TIR
- IASI geometric data: latitude, longitude, solar zenith angle, viewing angle, relative azimuth angle
- IASI cloud fraction: AVHRR cloud flags collocated to IASI
- Classification land/ocean taken from AVHRR Level-1 data (co-located to GOME-2 PMD as fractional land cover)

5.3 Output

The output is provided in EPS native and netCDF format and contains the retrieved aerosol parameters as well as correspondent input parameters required for the users. This Section summarizes the parameters obtained from the retrieval or auxiliary data. Note, that the table gives an overview about the important parameters with respect to physical relevance. If a complete list or a technical description is required, the Product format specification [AD 8] should be used.

The output product contains an aerosol and a cloud Section. Both Sections refer to (slightly) different geolocations, because there is a shift in geolocation between the different PMD bands. The retrieval usually combines different bands. The plotted values refer to the channel with the largest impact on the result (aodRefCh, altAodRefCh, altAodStoCh or codMainCh). The cloud fraction can be slightly different for the AOD and the COD retrieval due to the spatial shift of the PMD footprint.

5.3.1 Aerosol section

Parameter	***Description***
aerosol_optical depth	Aerosol optical depth at 550nm retrieved for the GOME-2 PMD ground pixel.
error_aerosol_optical_depth	Error of the AOD retrieved
aerosol_class	0: no dust / fine mode (ocean) 1: coarse mode (ocean) 2: thick Biomass burning 3: desert dust 4: volcanic ash/thick dust 5: volcanic ash with SO_2 10: Aerosol contaminated cloud 11: Ash contaminated cloud 15: no classification
flag_ash	0: no ash 1: ash 15: no classification
pmap_geometeric_cloud_fraction	Cloud fraction co-located with PMD pixel (corners corrected according to the time shift of the reference PMD band used for aerosol properties retrieval) as used for AOD PMAp for cloud-screening.
chlorophyll_pigment_concentration	Chlorophyll pigment concentration in mg/m^3 (ocean, clear sky)
quality_flags_aerosol	Quality flags of the aerosol product (1=problem found, 0=no problem detected). We provide the following flags: 1. Large cloud contribution to the signal (correction factor low) over sea 2. Observation geometry with typically enhanced errors in the retrieval over sea and land. 3. Measured signal exceeds upper or lower limits over sea and land 4. Limitation in aerosol type preclassification over sea, in particular fine/coarse mode classification. 5. Signal has an enhanced dependence on the actual wind speed 6. Bad fit 7. Thick aerosols
retrieval_algorithm	Retrieval algorithm used by the AOD retrieval 0: ocean, main retrieval for clear-sky pixels (Section. 3.3.2) 1: ocean, simplified retrieval for partly cloudy pixels (Section 0) 2: ocean, alternate retrieval, AOD from reflectance (Section. 3.3.4) 3: ocean, alternate retrieval, AOD from stokes fraction (Section. 3.3.4) >3: land, not implemented 4: land, daek surfaces, cloud free 5: land, normal mode, cloud free 6: land, bright surfaces, cloud free

	7: land, dark surfaces, partly cloudy 8: land, normal mode, partly cloudy 9: land, bright surfaces, partly cloudy 15: no retrieval
avhrr_geometric_cloud_fraction	Geometric cloud fraction retrieved from AVHRR pixels inside the GOME-2 pixel.
flag_cirrus_cloud	Flag indicating the presence of cirrus clouds based on AVHRR measurements
flag_snow_ice	Flag indicating if a pixel is partly or completely covered by snow or ice. The flag is derived from the AVHRR cloud product.
split_window_btd	Average brightness temperature of AVHRR channel 4 and AVHRR channel 5
wind_speed	10m wind speed from ECMWF forecast [m/s]
land_fraction	Fractional coverage of land surfaces within the PMD
reflectance_inhomogeneity	Variance of the reflectances in AVHRR channel 1 within the GOME-2 PMD pixel.

5.3.2 Cloud section

Parameter	*Description*
COD	Cloud optical depth retrieved for the GOME-2 PMD ground pixel.
CLOUD_TOP_TEMPERATURE	Cloud top temperature from AVHRR channel 4
QUALITY_FLAG_COP	Quality flags of the cloud product (1=problem found, 0=no problem detected). We provide the following flags: 0: low accuracy for the actual observation geometry 1: albedo retrieval failed, surface albedo taken from climatology 2: large error due to significant impact of the surface on the result 3: sun glint
AVHRR_CLOUDFRACTION-_COP	Geometric cloud fraction retrieved from AVHRR pixels inside the GOME-2 footprint.
LAND_FRACT_COP	Fractional coverage of land surfaces within the PMD
RADIANCE_-INHOMOGENEITY_COP	Variance of the radiances in AVHRR channel 1 within the GOME-2 PMD pixel.

6 CONFIGURATION AND SPECIFIC INSTRUMENT CALIBRATION CORRECTIONS FOR PMAP

This section summarizes

- Specific instruments calibrations used for PMAp which are not part of the operational Level-1 products for GOME-2, AVHRR and IASI.
- Description of the configuration using an external parameter file in XML format which adjusts the retrieval algorithm to the requirements of a specific instrument or conditions. PMD bands are labelled from 0–14 (ordered by wavelengths, starting with the lowest wavelengths). AVHRR channels are from 0–4 (1,2, 3A/B, 4, 5).

6.1 Description of the parameters

6.1.1 Global aerosol retrieval parameter (land and ocean)

Parameter name	*Type*	*Description*
lowAodFail	float	If the retrieved AOD is below this threshold, a retrieval failure is assumed.
upAodFail	float	If the retrieved AOD is above this threshold, a retrieval failure is assumed.
minAod	float	Lowest possible AOD. If a retrieved AOD is below this value without retrieval failure, the AOD is set to this value.
maxAod	float	Highest possible AOD. If a retrieved AOD is above this threshold without retrieval failure, the AOD is set to this value.
landFractTh	float	maximum percentage of land surfaces within the PMD to apply the ocean-type aerosol retrieval algorithm
albOceanTestCh	int	selects a band used to detect persistant high surface reflectance from the albedo climatology over ocean
albedoOceanThre	float	If the albedo taken from climatology is above this threshold (in band *albOceanTestCh*), the pixel is considered to be covered by sea ice (no AOD retrieval)
lowAlbedoClimTestCh	float	First albedo map (lower wavelengths) to check the albedo climatology for persistent snow-/ ice coverage
highAlbClimTestCh	int	Second albedo map (higher wavelengths) to check the albedo climatology for persistent snow-/ice coverage
lowAlbClimTestThre	float	Minimum albedo in *lowAlbClimTestCh* to consider a pixel in the surface albedo database to be affected by snow/ice.
albClimTestRat	float	Maximum ratio between the albedo in *highAlbClimTestCh* and *lowAlbClimTestCh* to consider a pixel in the surface albedo database to be affected by snow/ice.
fAvhrrReadCoeffFrom Product	int	If this parameter is set to 1, scaling and calibration coefficients for AVHRR are taken from the Level-1 file instead of using this parameter file.
avhrrCh4Const1	float	Constant for brightness temperature calculation for AVHRR channel 4 (see [L1AVH])
avhrrCh4CentralWl	float	Central wavelength for AVHRR channel 4 (see [L1AVH])
avhrrCh4Const2Slope	float	Slope used in the brightness temperature calculation for channel 4 (see [L1AVH])
avhrrCh5Const1	float	Constant for brightness temperature calculation for AVHRR channel 5 (see [L1AVH])

Parameter name	*Type*	*Description*
avhrrCh5CentralWl	float	Central wavelength for AVHRR channel 5 (see [L1AVH])
avhrrCh5Const2Slope	float	Slope used in the brightness temperature calculation for channel 4 (see [L1AVH])
avhrrConstC1	float	AVHRR constant C1 in brightness temperature conversion (see [L1AVH])
avhrrConstC2	float	AVHRR constant C2 in brightness temperature conversion (see [L1AVH])
qualityT1Sunglint	float	T1 threshold for sunglint detection using formula from the Level-1 Product Format Specification.
avhrrColocStdDev	float	Standard deviation of AVHRR reflectances collocated to GOME-2 within the the correlation to GOME-2 PMD reflectances. This value is used to estimate the impact of the collocation uncerteinties to the error of the AOD
avhrrSortChannel	float	Channels and their order used for the outlier correction (calculation of median-corrected averages, see sect. 3.1.2.2 a.)
minAmountMeasHomo	float	Minimum amount of remaining measurements for successful homogenization/outlier corrections (if e.g. outliers are removed, this value is the minimum amount of remaining measurements to retrieve an AOD)
varianceVisHomoVisIR	float	Maximum variance in the visual spectral range (AVHRR CH1) to skip pixels in the VisIR homogenization (pixels are skipped, if variance is high in the IR and low in the VIS)
varianceIRHomoVisIR	float	Minimum variance in the thermal infrared (AVHRR CH 4) to skip pixels in the VisIR homogenization (pixels are skipped, if variance is high in the IR and low in the VIS)
maxR4CleanedVariance	float	Maximum variance in AVHRR CH4 after application of R4 homogenization (skipping coolest pixels until variance falls below the threshold)
maxR3CleanedVariance	float	Maximum variance in AVHRR CH3A after application of R3 homogenization (skipping coolest pixels until variance falls below the threshold)
albedoChannel1	float[]	First MERIS albedo map used (one entry for each PMD band)
albedoChannel2	float[]	Second MERIS albedo map used (one entry for each PMD band)
albedoWeighting	float[]	Weighting of the first and the second albedo map (one entry for each PMD band)

6.1.2 Parameters for the aerosol retrieval over ocean

Parameter name	*Type*	*Description*
aodRefChOcean	int	PMD band used for the retrieval of the AOD in the main retrieval over ocean (Section. 3.3.2). The channel should be at the red edge or the NIR.
chlUvRefChOcean	int	PMD band used for chlorophyll detection based on absorption in the UV (main retrieval Section. 3.3.2)
chlVISRefChOcean	int	PMD band used for chlorophyll detection based on increased ocean surface reflectance in the VIS range (main retrieval Section. 3.3.2)
altAodRefChOcean	int	PMD band used for AOD retrieval using PMD reflectance within the alternate retrieval (Section. 3.3.4)
altAodStoChOcean	int	PMD band used for AOD retrieval using PMD stokes fraction within the alternate retrieval (Section. 3.3.4)
avhrrMainChOcean	int	AVHRR channel used for cloud correction of the reflectance in combination with the aodRefCh. It is recommended to use a band close to aodRefCh.
gridIncFacOcean	float	The grid size provided by the input LUT for q and I can be increased by this factor for a χ^2-minimization described in Section. 3.3.2 to estimate chlorophyll load and the starting value of the AOD. The new grid points are calculated by linear interpolation between the grid points provided within the LUT database.
chi2RefChRef3Ocean	int[]	A vector of bands which is used to calculate the χ^2-difference in reflectance within the alternate retrieval (Section. 3.3.4). This set is used, if the AOD is calculated from the reflectance in the altAodRefCh band.
chi2StoChRef3Ocean	int[]	A vector of bands which is used to calculate the χ^2-difference in stokes fraction within the alternate retrieval (Section. 3.3.4). This set is used, if the AOD is calculated from the reflectance in the altAodRefCh band.
chi2RefChStoOcean	int[]	A vector of bands which is used to calculate the χ^2-difference in reflectance within the alternate retrieval (Section. 3.3.4). This set is used, if the AOD is calculated from the stokes fraction in the altAodStoCh band.
chi2StoChStoOcean	int[]	A vector of bands which is used to calculate the χ^2-difference in stokes fraction within the alternate retrieval (Section. 3.3.4). This set is used, if the AOD is calculated from the stokes fraction in the altAodStoCh band.

Parameter name	***Type***	***Description***
chi2RelTestThreOcean	int[6]	Upper thresholds in chi2RefChRef3, chi2StoRefRef3, chi2RefChRef3+chi2StoRefRef3 (alternate retrieval with reflectance, index 0,1, and 2) and chi2RefChSto3, chi2RefSto3, chi2RefChSto3+chi2StoChSto3 (alternate retrieval wit stokes fraction, index 3,4 and 5). A retrieved AOD is considered to be reliable only if the threshold tests for the selected retrieval method are passed.
aodRefGridPointOcean	int	Grid point in the AOD, which determines the default AOD used by the algorithm for sensitivity analysis (impact of wind speed, surface etc.). This AOD is used in the formula of Section. 3.2.3
minAerSurRatModeRef3Ocean	float	Maximum impact of the surface to the signal for the alternate retrieval using reflectances. This value is applied as *minaodsignal* in the formula a.) of Section. 3.2.3
minAerSurRatModeStoOcean	float	Maximum impact of the surface to the signal for the alternate retrieval using stokes fractions. This value is applied as *minaodsignal* in the formula a.) of Section. 3.2.3
minAerSurRatMainOcean	float	Maximum impact of the surface to the signal for the main retrieval. This value is applied as *minaodsignal* in the formula a.) of Section. 3.2.3
minStokesOcean	float	Minimum value in predicted stokes fraction (Rayleigh case) to run the alternate retrieval using stokes fractions (Section. 3.3.4)
windSpeedRangeOcean	float[2]	The reflectance difference predicted by the model for these two wind speeds is used to estimate the impact of the windspeed to the signal (index 0: lower wind speed, index 1: higher wind speed).
maxWindSensThreOcean	float	Maximum impact of the wind speed to the measured signal in Rayleigh case. The main retrieval mode requires that the expected relative difference in Rayleigh signal between the wind speeds defined by windSpeedRange is below this threshold. See formula b.) of Section. 3.2.3.
chlDefaultOcean	float	If the chlorophyll is not retrieved by the algorithm this default value is used by the AOD algorithm.
minScatgomeOcean	float	Minimum scattering angle required for AOD retrieval (to avoid retrievals for measurements affected by forward scattering)
minSzaGomeOcean	float	Minimum SZA [deg] to run GOME-2 AOD algorithm
maxSzaGomeOcean	float	Maximum SZA [deg] to run GOME-2 AOD algorithm
minVzaGomeOcean	float	Minimum VZA [deg] to run GOME-2 AOD algorithm
maxVzaGomeOcean	float	Maximum VZA [deg] to run GOME-2 AOD algorithm
minCosRaziGomeOcean	float	Minimum cos(RAZI) to run GOME-2 AOD algorithm

Parameter name	***Type***	***Description***
maxCosRaziGomeOcean	float	Maximum cos(RAZI) to run GOME-2 AOD algorithm
maxLatGomeOcean	float	Maximum latitude [deg] to run GOME-2 AOD algorithm
minLatGomeOcean	float	Maximum latitude [deg] to run GOME-2 AOD algorithm
maxCloudGomeOcean	float[4]	Maximum AVHRR cloud fraction to run GOME-2 AOD retrieval. The cloud fraction threshold has to be set for each AVHRR cloud test separately (0=T4T5 test, 1=T4 test, 2=albedo test, 3=uniformity test)
maxCloudFractOcean	float	Maximum AVHRR cloud fraction to run GOME-2 AOD retrieval (combination of tests used for the correspondent aerosol class)
defAerTypeIndOcean	int	Index of the default aerosol model which is used by the algorithm if a fit of the model is not performed. This parameter gives the index in the *useModel* list.
defDustTypeIndOcean	int	Index of the default dust aerosol model which is used by the algorithm if a fit of the model is not performed, but tests indicate a dust-type aerosol. This parameter gives the index in the *useModel* list.
defAshTypeIndOcean		Index of the default volcanic ash aerosol model which is used by the algorithm if a fit of the model is not performed, but tests indicate a ash-type aerosol. This parameter gives the index in the *useModel* list.
microFitRefChOcean	int[]	Bands in reflectance used to fit the aerosol model (Section. 3.4) for cloud free pixels.
microFitStoChOcean	int[]	Bands in stokes fraction used to fit the aerosol model (Section. 3.4) for cloud free pixels
microFitModeOcean	int	0=retrieval for clear-sky pixels only, 1=retrieval for clear sky and partly cloudy pixels (if cloud fraction is below the thresholds)
chListOcean	int[15]	Each PMD band is addressed to a band number in the LUT (starting from 0 to 15). If the LUT data is not available for some PMDs, the entries should be set to -1 for these bands.
useModelOcean	int[]	List of aerosol models included to the AOD retrieval.
microMinRefOcean	float	Minimum value in reflectance (aodMainCh) of the measurement required to use the reflectance for the selection of the aerosol model. Bands with lower reflectance are excluded.
microMinStoOcean	float	Minimum value in stokes fraction (aodMainCh) of the measurement required to use the stokes fraction for the selection of the aerosol model. Bands with lower (absolute values of the) stokes fraction are excluded.

Parameter name	*Type*	*Description*
defWindSpeedOcean	float	Wind speed used for AOD retrieval, if ECMWF forecast value is not available.
windLimitVisNIRTestsOcean	float	Maximum ratio of the wind speed-dependent TOA Rayleigh signal difference and the aerosol signal to apply pre-classification tests for dust (see also Section. 3.2.3).
minRefRatTypeTestsOcean	float	Minimum ratio of the measured AVHRR reflectance in *avhrrMainCh* and the modelled clear-sky reflectance to apply aerosol type preclassification.
numStrictAshTestsOcean	int	The first *numStrictAshTests* volcanic ash tests are considered as valid for areas where no aerosol type is retrieved.
ashThresholdsOcean	int[60]	Ten tests to detect volcanic ash. Each test contains 6 thresholds. Only one test needs to be passed to classify a pixel as ash. See Section. 0.
dustThresholdsOcean	int[4]	Two tests to detect desert dust. Each test contains two thresholds. Only one test needs to be passed to classify a pixel as dust. See Section. 0.
fineThresholdsOcean	int[6]	Three tests to detect non-dust aerosols. Each test contains two thresholds. Only one test needs to be passed to classify a pixel as non-dust. See Section 0
ashModelOcean	int[8]	Switches on (1) or off (0) aerosol models in the case of volcanic ash classification. Only models switched on are included to the aerosol type fit for clear-sky cases.
dustModelOcean	int[8]	Switches on (1) or off (0) aerosol models in the case of desert dust pre-classification. Only models switched on are included to the aerosol type fit for clear-sky cases.
noDustModelOcean	int[8]	Switches on (1) or off (0) aerosol models in the case of non-dust pre-classification. Only models switched on are included to the aerosol type fit for clear-sky cases.
allModelOcean	int[8]	Switches on (1) or off (0) aerosol models in case no pre-classification was performed. Only models switched on are included to the aerosol type fit for clear-sky cases.
qualityMinCorrFactorOcean	float	Minimum correction factor to convert cloudy to clear-sky reflectance to expect good quality.
qualityMaxSzaOcean	float	Maximum SZA to expect good quality in aerosol retrieval
qualityMaxVzaOcean	float	Maximum VZA to expect good quality in aerosol retrieval

Parameter name	***Type***	***Description***
qualityMaxAbsCosRaziOcean	float	Maximum absolute value |cos(RAZI)| to expect good quality in aerosol retrieval
qualityChi2ClearskyfullLimitOcean	float	Maximum χ^2-difference using the bands microFitRefCloudy and microFitStoCloudy to expect good quality.
qualityMaxWindSensThreOcean	float	Maximum impact of wind speed to the signal (Section. 3.2.3, formula c.) to expect good quality
qualityMinAerSurRatMainOcean	float	Maximum impact of the clear-sky TOA reflectance to the total signal (Section. 3.2.3, formula b) to expect good quality
qualityCloudMaxSzaOcean	float	Maximum SZA to expect good quality in cloud retrieval
qualityCloudMaxVzaOcean	float	Maximum VZA to expect good quality in cloud retrieval
qualityCloudMaxAbsCosRaziOcean	float	Maximum |cos(RAZI)| to expect good quality in cloud retrieval
qualityCloudClearImpactOcean	float	Maximum ratio of clear-sky reflectances and the measured reflectance to expect good quality of the cloud retrieval
qualityMinScatGomeOcean	float	Minimum scattering angle to consider good quality of the retrievals
minAodsForErrorOcean	int	Minimum amount of AODs (calculated for slightly different conditions/assumptions) to calculate a brute force error of the AOD (standard deviation of all AODs calculated)
R3R1CloudFreeDust	float	Minimum ratio AVHRR CH3A/AVHRR CH1 to include a pixel as cloud free for thick dust aerosol type (AVHRR albedo test ignored, AVHRR dust test positive). Currently not used in the retrieval.
R2R1CloudFreeDust	float	Minimum ratio AVHRR CH2/AVHRR CH1 to include a pixel as cloud free for thick dust aerosol type (AVHRR albedo test ignored, AVHRR dust test positive). Currently not used in the retrieval.
relSigChi2DiffOcean	float	Maximum relative difference in χ^2-difference (normalized by average) to consider a fit over different aerosol models as significant (if the aerosol model with the best fit and the second best fit does not differ by at least this value in χ^2-difference (normalized by average), the result of the fit is considered as not significant.
absSigChi2DiffOcean	float	Maximum relative difference in χ^2-difference (normalized by average) to consider a fit over different aerosol models as significant (if the aerosol model with the best fit and the second best fit does not differ by at least this value in χ^2-difference (normalized by average), the result of the fit is considered as not significant.
maxAodDustTest	float	Currently not used
maxAbsErrorOcean	float	Maximum absolute error (if the AOD error is above maxAbsError AND maxRelError, the pixel is skipped)
MaxRelErrorOcean	float	Maximum relative error (if the AOD error is above maxAbsError AND maxRelError, the pixel is skipped)

Parameter name	*Type*	*Description*
clearSkyMaxRelDiffOcean	float	Maximum (relative) reflectance difference between the average of all AVHRR pixels within the GOME-2 pixel and the average of the pixel classified as clear sky to classify the whole GOME-2 footprint as clear sky.
clearSkyMaxAbsDiffOcean	float	Maximum (absolute) reflectance difference between the average of all AVHRR pixels within the GOME-2 pixel and the average of the pixel classified as clear sky to classify the whole GOME-2 footprint as clear sky
dustTestT5T4LengthOcean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
dustTestT5T4OffsetOcean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
dustTestT4maxOcean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
dustTestT4minOcean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
dustTestColorAngleConst1Ocean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
dustTestColorAngleConst2Ocean	float	Parameter in the AVHRR dust test, see sect. 3.1.1.5
minClearDust	float	currently not used
minIRClearDust	float	currently not used
maxLandFractOcean	float	Maximum fractional land coverage to process PMAp algorithm for AOD over ocean
maxSnowIceFracOcean	float	Maximum part of the pixel covered by snow/ice to allow a retrieval (correction scheme identical to cloud)
minClearSkyFracOcean	float	Minimum ratio of AVHRR pixels within the GOME PMD pixel classified as completely cloud free to perform a retrieval (threshold applied after all cloud and homogeneity tests, no applicable for thick events with cancelled AVHRR cloud filter)

Table 6: Aerosol Algorithm External Parameter File: Type and Description

6.1.3 Parameters for the aerosol retrieval over land

Parameter name	*Type*	*Description*
chListLand	int[15]	Each PMD band is addressed to a band number in the LUT (starting from 0 to 15). If the LUT data is not available for some PMDs, the entries should be set to -1 for these bands.
aodRefChOcean	int	PMD band used for the retrieval of the AOD in the main retrieval over land. The channel should be between 400 and 500nm. The channel is used if the albedo is too high in gomeCloudChannel.
aodRefChBrightLand	int	PMD band used for the retrieval of the AOD if the surface albedo in aodRefChLand and gomeCloudChLand is too high.
gomeCloudChLand	int	PMD band overlapping with the AVHRR channel used for cloud correction
avhrrCloudChLand	int	AVHRR channel for cloud correction oberplapping with gomeCloudChLand
useModelLand	int[]	List of aerosol models included to the AOD retrieval.
maxAlbDiffLongChLand	float	Maximum exceed of surface albedo in aodCloudChLand compared to aodRefChLand to select aodCloudChLand for the interpolation of the AODs
minAlbDiffShortChLand	float	Minimum exceed of surface albedo in aodRedChLand compared to aodRefChBrightland to select aodRefChBrightLand for the interpolation of the AODs
maxRadChi2PerChLand	float	Maximum χ^2 difference per channel for reflectances (excluding stokes fractions) to consider an AOD retrieval as reasonable. Retrieval results not fulfilling this threshold are skipped.
minT4ForDustDefaultLand	float	Minimum brightness temperature from AVHRR ch4 to allow the selection of dust aerosols as default model
minBTDForDustDefaultLand	float	Maximum brightness temperature difference between AVHRR ch4 and AVHRR ch5 to allow the selection of dust aerosols as default model
maxCFOptDiffCh1Land	float	Maximum difference between two selections of potential cloud free pixels to classify the cloud free part as homogeneious in channel 1
maxCFOptDiffCh2Land	float	Maximum difference between two selections of potential cloud free pixels to classify the cloud free part as homogeneious in channel 2
maxCFOptDiffCh3ALand	float	Maximum difference between two selections of potential cloud free pixels to classify the cloud free part as homogeneious in channel 3A

Parameter name	*Type*	*Description*
minCloudCorrFactorShortLand	float	Minimum correction factor for cloudy radiances (in the band the AOD is interpolated) to allow AOD retrieval if the AOD is interpolated aodRefChLand or aodRefChBrightLand
minCloudCorrFactorLongLand	float	Minimum correction factor for cloudy radiances gomeCloudCh to allow AOD retrieval if the AOD is interpolated in gomeCloudCh
aodForCloudlayerLand	float	AOD assumed for the cloud layer (thick, bright cloud) in the cloud correction of PMD reflectances
BadFitLimRefLand	float	maximum χ^2 difference per band for reflectances to consider a fit as reasonable
BadFitLimStoLand	float	maximum χ^2 difference per band for stokes fractions to consider a fit as reasonable
maxCloudGomeLand	float[]	Maximum cloud fraction for the individual AVHRR cloud tests to allow AOD retrieval for cases not detected as thick aerosol event
ashThresholdsLand	int[1]	Threshold in brightness temeperature difference (AVHRR ch4 and ch5) to classify a pixel as volcanic ash/ thick dust
microFitRefChLand	int[]	List of reflectance bands used for the fit of the best aerosol type / microphysical properties for cloud free cases
microFitStoChLand	int[]	List of stokes fraction bands used for the fit of the best aerosol type / microphysical properties for cloud free cases
microFitRefChCloudyLand	int[]	List of reflectance bands used for the fit of the best aerosol type / microphysical properties for partly cloudy cases
minStoFitLand	Float	Minimum (absolute value of) stokes fraction (modelled for clear-sky, aerosol free atmosphere) to include stokes fractions to the fit of the aerosol type
defAerTypeIndLand	int	Index of the default non-dust aerosol model which is used by the algorithm. This parameter gives the index in the *useModelLand* list.
defDustAerTypeIndLand	int	Index of the default dust aerosol model which is used by the algorithm. This parameter gives the index in the *useModelLand* list.
allModelLand	Int[]	Switches on (1) or off (0) aerosol models. Only models switched on are included to the aerosol type fit.
relSigChi2DiffLand	float	Minimum relative improvement in χ^2-difference of the model with the best fit compared to the default model to consider the result of the fit as significant solution. If the fit is not significant, the default model is used.

Parameter name	*Type*	*Description*
absSigChi2DiffLand	Float	Minimum absolute improvement in χ^2-difference of the model with the best fit compared to the default model to consider the result of the fit as significant solution. If the fit is not significant, the default model is used.
minScatGomeLand	float	Minimum scattering angle required for AOD retrieval (to avoid retrievals for measurements affected by forward scattering)
minSzaGomeLand	float	Minimum SZA [deg] to run GOME-2 AOD algorithm
maxSzaGomeLand	float	Maximum SZA [deg] to run GOME-2 AOD algorithm
minVzaGomeLand	float	Minimum VZA [deg] to run GOME-2 AOD algorithm
maxVzaGomeLand	float	Maximum VZA [deg] to run GOME-2 AOD algorithm
minCosRaziGomeLand	float	Minimum cos(RAZI) to run GOME-2 AOD algorithm
maxCosRaziGomeLand	float	Maximum cos(RAZI) to run GOME-2 AOD algorithm
maxLatGomeLand	float	Maximum latitude [deg] to run GOME-2 AOD algorithm
minLatGomeLand	float	Maximum latitude [deg] to run GOME-2 AOD algorithm
maxAlbedoMainChLand	float	Maximum albedo in the band the AOD interpolated. If the surface albedo exceed this threshold, no AOD is retrieved.
maxAlbedoFitLand	float	Maximum surface albedo to include a reflectance band into the fit of the aerosol types (bands with higher surface albedo are exclude for the fit in reflectances)
defCloudCorrAlbedoLand	float	Cloud albedo used to correct PMD reflectances for cloud contributions
defCloudCorrPressureLand	float	Cloud pressure used to correct PMD reflectances for cloud contributions
maxCloudFractLand	float	Maximum AVHRR cloud fraction (combination of all cloud tests) to retrieve AOD for cases not detected as thick aerosol event.
minLandFractLand	float	Minimum part of the GOME-2 covered by land surfaces (no water) to allow PMAp retrieval over land
clearSkyMaxRelDiffLand	float	if the relative difference between the average of all AVHRR reflectances and the average of the AVHRR pixels selected as clear sky is below this threshold, a footprint is considered as completely cloud free.
clearSkyMaxAbsDiffLand	float	if the absolute difference between the average of all AVHRR reflectances and the average of the AVHRR pixels selected as clear sky is below this threshold, a footprint is considered as completely cloud free

Parameter name	*Type*	*Description*
maxSnowIceFracLand	float	Maximum part of the pixel covered by snow/ice to allow a retrieval (correction scheme identical to cloud)
minClearSkyFracLand		Minimum ratio of AVHRR pixels within the GOME PMD pixel classified as completely cloud free to perform a retrieval (threshold applied after all cloud and homogeneity tests, no applicable for thick events with cancelled AVHRR cloud filter)
surAlbedoSourceDesert	int	Surface albedo database selection for AOD retreievals over bright surfaces
surAlbedoSourceDark	int	surface albedo database selection for AOD retrieval over surfaces dark at 640nm
surAlbedoSourceMain	int	surface albedo database selection for standard AOD retrieval over land
minAodsForErrorLand	int	miniumum of ensemble values calculated for the AOD error to report the AOD error.
albedoErrorMode	int	selects different options how the error of the surface albedo is estimated within the AOD error calulation
relErrorAlbedoMode0	float	relative error of the surface for albedoErrorMode==0 (applicable if larger than the absolute error)
absErrorAlbedoMode0	float	absolute error of the surface albedo for albedoErrorMode==0 (applicable if larger than the relative error)

6.1.4 Parameters for demonstrational products

Parameter name	*Type*	*Description*
codMainCh	int	PMD band used for cloud optical depth retrieval. The band is compatible with the wavelengths provided by the LUT
avhrrCloudCh	int	AVHRR channel used in combination with codMainCh for COD retrieval.
defOceanAlbedo	float	Effective ocean surface albedo if albedo cannot be retrieved for a particular measurement
minAlbedo	float	Minimum surface albedo considered as a valid value
maxAlbedo	float	Maximum surface albedo considered as a valid value
minCod	float	Minimum COD considered as a valid value
maxCod	float	Maximum COD considered as a valid value

Parameter name	*Type*	*Description*
minSzaCloud	float	Minimum SZA to allow COD retrieval
maxSzaCloud	float	Maximum SZA to allow COD retrieval
minVzaCloud	float	Minimum VZA to allow COD retrieval
maxVzaCloud	float	Maximum VZA to allow COD retrieval
minCosraziCloud	float	Minimum cos(RAZI) to allow COD retrieval
minCosraziCloud	float	Maximum cos(RAZI) to allow COD retrieval
maxLatCloud	float	Maximum latitude to allow COD retrieval
minLatCloud	float	Minimum latitude to allow COD retrieval
minScatCloud	float	Minimum scattering angle required for COD retrieval (to avoid retrievals for measurements affected by forward scattering)
surAlbedoSourceCloud	int	surface albedo database selection for COD retrieval (used over land if albedo is not retrieved from measurement)
maxSnowIceFracCloud	float	maximum part of the pixel covered by snow or ice to perform COD reterieval

6.2 Default Values

If the value of a parameter is not defined (missing parameter file) a default value is used which should give a fairly reasonable result on Metop A using the databases delivered with the software. The hardcoded default values may represent outdated values of the METOP-A retrieval. The values defined for operational retrievals are given in the auxiliary parameters file and may differ from these values both for METOP-A and METOP-B. The values given in this table are used if the auxiliary file is missing or the definition of the parameter in the auxiliary file is wrong. A warning is raised for these cases. It makes sense to analyse the situation if such a warning is raised.

IMPORTANT: ***The default values are hard-coded once for the oldest instruments. They are not updated for new instruments, new scientific developments or technical changes. An external parameter file should always be used. The default values just should prevent the retrieval from a complete failure, but a fall-back to these defaults is always a serious issue for the product quality. This has to be reported to the users and must be fixed immediately. It is recommended to remove data processed with the defaults from the archives.***

6.2.1 Default values for global aerosol processings

Parameter	*Value*
lowAodFail	0.0
upAodFail	5.0
minAod	0.0
maxAod	4.0
landFractTh	0.05
albOceanTestCh	8
albOceanThre	0.1
lowAlbClimTestCh	1
highAlbClimTestCh	9
lowAlbClimTestThre	0.15
albClimTestRat	2
avhrrColocStdDev	0.05
avhrrSortChannel	3 2 1 0
fAvhrrReadCoeffFromProduct	1
avhrrCh4CentralWl	927.20
avhrrCh4Const1	0.5512600
avhrrCh4Const2Slope	0.998509
avhrrCh5CentralWl	837.70
avhrrCh5Const1	0.3471600
avhrrCh5Const2Slope	0.998509
avhrrConstC1	1.191062e-5
avhrrConstC2	1.4387863

Parameter	*Value*
calibSlopeAvhrrCh4	0.0053139
calibSlopeAvhrrCh5	0.00490524
calibOffsetAvhrrCh4	0.0735
calibOffsetAvhrrCh5	0.1051
qualityT1Sunglint	15.0
minAmountMeasHomo	0.1
varianceVisHomoVisIR	0.05
varianceIRHomoVisIR	0.02
maxR4CleanedVariance	0.002
maxR3CleanedVariance	0.002
albedoChannel1	[-1 -1 -1 -1 -1 0 0 0 1 2 4 4 5 7 9]
albedoChannel2	[-1 -1 -1 -1 -1 0 0 0 1 3 4 5 6 8 9]
albedoWeighting	[-1 -1 -1 -1 -1 0 0 0 0 1 0 1 1 1 0]

6.2.2 Default values for aerosol processings over ocean

Parameter	*Value*
aodRefChOcean	12
chlUvRefChOcean	7
chlVISRefChOcean	10
altAodRefChOcean	9
altAodStoChOcean	9
avhrrMainChOcean	0
gridIncFacOcean	10
chi2RefChRet2Ocean	[8, 9, 10, 11, 12, 13, 14]
chi2StoChRet2Ocean	[8, 9, 10, 11, 12, 13, 14]
chi2RefChRet3Ocean	[9, 10, 11, 12, 13, 14, 15]
chi2StoChRet3Ocean	[9, 10, 11, 12, 13, 14, 15]
chi2RelTestThreOcean	[0.04, 0.02, 0.03, 0.15, 0.1, 0.05]
aodRefGridPointOcean	1
minAerSurRatModeRef3Ocean	0.5
minAerSurRatModeStoOcean	0.2
minAerSurRatMainOcean	0.2
minStokesOcean	0.1
windSpeedRangeOcean	[3.0, 12.0]
maxWindSensThreOcean	0.5
chlDefaultOcean	1e-05

Parameter	*Value*
minScatGomeOcean	90
minSzaGomeOcean	0.0
maxSzaGomeOcean	78.0
minVzaGomeOcean	0.0
maxVzaGomeOcean	65
minCosRaziGomeOcean	-1.0
maxCosRaziGomeOcean	1.0
maxLatGomeOcean	75.0
minLatGomeOcean	-75.0
maxCloudGomeOcean	[0.95, 0.95, 0.3, 0.95]
defAerTypeIndOcean	0
defDustTypeIndOcean	5
defAshTypeIndOcean	7
microFitRefChOcean	[7, 8, 9, 10, 11, 12, 13, 14]
microFitStoChOcean	[9, 10, 11, 12, 13, 14]
microFitChCloudyOcean	[14, 1]
microFitModeOcean	0
chListOcean	[-1, -1, -1, -1, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
useModelOcean	[1, 2, 5, 8, 12, 15, 18, 27]
microMinRefOcean	0.002
microMinStoOcean	0.05
defaultWindSpeedOcean	6.0
windLimitVisNirTestsOcean	0.15
minRefRatTypeTestsOcean	1.5
numStrictAshTestsOcean	3
ashThresholdsOcean	-1.6 0.0 0.0 0.0 0.0 0.0, -0.9 0.5 0.5 0.7 0.0 0.0 -0.9 0.5 0.7 0.5 0.0 0.0 -0.7 0.7 0.7 0.7 0.0 0.0 -0.5 0.9 0.8 0.8 0.0 0.0 -0.5 0.0 0.9 0.0 0.0 0.0 -0.5 0.0 0.0 0.9 0.0 0.0 -0.5 0.7 0.7 0.7 0.2 0.0 -0.5 0.0 0.7 0.0 0.2 0.1 -0.5 0.0 0.0 0.7 0.2 0.1
dustThresholdsOcean	1.4 0.7 1.2 0.8
fineThresholdsOcean	0.6 1.0 0.4 1.2 0.2 2.0
ashModelOcean	0 0 0 0 0 1 1 1

Parameter	*Value*
dustModelOcean	0 0 0 0 0 1 1 1
noDustModelOcean	1 1 1 1 1 0 0 0
allModelOcean	1 1 1 1 1 1 1 1
maxCloudFractOcean	0.65
avhrrCloudChOcean	0
maxCloudClearImpactOcean	0.7
qualityMinCorrFactorOcean	0.25
qualityMaxSzaOcean	75.0
qualityMaxVzaOcean	55.0
qualityMaxAbsCosRaziOcean	0.999
qualityChi2ClearskyfullLimitOcean	0.1
qualityMaxWindSensThreOcean	1.0
qualityMinAerSurRatMainOcean	1.0
qualityMinScatGOME-2Ocean	105.0
minAodsForErrorOcean	30
R3R1CloudFreeDust	0.85
R2R1CloudFreeDust	0.85
relSigChi2DiffOcean	1.0
absSigChi2DiffOcean	0.0005
maxAodDustTestOcean	2.0
maxAbsErrorOcean	0.1
maxRelErrorOceam	0.8
clearSkyMaxRelDiffOcean	0.05
clearSkyMaxAbsDiffOcean	0.0002
dustTestT5T4LengthOcean	2.5
dustTestT5T4OffsetOcean	0.5
dustTestT4maxOcean	289.0
dustTestT4minOcean	277.33
dustTestColorAngleConst1Ocean	12.0
dustTestColorAngleConst2Ocean	6.0
minClearDustOcean	0.05
minIRClearDustOcean	0.2
maxLandFractOcean	0.0001
maxSnowIceFracOcean	0.2
maxClearSkyFracOcean	0.2

6.2.3 Default values for aerosol processings over land

Parameter	*Value*
useModelLand	1 1 1 1 1
chListLand	[-1 -1 -1 -1 -1 0 1 2 3 4 5 6 7 8 9]
aodRefChLand	8
aodRefBrightChLand	7
avhrrCloudChLand	0
gomeCloudChLand	12
maxAlbDiffLongChLand	0.015
maxAlbDiffShortChLand	0.015
maxRadChi2PerChLand	0.005
minT4ForDustDefaultLand	285.0
minBTDForDustDefaultLand	0.8
maxCFOptDiffCh1Land	0.003
maxCFOptDiffCh2Land	0.003
maxCFOptDiffCh3Aland	0.003
minCloudCorrFactorLongLand	0.2
minCloudCorrFactorShortLand	0.7
aodForCloudlayerLand	0.1
BadFitLimRefLand	0.02
BadFitLimStoLand	0.05
maxCloudGomeLand	[0.6 0.6 0.3 0.5]
ashThresholdsLand	-2.2
microFitRefChLand	[7 8 9 10 11 12]
microFitStoChLand	[7 8 9 10 11 12 13 14]
minStoFitLand	0.1
defAerTypeIndLand	0
defAerTypeIndLand	4
allModelLand	[1 1 1 1 1]
relSigChi2DiffLand	1
absSigChi2DiffLand	0.0005
minSzaGomeLand	0.0
maxSzaGomeland	78.0
minVzaGomeLand	0.0
maxVzaGomeLand	65
minCosRaziGomeLand	-1.0
maxCosRaziGomeLand	1.0

Parameter	*Value*
maxLatGomeLand	75.0
minLatGomeLand	-75.0
minScatGomeLand	90
maxAlbedoMainChLand	0.1
maxAlbedoFitLand	0.05
defCloudCorrAlbedoLand	0.8
defCloudCorrPressureLand	700
maxCloudFractLand	0.65
minLandFractLand	0.999
clearSkyMaxRelDiffLand	0.05
clearSkyMaxAbsDiffLand	0.006
surAlbedoSourceDesert	0
surAlbedoSourceDark	0
surAlbedoSourceMain	0
albedoErrorMode	0
abserrorAlbedoMode0	0.005
relErrorAlbedoMode0	0.1
minAodsForErrorLand	25

6.2.4 Default values for demonstrational aerosol products

Parameter	*Value*
codMainCh	12
defOceanAlbedo	0.02
minAlbedo	0.0
maxAlbedo	1.0
minCod	0.0
maxCod	60.0
minSzaCloud	0.0
maxSzaCloud	85.0
minVzaCloud	0.0
maxVzaCloud	65.0
minCosraziCloud	-1.0
maxCosraziCloud	1.0
minScatCloud	90.0
maxLatCloud	75.0
minLatCloud	-75.0

Parameter	*Value*
codAlbedoMaps	5 6
codAlbedoWeighting	1.0
qualityCloudMaxSza	75
qualityCloudMaxVza	55
qualityCloudMaxAbsCosRazi	0.999
qualityCloudClearImpact	0.1
maxSnowIceFracCloud	0.0001
surAlbedoSourceCloud	0

Table 7: Default Values to be used for Aerosol Algorithm External

6.3 Calibration of the AVHRR thermal infrared channels

We use a correction of the radiances from AVHRR channel 4 and 5 based on a regression. The correction and their description is taken from [AD 10].

Denoting the original AVHRR/3 Level 1B Earth view radiances as R_{Orig}, the general formula to calculate corrected radiances R_{Cor} is given as:

$$R_{Cor} = R_{Orig} + \Delta R$$

For the considered cases, the correction term ΔR is a linear function of the original radiances R_{Orig}, i.e.:

$$\Delta R = A + B \cdot R_{Orig}$$

Combining both equations and rearranging the terms lead to:

$$R_{Cor} = A + (1 + B) \cdot R_{Orig}$$

The unit of R_{Orig}, R_{Cor} and A has to be same, which is mW/(m^2 sr cm^{-1}).

Metop-C, channel 4	TBD	TBD
Metop-C, channel 5	TBD	TBD

Table 8 summarizes the coefficients for the channels 4 and 5 of AVHRR/3 onboard Metop-A and Metop-B (Metop-C coefficients are TBD).

Satellite and Channel Number	A in $mW/(m^2\ sr\ cm^{-1})$	B
Metop-A, channel 4	+0.0735	-0.0053139
Metop-A, channel 5	+0.1051	-0.00490524
Metop-B, channel 4	-0.1109	-0.00266674
Metop-B, channel 5	-0.3529	+0.0036633
Metop-C, channel 4	TBD	TBD
Metop-C, channel 5	TBD	TBD

Table 8: Regression coefficients to be applied to the AVHRR/3 Earth View Radiances.

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