Algorithm Theoretical Basis Document (ATBD)

MERIS Regional Case 2 Water BEAM Extension

Atmospheric Correction ATBD

Version 1.1, 24. November 2006

Roland Doerffer & Helmut Schiller

GKSS Forschungszentrum Geesthacht GmbH

21502 Geesthacht

ESRIN Contract: No. 18639/04/I-LG

MERIS Case 2 Water Algorithms Development

Distribution

Name:

P. Regner (ESA / ESRIN)

C. Brockmann (BC)

Change Record

Issue	Revision	Date	Description
Draft 0.1	0	24.10.2005	Initial draft
Draft 0.8	1	23.8.2006	Draft
Final Version 1.1	1.0	24.11.2006	Final Version

1 Abstract

This document describes a procedure for the atmospheric correction of radiance spectra measured with the Medium Resolution Imaging Spectrometer (MERIS) over turbid case II water. MERIS is part of the European Environmental Satellite ENVISAT as one of 10 instruments and is operated by the European Space Agency ESA.

For the evaluation of its data products by users a software package BEAM has been developed for by Brockmann Consult on behalf of ESA. This package mainly allows an analysis of the standard data products of level 1 and level 2 provided by ESA. However, these standard products do not provide optimal results for all areas. In particular case 2 water areas may require adapted algorithms to retrieve the concentrations of water constituents or to provide the inherent optical properties. Also the case 2 water atmospheric correction procedure, as included in the standard MERIS ground segment, may not be optimum in special cases, in particular in turbid waters. In order to enable users to derive products also for those special or regional cases, where the standard processor is not sufficient, a processor has been developed in form of a plug-in for BEAM, which consists of a procedure for atmospheric correction and a procedures for determining inherent optical properties and concentrations of water constituents.

This ATBD describes the atmospheric correction procedures of this plug-in.

The atmospheric correction procedure is based on radiative transfer simulations. Its core is a neural network, which is used for the parametrization of the relationship between the top of atmosphere radiances in the near infrared bands of MERIS and (1) the atmospheric path radiances, and (2) the transmittances between bottom of atmosphere (BOA) and top of standard atmosphere (TOSA), from which the downwelling irradiance at water level of the first 9 bands of MERIS can be determined as well as the transport of the water leaving radiance to TOSA. These quantities are used to calculate the water leaving radiance reflectances RLw of the first 9 MERIS bands, which are then input to another procedure for retrieving the IOPs and concentrations of the water constituents (s. ATBD water constituents).

The model atmosphere comprises two parts: (1) a standard atmosphere, which includes 50 layers with variable concentrations of different aerosols, cirrus cloud particles and suspended particles in water, but with a constant air pressure - and ozone profile, and (2) a layer on top of the standard atmosphere, which contains only air molecules and ozone. The optical thickness ("Rayleigh" - scattering and absorption) of this upper layer is determined by the difference between the actual and the standard atmosphere with respect to surface pressure and ozone content.

Three interfaces are defined: top of the actual atmosphere (TOA), top of standard atmosphere (TOSA) and bottom of atmosphere (BOA).

Thus, the atmospheric correction comprises two steps:

1. Calculation of the path radiances and transmittances of the variable "Rayleigh - ozone-layer" by using actual values of sea surface pressure and total ozone content from the ancillary data of

MERIS and subtracting the standard values. Thus, the path radiance might become negative or the transmittance might become > 1 in cases where the air pressure and ozone content differences are negative. The path radiance and transmittances of this 'correction layer' are used to calculate the downwelling solar irradiance and the upward directed radiance at the top of standard atmosphere (TOSA).

2. Calculation of the path radiances at TOSA, the radiance transmittances between the bottom of atmosphere (BOA, at sea level) and TOSA and the dowelling irradiance at BOA, and, from these three quantities, the water leaving radiance reflectance. This calculation is done with the neural network, which is trained with simulated radiances. It includes effects of different aerosols, cirrus clouds, specularly reflected sun and sky radiance and the coupling between all these components and the air molecules. Furthermore, the procedure takes a variable amount of particles in the water layer into account to extend the scope of algorithm to turbid case 2 waters, where the reflection by the water body in the near infrared spectral bands cannot be neglected due to high suspended matter concentrations.

Input to the neural network are the TOSA radiances of 4 near infrared MERIS bands (708, 756, 778, 865 nm) as well as the solar zenith angle, the viewing zenith angles and the difference between viewing and sun azimuth angle. Output of the procedure are the water leaving radiance reflectances of the first 9 MERIS bands.
The core of the algorithm is a multiple non-linear regression method ("Neural Network"). Its coefficients are determined from a large set of simulated conditions for the input variables (4 radiances reflectances, 3 angles) and corresponding output variables (9 path radiance reflectances, 9 downwelling irradiances at BOA from which also the transmittance of the water leaving radiance to TOSA is computed). The coefficients of the NN are computed by using a feed forward backpropagation optimisation ("training") technique. The data set for training and testing is produced by radiative transfer simulations using an ocean-atmosphere Monte Carlo photon tracing model, which has been developed at GKSS.

2 Preface

One instrument of the ENVISAT earth observation mission of the European Space Agency ESA is the Medium Resolution Imaging Spectrometer MERIS. This instrument is used to measure properties of the atmosphere and land surfaces and the concentrations of water constituents.

This ATBD describes the atmospheric correction procedure, which is used to calculate water leaving radiance reflectances from top of atmosphere radiances. One requirement for this procedure is to include turbid case 2 waters into the scope of the algorithm. Since the MERIS atmospheric correction procedure for case II water is adapted to only a limited extend to waters with high concentrations of suspended solids and yellow substances, it was necessary to write a new procedure for BEAM. This opportunity was used to develop and test a new type of atmospheric correction method which is based on inverse modelling and its parametrization by a neural network. It takes into account the effect of cirrus clouds, specularly reflected sun light (sun glint) and scattering by water particles.

One particular problem was the correction of sun glint, since MERIS has no tilting mechanism so that in many cases half of the image is contaminated by sun glint.

3 ATBD History

The procedure described in this document is the first version and does not has a precursor.

4 Introduction

Remote sensing of water constituents require a careful atmospheric correction since more than 90% of the upward directed radiance at satellite altitude stems from the atmosphere including direct sunlight and skylight which are specularly reflected at the sea surface. Small errors in determining the optical properties of the atmospheric may induce large errors in the retrieval of water constituent concentrations.

During the era of the Coastal Zone Colour Scanner (CZCS) atmospheric correction schemes have been developed for open ocean case I water, which are based on the following assumptions:

- the atmospheric path radiance can be split in a molecular scattering component (Rayleigh scattering) and an aerosol scattering component,
- the water leaving radiance in the near infrared spectral bands is neglectable small (due to high water absorption) so that the radiance at top of atmosphere, after subtracting the contribution by molecular scattering, is only influenced by aerosols,
- the spectral extinction of aerosols can be described by an exponential function, which allows an extrapolation from the near infrared to the blue-green spectral range.

Different versions of this procedure have been discussed in various papers; their underlying principles are summarised in an overview by Gordon and Morel [1983].

However, the new generation of ocean colour sensors requires a more sophisticated procedure in order to utilise the higher radiometric accuracy of these sensors for the retrieval of water substances. In particular the assumptions that (1) the spectral distribution of the extinction can be described by a single number, i.e. the Angstrom exponent, and (2) the atmosphere can be separated into a Rayleigh- and an aerosol layer, lead to errors which are not acceptable with respect to the increased sensor accuracy as present in MERIS.

Thus, the new atmospheric correction procedures for case I water such as developed for SeaWiFS, MODIS and MERIS include the aerosol-Rayleigh coupling as well as a detailed description of the spectral variability of different aerosol types (s. Antoine and Morel, 1998).

Three problems are not or not sufficiently solved so far for the operational atmospheric correction of ocean colour data: (1) atmospheric correction over turbid water, where also the near infrared spectral bands are influenced by scattering of suspended particles, (2) the scattering by thin or subvisible cirrus clouds including aged jet trails and (3) specularly reflected sun light which is present even in the nadir radiances, and, of course, a combination of these problems.

All of these factors are included in the correction procedure as described in this ATBD.

5 Algorithm Overview

In conventional atmospheric correction procedures two properties have to be determined from the radiance or reflectances in the near infrared spectral range: (1) the angstrom exponent, which assumes and describes an exponential spectral shape of the path radiance spectrum of aerosols, and which has to be determined from at least two of the NIR bands, and (2) the path radiance in one of the near infrared bands. The path radiances in the blue-green spectral bands are then calculated by extrapolation using the exponent and radiance of one of the NIR bands.

However, this method cannot be applied to case II waters with high suspended matter concentrations, where the backscattering of water cannot be neglected in the NIR bands. The problem can be solved by inverse modelling of the radiative transfer, where the concentrations of water constituents as well as of aerosols are modified and, thus, determined with the help of an optimization procedure, which is used to minimize the deviation between the measured and the modelled radiance spectra. This approach was applied to CZCS images, where only four spectral channels were available for retrieving water constituents and aerosols (Doerffer & Fischer, 1993). Due to the lack of near infrared bands, it was only possible to retrieve the aerosol path radiance by assuming a constant aerosol type (Angstrom exponent) for the entire image.

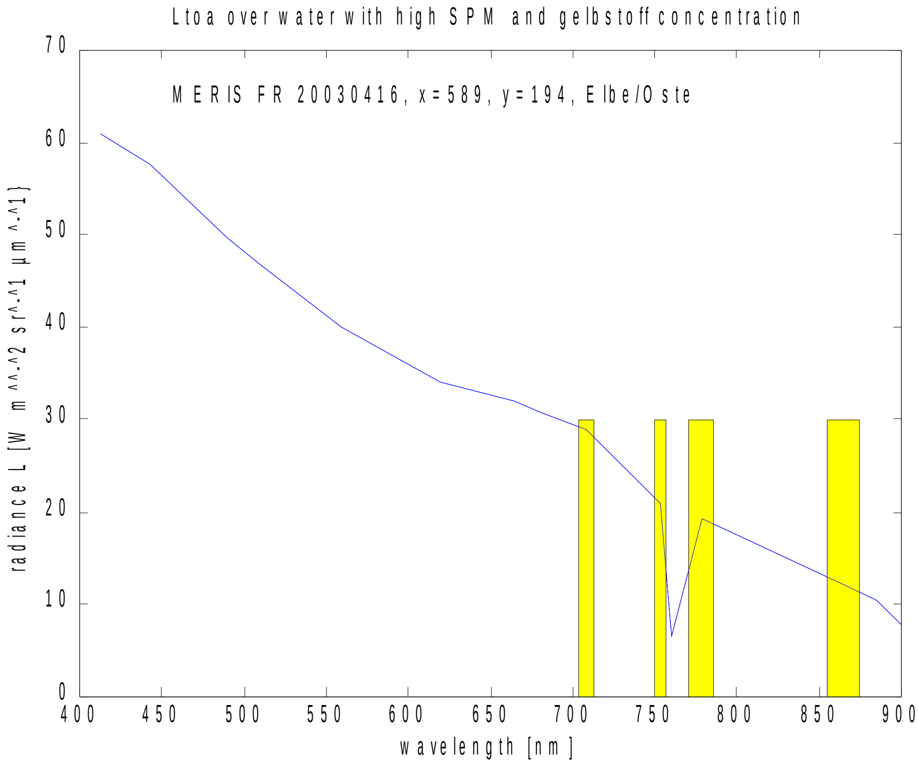

Fig. 1 Scheme of the atmospheric correction algorithm based on inverse modelling of radiative transfer and its parametrization with a multiple non-linear regression procedure ("feed forward backpropagation neural network"). From Ltoa 4 bands at 708, 753, 778 and 865 nm are used to determine the path radiance and transmittance in the visible spectral range

Another major problem is the influence of thin cirrus clouds including aged jet trails, which may sustain for hours under humid conditions. These thin cirrus causes most of the problems particularly in the retrieval of phytoplankton pigment and yellow substance. Furthermore, even with a simple model, such as used for the CZCS data, the inversion method requires an amount of computational time which is not acceptable for the mass processing of satellite scenes.

To combine a realistic description of the processes in the atmosphere using a detailed radiative transfer model with the required high computational efficiency, a neural network procedure was developed.

The NN technique was first tested for the atmospheric correction of MERIS data (Doerffer & Schiller, 1995) using the concentrations of three substances and one aerosol as independent variables. However, also this approach did not consider different aerosol types or an Angstrom coefficient as an independent variable. Thus, the atmospheric correction procedure for MERIS, as described in this ATBD, includes the following features:

- The forward model is a Monte Carlo photon tracing model, which describes in a realistic way the radiative transfer within the ocean-atmosphere system. It consists of an atmosphere with 50 layers, a rough sea surface and a homogeneous water body below.
- A large range of different aerosols with different optical properties and a realistic vertical distribution is used in the forward calculations.
- Scattering by thin cirrus clouds at top of troposphere has been included.
- The water body includes scattering particles to extend the scope of the atmospheric correction to turbid waters.
- Specularly reflected direct sun radiation (sun glint) and sky radiation (skylight glint) is taken into account for the full swath of MERIS.

1 Algorithm Description

1.1 Theoretical Description

1.1.1Physics of Problem

A coastal atmosphere may contain different kinds of aerosols with different optical properties and with a rapidly changing distribution on the vertical, horizontal and temporal scale. The mean aerosol climate depends on the area (industrial coast, volcanoes, deserts, air traffic with jet trails) and the main wind direction. However, the actual aerosol composition and the vertical distribution above a pixel cannot be determined from climate data but only from observations at the time of overflight. Thus, for atmospheric correction of satellite images, it is important to derive the optical properties of the atmosphere from the radiance measurements of the sensor itself.

Because of the complicated mixture of different aerosols and its vertical distribution, and the limited number of independent spectral information, it is necessary to reduce the complexity of all variables to a small number of components, which describe the optical variability. Since for atmospheric correction it is not the task to identify different aerosols, it is sufficient to correct for its impact on the top of atmosphere radiances.

MERIS has 4 spectral bands which are used for atmospheric correction in the procedure described here (708, 753, 778 and 865 nm). An important assumption is that the toa-radiances of these four bands are sufficient to describe the spectral radiance variability caused by aerosols, cirrus clouds, sun glint and suspended particles. Since there are more independent variables then spectral bands, from which the parameters can be determined, the prerequisite for this assumption is that the many variables can be reduced to only a small number of components. This reduction is implicitly included in the training of the neural network.

In the next sections we will describe all components of the system in detail.

1.1.1.1 Aerosols

The properties of the aerosols, which are used in the simulations and which define the scope of the algorithm, are adopted from WCRP 112 (1986), Shettle & Fenn (1979), from the MERIS atmospheric correction ATBD (Antoine & Morel, 1997) and from the Mie program of the Institute for Space Science, FUB Berlin (Heinemann, 1997).

According to the recommendations of WCRP112, aerosols are constructed from basic aerosol components, which consists of spherical particles with a log-normal or a modified gamma size frequency distribution. Properties of these components are given in table 2.

According to Shettle & Fenn the refractive index of some of the aerosols depends strongly on the relative humidity. Thus, their optical properties have been defined as given in table 2.

From these basic components different aerosol models have been defined as described in WCRP 112, those 4 which are used in this ATBD are:

1. The continental (background) aerosol consists of 70% of dust-like particle, 29% of water soluble and by 1% of soot.
2. The maritime model consists of 95% of oceanic component and a 5% fraction of water-soluble. The refractive index depends on the relative humidity (RH), for the simulation an RH of 45% and 99 % has been used.
3. Urban / Industrial aerosol model consists of 17% of dust-like particle, 61% of water soluble and by 22% of soot, two RHs with 45% and 95%.
4. The stratospheric aerosol is a 75% solution of sulfuric acid in water.

aerosol component	refr.index real (550)	refr. Index imag.	D	r0	rb	P1	P2	rmax	step
water sol.	1.530	0.600E-02	1	0.500E-02	2.990	0.00	0.00	20.0	0.002
dust-like	1.530	0.800E-02	1	0.500E-00	2.990	0.00	0.00	40.0	0.020
soot	1.750	0.440E-00	1	0.118E-01	2.000	0.00	0.00	30.0	0.005
h2so4	1.430	1.000E-08	3	0.324E-03	18.00	1.00	1.00	4.8	0.001
oceanic	1.381	0.426E-08	1	0.300E-00	2.510	0.00	0.00	40.0	0.020

Table 1 Basic aerosol components, as defined in WCRP112 (1986) and Heinemann & Schüller(1995) and used for Mie calculations

1.1.1.2 Cirrus

For simulation of cirrus clouds the scattering function of cirrus ice crystals derived from ray-tracing simulations with fractal-shaped crystals have been adapted from Macke et al. (1996). Because of the large size of the cirrus particles a flat spectral scattering is assumed.

The mean cirrus altitude and geometrical thickness is defined according to statistical parameters from a one year lidar monitoring at LMD (geog. position at 48 N, 02 E) during CIRREX'93 (Elouragini et al., 1996), s. table 2.

Cirrus parameter	Daily average minimum	Daily average maximum	Yearly average	Standard deviation	Normalized standard deviation
base (km)	5.0	11.0	8.0	1.7	0.21
top (km)	8.0	13.0	10.8	1.3	0.12
geometrical thickness (km)	0.5	6.0	2.8	1.5	0.54
extinction coefficient (m-1)	0.010	0.42	0.079	0.046	0.58
backscattering coefficient	0.001	0.025	0.0047	0.0027	0.57
optical depth	0.1	1.2	0.25	0.15	0.6

Table 2 Parameters of statistical distributions for cirrus altitude, geometrical thickness, and optical parameters at 530 nm as recorded during CIRREX'93

1.1.1.3 Suspended matter

To simulate the backscattering by suspended particles of turbid case 2 waters, a non-absorbing hydrosol is included (the same as in the water retrieval algorithm), which spectral scattering coefficient *b* is described by

$$b(\lambda) = b_{550}\,(\frac{\lambda}{550})^{-0.812}$$

with λ, the wavelength in nm, and b_{550} the scattering at 550 nm, which is about 0.6 for 1 mg/l SPM. The range used for simulation is 0 - 50 mg/l SPM.

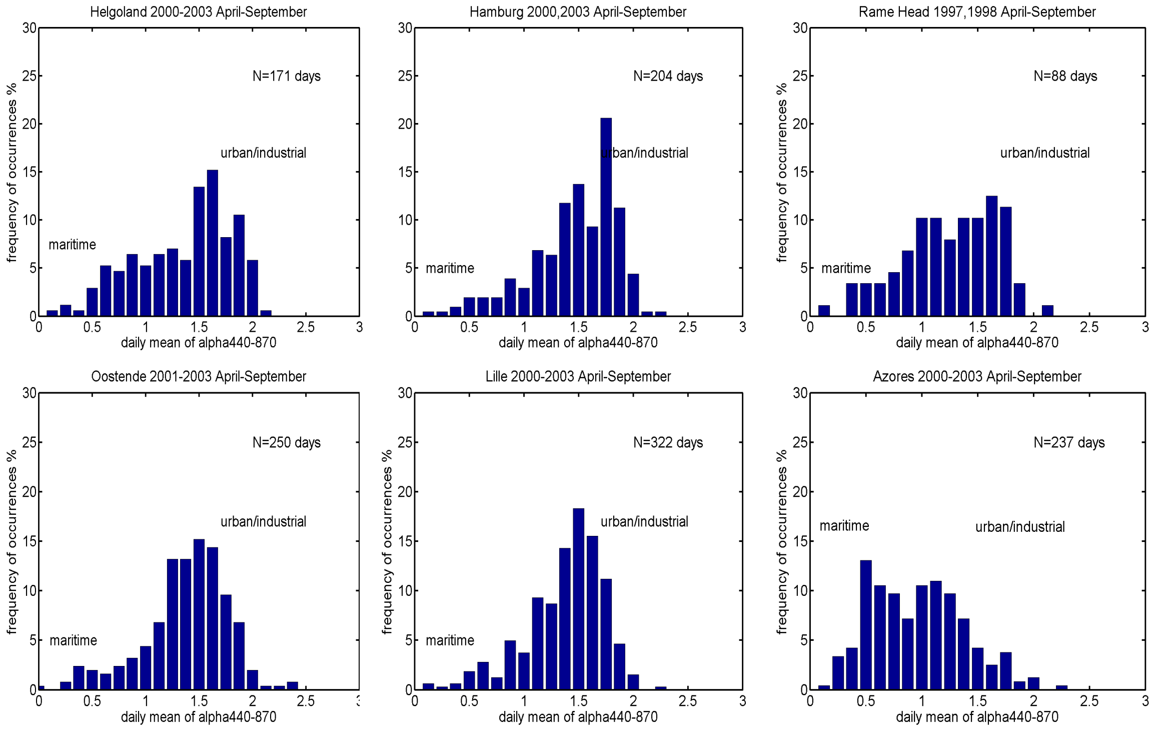

Fig. 2 Angstrom coefficients as measured at different coastal and oceanic sites (AERONET data), which were used as the basis for the coastal aerosol model

1.1.1.4 Rayleigh scattering

The vertical profile of the Rayleigh scattering coefficient is given by Elterman(1968) for the standard atmospheric pressure of 1013.25 hPa at sea level. The profiles with 50 1 km-layers are tabulated for each MERIS band in 7 files.

1.1.1.5 Ozone absorption

The vertical ozone profile is taken from Elterman(1968). The density profile is given in cm ozone per km for a surface pressure of 1013.25 hP. The total ozone column content is 0.35 cm. The extinction profiles with 50 1-km-layers are tabulated for each MERIS band in 10 files

1.2 Vertical distribution in the model

The atmosphere model is separated in two parts: (1) part one contains the variable aerosol/cirrus concentrations and the suspended particles in water with a constant Rayleigh scattering and ozone absorption profile. (2) Part 2 is on top of this standard atmosphere with only a variable ozone and Rayleigh scattering atmosphere. This second layer is used to correct for the deviations of these two quantities from the standard profile of part 1 with constant values and, thus, may get negative values or transmittances > 1. The ozone content and and surface pressure are included in the MERIS standard product (L1).

The aerosol / cirrus optical thicknesses for this model atmosphere are given in table 3.

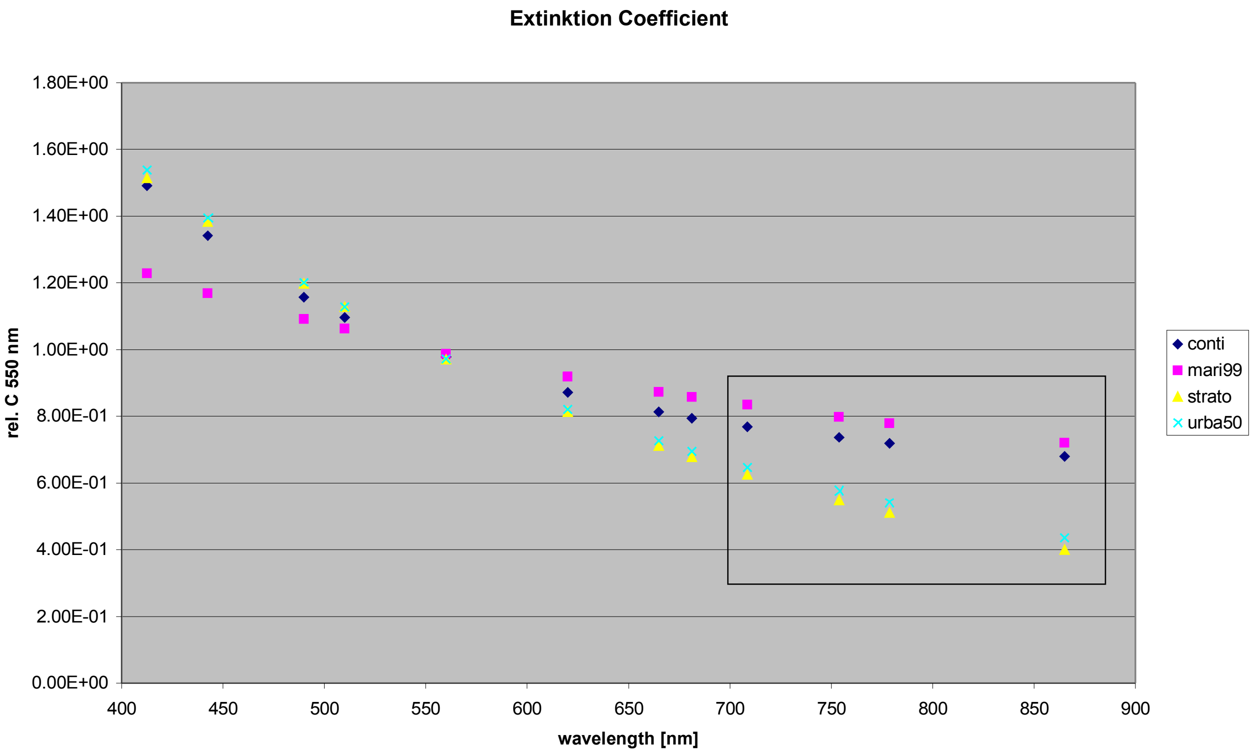

Fig. 3 Extinction of aerosols, normalized at 550 nm, urban aerosol with 50% humidity, maritime aerosol with 99% humidity.

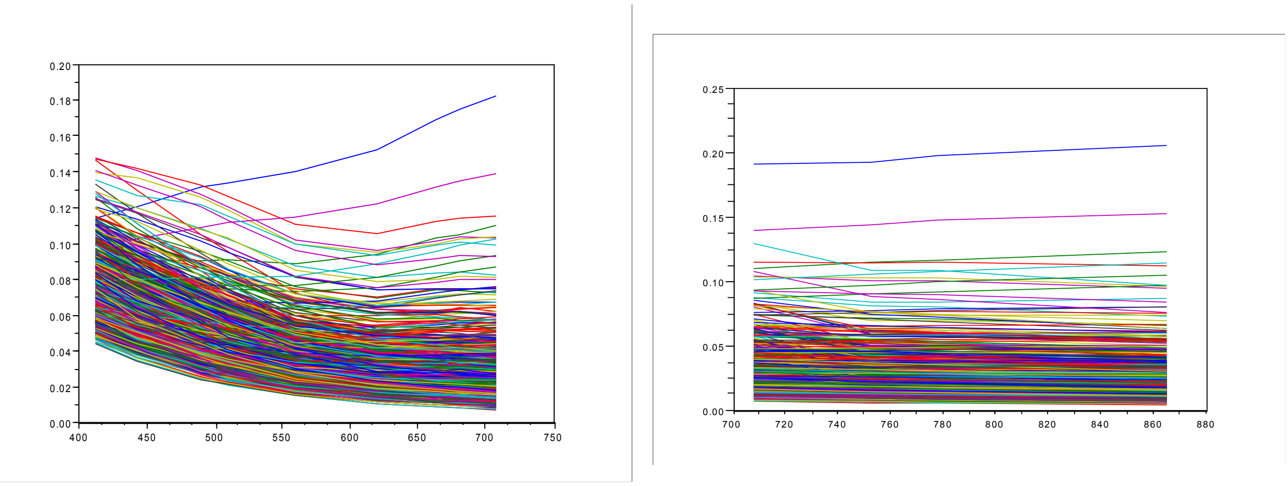

Fig. 4 Radiance reflectance with sun glint for NIR range wavelengths 708 753 778 865 nm and for vis range 412 – 708 nm

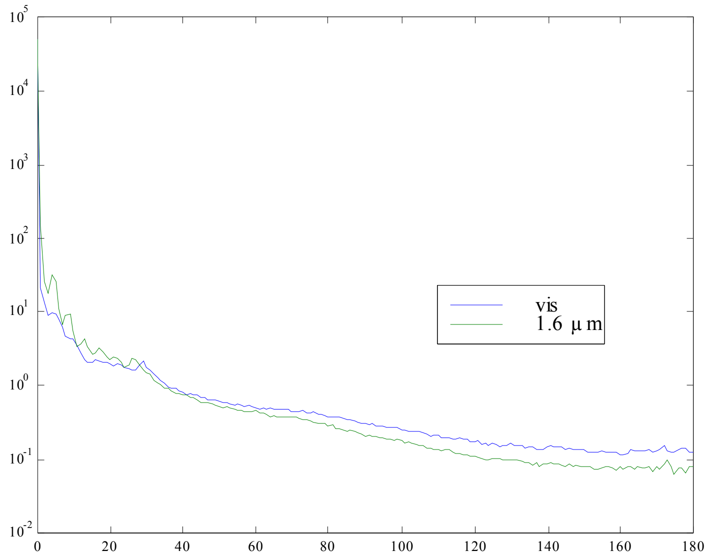

Fig. 5 Phase function cirrus ice particles (data from Macke et al., 1996)

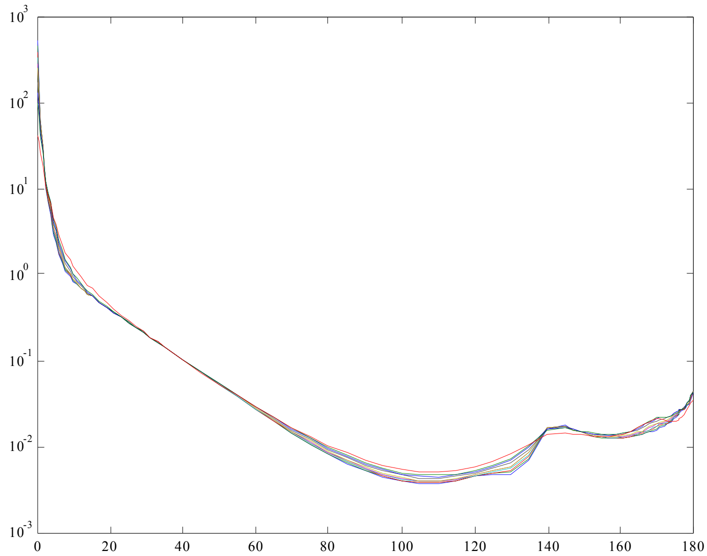

Fig. 6 Phase function of maritime aerosol of 99% humidity for wavelength range 408 - 900 nm

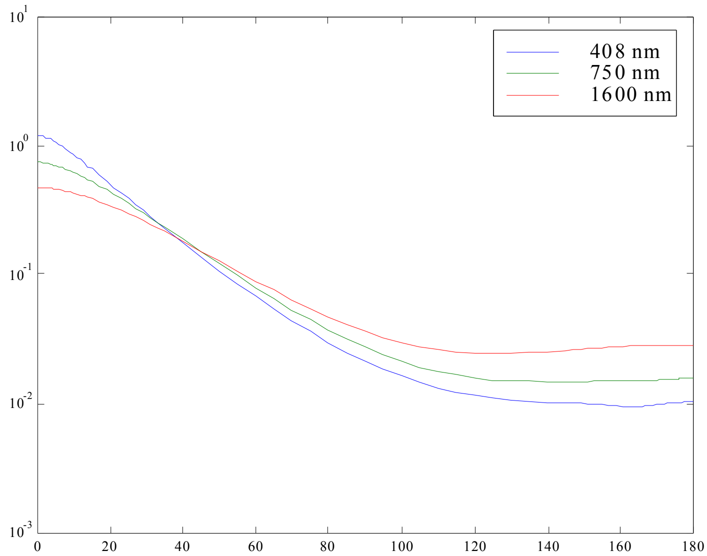

Fig. 7 Phase function of urban aerosol (50% humidity)

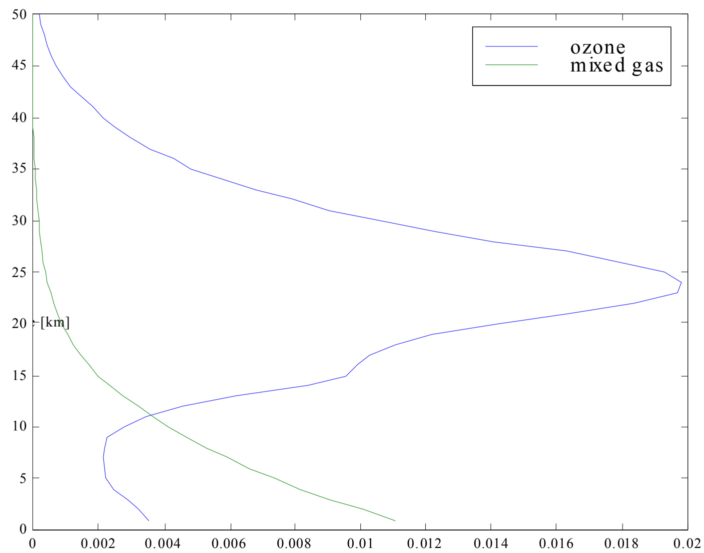

Fig. 8 Mixed gas extinction (550 nm) and ozone density profile

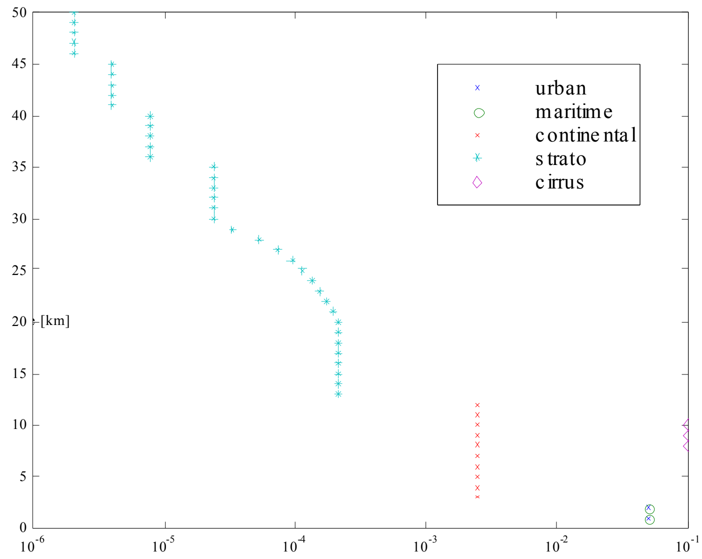

Fig. 9 Vertical profile of extinction at 550 nm for different aerosols

2 Radiative transfer modelling

The procedure used to determine the relationship between the aerosols, cirrus and SPM as well as sun and sky glint on one hand and the radiance reflectance on the other hand is an angular resolving ocean-atmosphere photon tracing Monte Carlo radiative transfer code which was developed by GKSS based on publications by Gordon (1994), Mobley(1994), Morel & Gentili (1991).

In its realisation for this application it has the following features:

- atmosphere with 50 layers using vertical profiles for Rayleigh scattering, ozone absorption and scattering and absorption of five different aerosols.
- air/sea interface with flat or wind dependent rough sea surface
- unstratified water column
- bottom at a depth with no effect on water leaving radiance

Processes which are not included in the simulation are:

- polarization
- any inelastic scattering (fluorescence, Raman scattering)
- wind direction

The detector is positioned (1) just above the water surface for counting the downwelling irradiance and the upwelling nadir water leaving radiance and (2) at top of the standard atmosphere to determine the TOSA rdiance reflectance for different viewing and solar angles. The angular distribution of radiance is resolved with an angle of 7.5 degrees in azimuth and zenith distance.

Photons start with a weight of 1 for all wavelengths at top of atmosphere (layer 51 of the model atmosphere) from a sun disc of 0.5 degree apparent diameter. The weight is multiplied with the cosine of the sun zenith angle. At each event the photon weight is multiplied with the single scattering albedo, ω_0, of the layer in which the event happens, to take into account for the probability of absorption. The travel distance between two interaction events is calculated from a random pull. When the weight is reduced to a value of < 0.01 a "Russian Roulette" decision procedure is started to either end the life of the photon or increase the weight again.

Aerosol	*Layer [km]*	*Optical density at 550 nm*	*Extinction at 550 nm [km^{-1}]*
maritime (45%, 95% rel. hum.)	0 - 2 km	0-0.05 0-0.05	0.05
urban (45%, 95% rel. hum.)	0 - 2 km	0-0.15 0-0.15	0.15
continental	2-12	0-0.025	0.0025
cirrus	8-11	0-0.3	0.1
stratosphere	12-50	0-0.0038	0.0001
max. thickness		0.7288	

Table 3 The model atmosphere: range for simulations and the scope of the algorithm.

The type of scattering is determined from the concentration mixture of the different media or constituents in water or air. Probability tables for the random pull of the type of scattering are pre-generated for each layer. The scattering angle at each event is randomly pulled from large tables which contain, for each media or constituent, the pre-calculated probabilities for the scattering angle in theta.

The weights of photons, which reach the air/sea interface layer in downwelling direction, are counted for calculating the downwelling vector irradiance.

The wave slope angles are randomly pulled from a probability table, which is calculated using the Cox & Munk (1954) wind dependent sea surface slope distribution. This distribution is isotropic with respect to the azimuth, i.e. it does not take into account the wind direction.

The simulation for one case and one wavelength is completed when a predefined number of photons have reached the radiance detector, i.e. the number of started photons is variable in order to account for strong differences in ω_0 of different concentrations mixtures and wavelengths. The standard deviation from this photon counting is also recorded. Furthermore, all sun glint photons are labelled and counted separately.

2.0.0.1 Wavelengths used for simulations

The 12 MERIS bands which have been used for the simulation are listed in table 4.

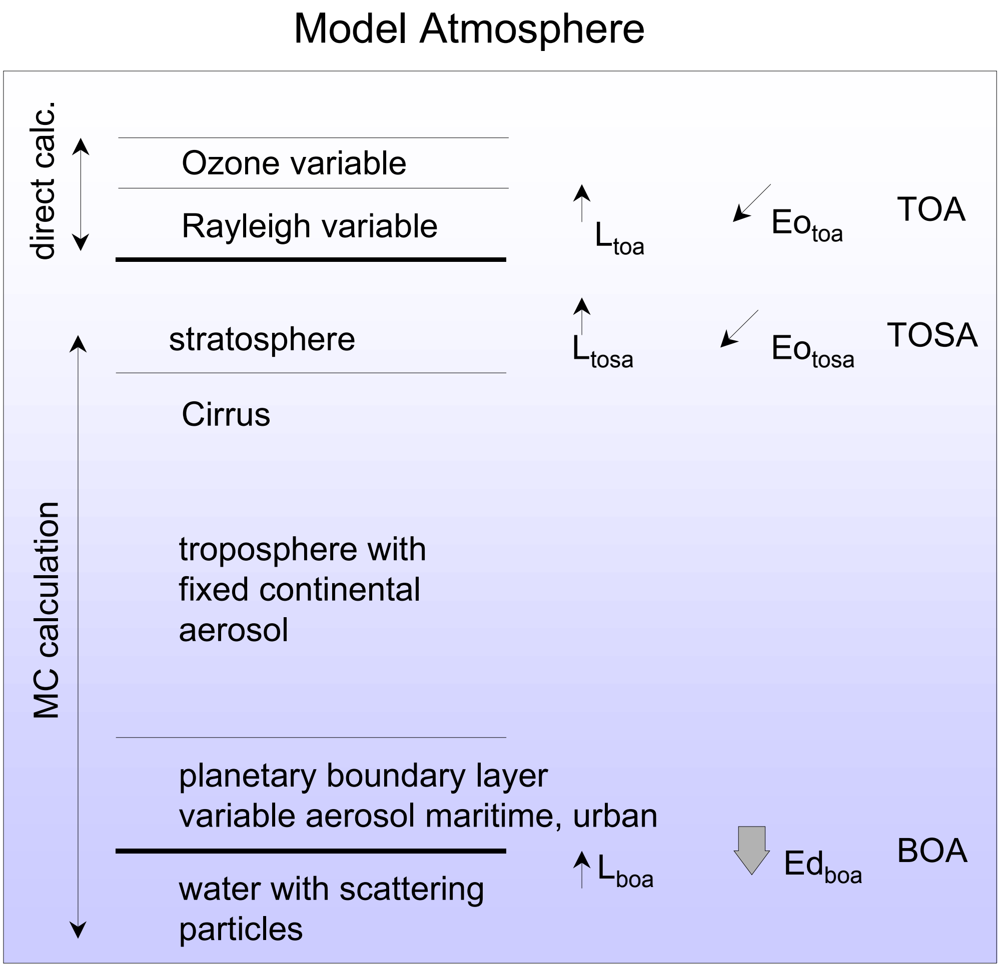

Fig. 10 Model atmosphere, TOA is top of atmosphere, TOSA top of standard atmosphere and BOA is bottom of atmosphere

MERIS band No.	***central wavelength***	***used for AC***	***applied to***
1	412		x
2	443		x
3	490		x
4	510		x
5	560		x
6	620		x
7	665		x
8	681		x
9	708	x	x
10	753	x	
11	760		
12	778	x	
13	865	x	
14	885		
15	900		

Table 4 MERIS bands used for atmospheric correction

2.1 Principle of the algorithm and scheme for forward calculations

The most critical task of the algorithm is to establish the relationship between the top of atmosphere radiance of MERIS channels at 708, 753, 778 and 865 nm and (1) the transmittance of the downwelling irradiance (sun - sea surface), (2) the transmittance of water leaving radiance to top of atmosphere, and (3) the atmospheric path radiance at top of atmosphere for various sun and viewing angles, concentration of different aerosols and cirrus and the concentration of suspended matter. This relationship requires that the variability of the optical properties of the system as presented by aerosols, cirrus, suspended matter can be represented by < 5 factors. From fig. 4 it is obvious that the high similarity in spectral shape should allow for this reduction.

To establish this relationship for the range of variability as described above, a multiple non-linear regression is calculated, which is based on a neural network. Using the Monte Carlo code a table of variables is calculated as a function of the sun zenith distance, different densities of the 6 aerosols and cirrus and the concentration of suspended matter in water.

In detail the algorithm includes the following steps:

1. Input parameters are the calibrated radiances at 12 MERIS bands, the solar zenith angle, the viewing zenith angle and the difference between sun and viewing azimuth angles, the solar irradiance at top of atmosphere, the surface pressure, the ozone concentration.
1. Calculation of a correction term for transmittance and path radiance using the difference between surface pressure and 1013.25 hPa standard pressure and the difference between column ozone content and mean ozone concentration of 350 DU.
1. Use the top of atmosphere radiance corrected by (2) as input to the neural net and calculate the transmittances and path radiances for the first nine MERIS bands (used for the retrieval of water constituents).
1. Calculate the water leaving radiance reflectance for the first nine bands by using the measured top of atmosphere radiance, top of atmosphere solar irradiance, the correction terms, the transmittances sun - sea surface, the transmittance water leaving radiance - top of atmosphere radiance and the atmospheric path radiance.

The scheme is presented in the flow diagram, figure 12.

$$Lcor = \frac{Ltoa - Lrcor}{tozcor\,trcor}$$

$$Edcor = Edtoa\,tozcor\,trcor$$

$$L_w = \frac{L_{cor} - L_{path}}{t_{atm}}$$

$$E_d(0+) = E_{dcor}\,t_{atmd}$$

with Lcor the nadir radiance at top of the standard atmosphere, Ltoa the radiance at satellite altitude, Edcor, the solar irradiance at top of the standard atmosphere, Lpath the atmospheric path radiance of the standard atmosphere, Lcor the path radiance of the correction atmosphere (may become negative), Ed(0+) the downwelling irradiance at sea level, tozcor the transmittance term for the ozone correction layer, trcor, the correction term for the rayleigh correction layer (both may become > 1), tatm, the nadir radiance transmittance from sea surface to top of standard atmosphere and tatmd, the transmittance of the downwelling irradiance from top of standard atmosphere to sea level.

2.1.1Construction of a ffNN for inverting MERIS data for atmospheric correction

For testing the behaviour and performance of the neural network a ffNN is designed for retrieving the transmittances and path radiances of the first 9 MERIS bands from top of atmosphere radiance reflectance spectra of bands at 708, 753, 778 and 865 nm.

2.1.2The construction of the actual ffNN approximating the inverse model

Within this section we describe the construction and the use of the ffNN procedure to derive the transmittances and path radiances from top of standard atmosphere radiance reflectance.

The Monte Carlo model as outlined in chapter 5 was used to calculate the top of standard atmosphere radiance reflectances, the water leaving radiance and the downwelling irradiance at sea level. The ranges of interest of the variables were defined to be those given in Table 3. The values were chosen to cover a large range of ocean and coastal aerosols, cirrus clouds and turbid coastal waters. The software which was used for designing the ffNN is the GKSS Neural Network Simulator FFBP v1.0 (Schiller, 1997). The steps to construct the Neural Network were as follows:

2.1.2.1 Construction of the `teaching'- and test-data-set

`Teaching'-sample:

Values of each of the independent variables (2 different aerosols in the boundary layer with different concentrations, 1 background aerosol in the free troposphere, 1 stratospheric aerosol, cirrus clouds, SPM concentration and sun zenith distance were randomly pulled from their min - max range (see Table 3) on an logarithmic scale. Using these input data the radiances at top of atmosphere of MERIS bands 708, 753, 778 and 865 nm and the corresponding top of standard atmosphere radiances and downwelling irradiances at sea level for a black ocean are calculated with the Monte Carlo code. The radiances are divided by the downwelling irradiance at standard top of atmosphere to get the TOSA (top of standard atmosphere) radiance reflectance. Covering equidistantly the log(min)-log(max) - range leads to a higher density at small values of the variables rather than at large values, which reflects the real situation. So during the `teaching phase ' the ffNN is tuned more at small values thereby achieving roughly constant *relative* errors instead of roughly constant errors. Altogether 50 400 MERIS spectra have been computed from which 20 000 have been used for training of the NN.

Test-sample:

The test-sample, consists of the remaining 30 000 spectra.

2.1.2.2 Construction of the ffNN:

Preparation:

A feed-forward / backpropagation NN with 7 \`neurones' in the input layer (radiance reflectances in 4 MERIS bands + 3 angles), 10 \`neurones' in the first hidden layer, 15 \`neurones' in the second hidden layer and 20 neurons in the third hidden layer was defined. The output layer containes 18 'neurones'. The NN is fully connected (each \`neurone' of a layer is connected with each \`neuron' of the following layer) and is initialised by assigning random numbers (uniformly in (0,1)) to the weights and biases.

'Teaching' :

For error-minimisation the backpropagation method with momentum and flat spot term was used. The \`teaching'-sample was applied to the ffNN in random order. At start the control parameters were set as follows: learning factor 0.6, momentum factor 0.2 and flat spot term 0.02. Each time if the error-function did not decrease any more the minimisation-parameters were divided by 3. The minimisation was continued until the error function was down to an average output error of 1.5%.

Test:

One problem in NN training is to find the right numbers of hidden layers and the number of neurones within these layers as well as the number of cases used for training in order to optimise the accuracy and avoid over-training which could weaken the interpolation power of the NN. The following procedure can and have been used to optimise the NN. During \`teaching' it was checked that the error function of the test-sample agreed with the error function of the \`teaching-sample' in proportion of the sample sizes. At the end of the minimisation the test-sample produced an average output error of 1.5%, which indicated a good generalisation.

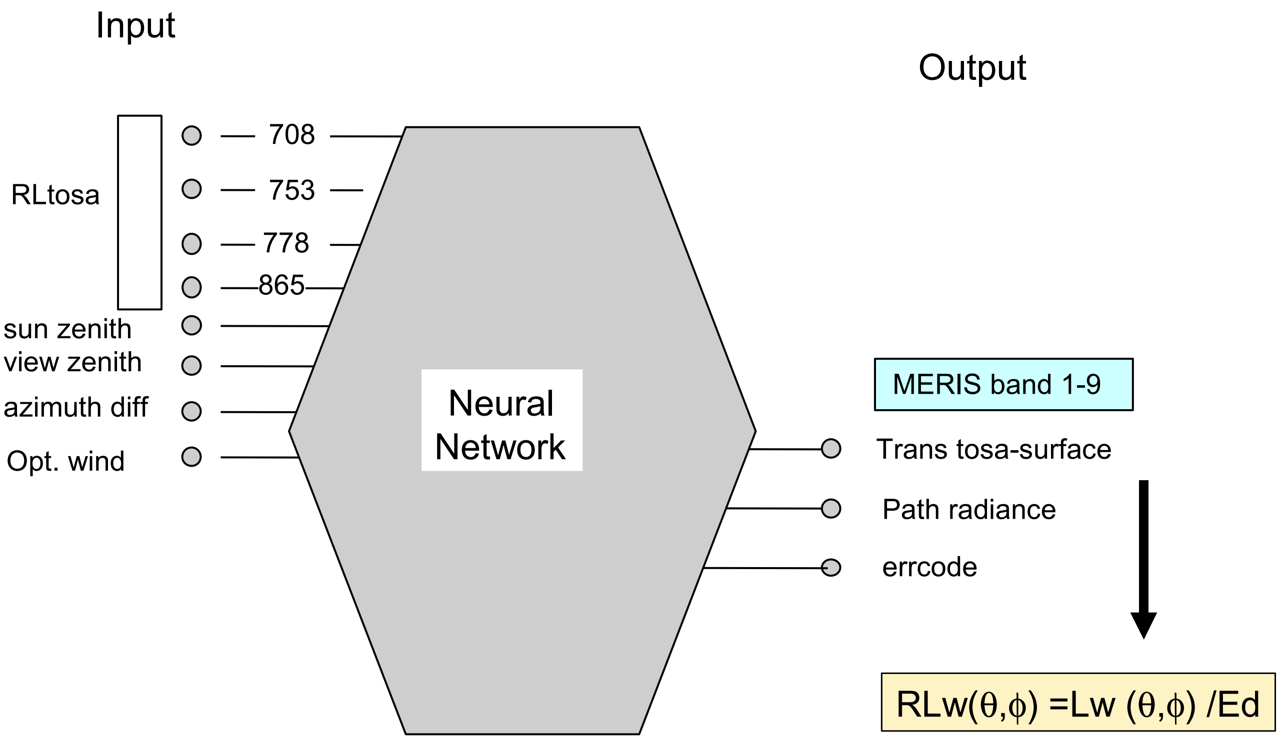

Fig. 11 In- and outputs of the NN procedure. In alternative versions networks were designed with only 3, 2 or 1 band as input. Furthermore, the transmittance surface -> tosa was computed from the diffuse transmittance.

Usage:

The weights and biases obtained by the `teaching' of the ffNN were used to generate a table including parameters of the architecture of the NN and all coefficients. An interface routine reads this table and constructs the network in a preparatory set-up step before using the net pixel by pixel. Also the backtransformation from the (0,1)-interval for the components are built into this function.

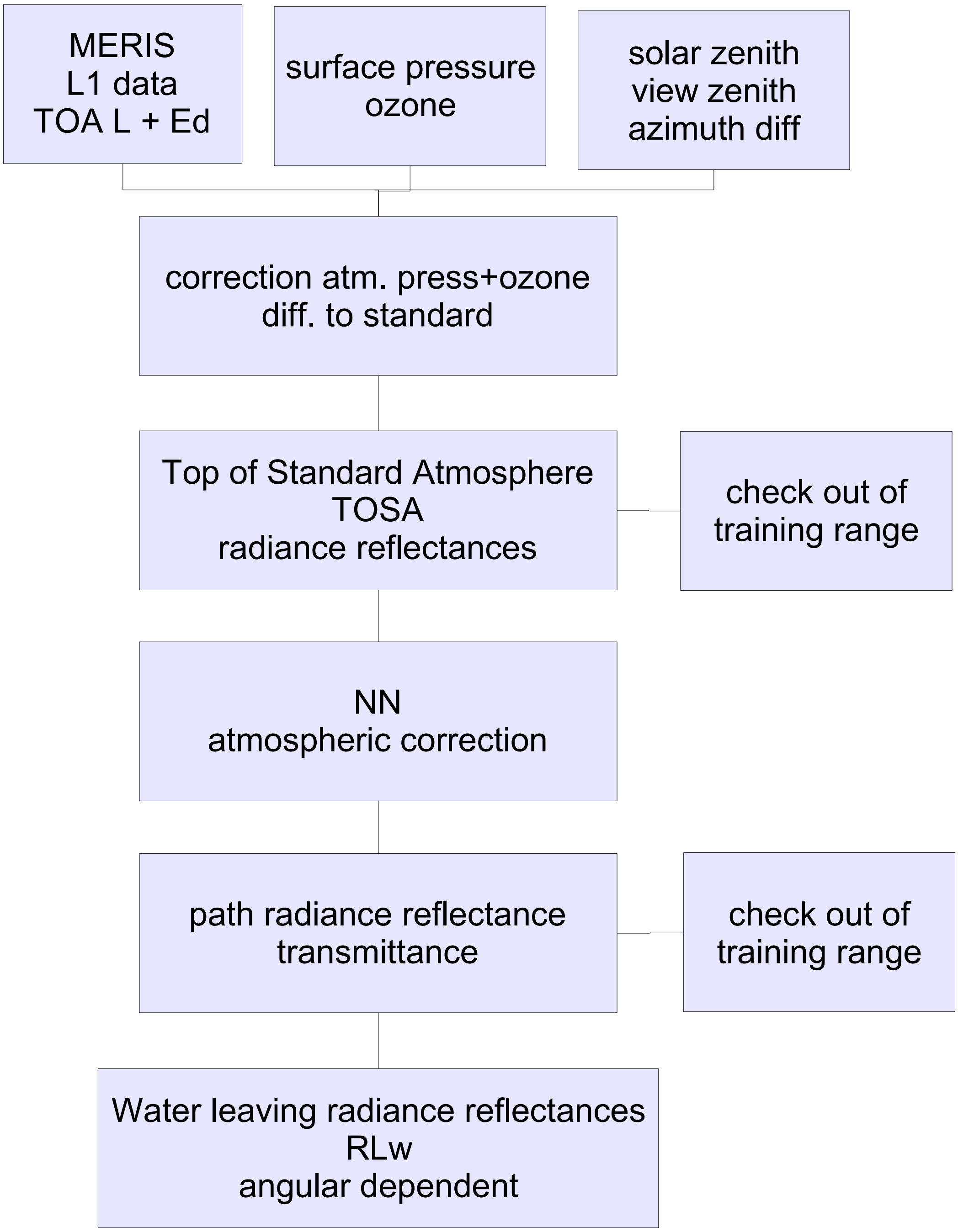

Fig. 12 Flow of atmospheric correction procedure

3 Computation of the aerosol optical thickness and the angstrom coefficient

The aerosol optical thickness approximately is computed from the transmittances, which is the output of the neural network (s above). Since this transmittance is computed for the standard atmosphere and the sun zenith angle for the considered pixel including standard values for surface pressure and ozone, we have (1) to compute tau for a sun zenith angle of 0 degree and then (2) to subtract from tau_total the rayleigh and ozone optical thickness for the standard atmosphere to estimate the tau_aerosol:

```
tau[i]= log(transd[i])*cos_teta_sun;
tau_aerosol[i]=tau[i]-0.5*tau_rayl_standard[i]-absorb_ozon[i];
```

The angstrom coefficient is computed from MERIS bands 6 (620 nm) and band 8 (681 nm):

```
ang_620_681=log(tau_aerosol[5]/tau_aerosol[7])/log(merband[7]/merband[5]);
```

Note that band index in program starts with 0.