Satellite retrieved aerosol properties for battlespace characterization and sensor performance

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ABSTRACT

Sea basing operations in coastal environments require a rapid and accurate description of the physical conditions in the region. Battlespace characterization and sensor performance assist in optimizing the efficiency and safety of operations, of which the detection of targets at low level above the sea surface is all-important. The environmental conditions of the marine boundary layer (MBL) – due to weather and atmospheric effects – change continuously in space and time, which certainly holds for the aerosol make-up. Models have been developed to describe the electro-optical propagation in the boundary layer as a function of meteorological parameters. EOSTAR is such an end-to-end model suite for EO sensor performance in which the Advanced Navy Aerosol Model (ANAM) is embedded for computing the aerosol extinction. While ANAM provides favourable results in open ocean conditions, in coastal zones the model lacks accuracy due to the presence of aerosols from a variety of sources that need to be assessed. In offshore wind conditions continental aerosols of anthropogenic and natural origin mix with marine aerosols produced in the surf zone and by wave breaking further offshore. Radiometers on satellites can be used to retrieve the spatial variation over an extended area determined by the swath width, with a resolution determined by the radiometer pixel size. In this contribution we explore the potential of satellite measurements to provide information on the aerosol properties over the range of interest in order to correctly handle their influence on transmission characteristics in the coastal zone. Results from measurements of the multidisciplinary Maritime REA/Battlespace Preparation 2007 trial, held during 20 April and 5 May 2007 near the vicinity of the island Elba along the west coast of Italy, are presented in this analysis. For one particular day, the satellite retrieved aerosol optical thickness (AOT) is to be compared with hand-held sun photometer measurements for quality assessment. The AOT values are converted into aerosol extinction coefficients for a pre-defined path. For one visible wavelength channel the transmission loss is computed with these coefficients and is compared with the computed transmission loss for the path in case of a) a single extinction coefficient obtained from measurements and b) a modeled extinction coefficient obtained from ANAM.

Keywords: Satellite retrieval, aerosol, EOSTAR, battlespace characterisation, sensor performance, ANAM, Maritime REA, battlespace preparation.

1. INTRODUCTION

The detection, tracking and neutralization of high-precision and low-signature anti-ship missiles require state-of-the-art electro-optic and infrared (EO/IR) systems. An example of this Navy technology is the development of Long-Range Infra-Red Search and Track (LR-IRST) systems, which allow for detection ranges of 20-25 km – a doubling in distance compared to the mid-90s. Refractivity, turbulence and atmospheric extinction at levels from close to the sea surface to about 30 m high need to be considered to assess phenomena and to describe the effects this part of the marine boundary layer has on the detection of low-altitude point targets at these long ranges. Relatively few publications focus on the particular domain of atmospheric effects on LR-IRST applications; see e.g. [*DeLeeuw et al*. 1995][2] for a general description. Extinction due to absorption and scattering by aerosols and molecular species reduces the contrast ratio of the target with the natural background. Small changes in the refractive index due to turbulent fluctuations of the airflow, the air temperature and the humidity result in scintillation and in beam wander.

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Variations of the mean refractive index with height due to atmospheric stratification cause ray bending, i.e. super-refraction or sub-refraction and mirage effects.

Recognizing the importance of atmospheric effects on LR-IRST quite some experimental programs were conducted over the past decades in order to collect the data required to develop and validate models describing these effects. With the advent of experimental data, models became more successful in describing the effects of the atmosphere on propagation of electro-optical radiation. For the near-surface region below deck height, efforts are underway to develop ANAM (Advanced Navy Aerosol Model [*Gathman et al*., 1998; *Van Eijk et al*., 2002][4,12]. EOSTAR (Electro-Optical Signal Transmission and Ranging) / ARTEAM (Advanced Ray Tracing in the Earth's Atmosphere), see [*Kunz et al*., 2004][6], is an end-to-end model suite for electro-optical sensor performance and utilizes ANAM to assess aerosol effects on (near-surface) transmission.

Results from several experimental aerosol programs have shown, however, that the ANAM aerosol code suffers from deficiencies in coastal areas. The cause lies in the presence of multiple aerosol types from various sources. At open ocean, the aerosols predominantly consist of sea salt particles, generated by breaking waves or direct tearing from the waves. In the coastal zone, the concentration of these aerosols can be enhanced by production in the surf zone. Also, the aerosol in the coastal zone consists of many more species, originating from natural or anthropogenic sources on the nearby land. Generally, these additional aerosols can be classified as rural, industrial or urban. The aerosol extinction, which quantifies the transmission losses of EO radiation, is calculated by Mie theory, which in turn requires the size and composition (refractive index) of the individual particles. It is here that the coastal zone presents a problem for ANAM, since the model has very limited provisions for the non-sea spray aerosol types. However, the problem cannot simply be remedied by introducing refractive index tables for additional aerosol types in ANAM: it is also necessary to assess the concentrations of the individual aerosol types. This assessment of a one, two or three type mixture combined with the temporal and spatial variation of the aerosol density in the horizontal and in the vertical direction in the MBL for a larger operation domain, raises a major problem in the accurate estimation of the aerosol extinction in the coastal zone. In this contribution we focus on the use of experimental data obtained from satellite instrumentation for retrieving aerosol properties that can be introduced directly in models such as EOSTAR describing the effects these aerosols have on EO-propagation, or alternatively, may be used to complement the model predictions by ANAM.

Satellite remote sensing of the planetary boundary layer involves the retrieval of aerosol properties from the sensor data at the top of the atmosphere (TOA). By means of retrieval algorithms properties like aerosol optical depth and aerosol classification can be extracted over regions spanning hundreds of kilometers, although for extended coastal operational zones, tens of kilometers are sufficient. The resolution of the satellite sensor should be high enough to resolve the spatial variability of the aerosol components. However, most Earth observation satellite sensors have a resolution (pixel size > 10 km^2) that is less suitable for the extraction of detailed information in the coastal zone. Current work at TNO on satellite aerosol retrieval, however, involves European satellite instrumentation (AATSR) with a sensor pixel resolution of 1 x 1 km^2, and this offers great possibilities for detailed aerosol assessments in coastal waters. See also [*Schoemaker, DeLeeuw, and Van Eijk*, 2005][10] for a preliminary study on the subject of this paper. The idea is to add the aerosol classification information from space-based data to the empirical/physical aerosol models like ANAM in order to obtain better results in EOSTAR for coastal operational areas. This paper aims to assess the possibilities on how to combine the retrieved satellite aerosol properties with the models at hand. Here we focus on the differences in the transmission losses that are expected to appear when more information of temporal and spatial behavior of the aerosol make-up is obtained. In order to accomplish this, we present results obtained during the Maritime REA / Battlespace Preparation 2007 trial, held during 20 April and 5 May 2007 near the Mediterranean island of Elba. MREA/BP'07 was a multidisciplinary experiment for obtaining an integrated 4D Recognized Environmental Picture (REP) in shallow waters for support of Antisubmarine Warfare (ASW) and amphibian landing operations. This was accomplished by combining data from remote sensing, in-situ and autonomous sensors with data from numerical models for EO, radar and underwater acoustics technologies. A small part in this trial covered the collection and retrieval of aerosol properties from in-situ and remote sensing measurements. In this respect we present the results obtained for one particular day, i.e. 23 April 2007, for which satellite data and in-situ data were available. For this day the satellite retrieved aerosol optical depth and the sun photometer retrieved aerosol optical depth are obtained for the 0.67 µm channel. From the validated satellite retrieved AOT the extinction for a predefined path perpendicular to the coast can be computed for every pixel in the path. An advantage of this approach is that near the coast and far off the coast the extinction is representative for the aerosol mixture present even if the mixture make-up is not known a priori. The aerosol distribution is considered non-uniform and the resulting transmission loss obtained by using one extinction coefficient for the path is compared with the loss obtained when using several extinction coefficients for the path. Combinations of in situ and satellite retrieved information is analyzed as well.

2. SATELLITE AEROSOL RETRIEVAL

2.1 Instrumentation

The satellite radiometer that has been used in this work is the AATSR (Advanced Along-Track Scanning Radiometer) instrument onboard the European ENVISAT (Environmental Satellite) orbiting the Earth at a height of approx. 800 km. This sensor has seven wavelength bands, four of which are in the visible and near-infrared parts of the spectrum (effective wavelengths 0.55, 0.67, 0.87, and 1.6 µm) and three of which are in the IR range of 3.7, 11 and 12 µm. The instrument has a conical scanning mechanism providing two views of the same location. Each scene pixel along the direction of the orbit track is first viewed by the radiometer at an incidence angle of 55° as it flies toward this scene. Then, some 150 seconds later, it records a second observation of the scene at an angle very close to the nadir view. The spatial resolution of the sensor pixel is 1 x 1 km^2 at nadir and the swath width is 512 km which results in an overpass over a given location – and thus a global coverage – every three days.

Rayleigh scattering and ozone corrections are required for a proper aerosol signature in the signal at the sensor. Over the dark surface of the waters these corrections are straightforward and a single view observation suffices. Land pixels however show very bright surface reflectances, so for single view aerosol retrieval over land, information is required on the reflective nature of the surface. By combining the two views of AATSR it is possible to eliminate the surface reflectance and surface albedo leaving only atmospheric corrections, see e.g. [*Veefkind et al*., 2000, *Robles González*, 2003][15,9]. The results in this paper are for an oceanic environment, the trial area near Elba, Italy. Hence a single viewing angle for retrieval suffices and the nadir looking angle is used for this purpose.

2.2 Retrieval procedure

At TNO aerosol properties are retrieved from AATSR data by means of an integrated algorithm. The dual view algorithm for application over land and the single view algorithm for application over the ocean have been merged into an efficient algorithm that allows for near real-time processing. The algorithm includes necessary corrections for surface and atmospheric effects including automated cloud screening procedures. Cloud-free pixels are essential for a proper retrieval of aerosol properties, so three tests for the presence of clouds are used based on cloud detection routines developed by [*Koelemeijer et al*., 2001][5]. Subsequently, corrections for ozone, surface contributions (ocean) and atmospheric (Rayleigh) contributions are involved. The final product of this procedure is the corrected measured reflectance at the satellite sensor, i.e. the level 1b satellite product.

The algorithm compares modelled satellite reflectances with the measured reflectances at the top of the atmosphere. The modelled reflectances are made a priori for an external mixture of two aerosol types and are compiled in look-up tables (LUT's). The mixture can be made of anthropogenic aerosol (sulphate/nitrate water soluble) and sea salt for example. Each LUT contains sets of reflectances for a number of possible aerosol atmospheres for an aerosol type for the complete sun-satellite geometry. This way the retrieval algorithm can interpolate for the right geometry and compute the necessary quantities efficiently. The generation of the two LUT's is done by means of the radiative transfer model SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) [*Ricchiazzi et al*., 1998][8]. This model requires as input the values of the phase function for each aerosol type for each wavelength en delivers the reflectances in tabular form for several aerosol atmospheres and all wavelengths for the complete sun-satellite geometry. A phase function can be obtained by a) doing a Mie computation beforehand with the physical properties of the aerosol, i.e. size, refractive index, etc., as input, or b) the use of direct ground-based measurements of the phase function for fine and/or coarse particles. We have chosen for the second option by making use of a vast database of measurements from the AERONET database and two types of phase functions (fine and coarse) for a maritime environment.

The retrieval algorithm computes the most likely aerosol mixture of the two types compared with the measured satellite data in an iterative way using an error minimization procedure, which immediately yields the aerosol optical thickness (AOT) for AATSR visible and NIR wavelengths (0.55, 0.67, 0.87, and 1.6 µm). The infrared channels (3.7, 11, and 12 µm) are used for the detection of cloud pixels. The AOT is defined as the column integrated extinction along a vertical path through the atmosphere from ground to satellite sensor and is therefore a measure for the amount of aerosols that scatter and/or absorb the reflected radiation from the sun. A value larger than zero gives a measure of the amount of scattering and/or absorbing aerosols in the whole atmospheric column. In most instances the AOT is between 0 and 1.5, while values larger than 1.5 are extreme. Aerosols can be found up to eight km from the surface. The high aerosols are fine dust and volcanic ash; these are often designated as stratospheric aerosol, although they still thrive high up in the troposphere. Tropospheric aerosol like sea salt and anthropogenic particles can be found in the first two kilometres above ground in the lower troposphere, or planetary boundary layer. In coastal environments most of the aerosols are to be found in the marine boundary layer; tens to hundreds of meters above sea level.

3. MARINE AEROSOL MODELS

3.1 NAM and ANAM

The Navy Aerosol Model (NAM) and the Advanced Navy Aerosol Model (ANAM) predict the aerosol concentration in the marine environment. The production of aerosol in this environment is due to breaking waves and/or direct wind tearing from wave crests. NAM describes the aerosol size distribution at deck height by a superposition of three lognormal curves (“modes”). Each mode is characterised by a width (assumed constant), a centre radius and amplitude. The centre radii of the modes are nominally 0.03, 0.24 and 2.0 µm, but are adjusted as function of the relative humidity. The largest or third mode (2 µm) consists of freshly produced marine aerosols. Its amplitude is determined by the instantaneous wind speed. The second mode (0.24 µm) consists of marine aerosols that have spent some time in the atmosphere (“aged” marine mode) and have adjusted their size to the ambient conditions. Since these particles have been produced elsewhere and transported to their present location, the amplitude of the second mode is determined by the wind speed history. Finally, the first mode (0.03 µm) consists of fine particles that represent a marine “background” concentration and a continental (dust) component. Its amplitude is determined by the so-called air mass parameter, which in turn is related to the visibility at 0.55 µm. Depending on the value of the air mass parameter, the first mode is separated in a hygroscopic (mode radius adjusted according to humidity) and a non-hygroscopic (fixed centre radius of 0.03 µm) part. This last component is referred to as the 0^{th} mode and is handled with an index of refraction representative for dust.

Two shortcomings have been identified in NAM. The first limitation applies to the near-surface area and involves an underestimation of the concentration of large marine aerosols (radius > 5 microns) [*De Leeuw et al.*, 1989][1]. ANAM remedies this shortcoming by the introduction of a height-dependent 4^{th} lognormal mode centred at a radius of 8.0 µm. The second limitation in both NAM and ANAM is the inaccurate prediction of aerosol concentration in the coastal zone (see, e.g., [*Van Eijk and De Leeuw*, 1993][13]). ANAM has only two types for the 0.03 µm size distribution mode (first mode) - 0^{th} type (dust particles) and 1^{st} type (hygroscopic sea salt-like particles) - and only one parameter (AMP, the air mass parameter) to cover this variability in the aerosol mixture. Moreover, surf aerosols are not included at all in NAM; whereas [*Neele et al.*, 1998][7] show that considerable aerosol production takes place in this region. The development of a coastal version of ANAM may remedy these shortcomings.

3.2 NOVAM

The Naval Oceanic Vertical Aerosol Model (NOVAM) [*Gathman and Davidson*, 1993][3] calculates the vertical variation of aerosol extinction coefficients across the marine atmospheric boundary layer. The NOVAM approach combines empirical and physical algorithms and requires surface layer meteorological observations as well as a radio sounding to higher elevations. As a first step, the empirical NAM is used as a kernel to provide the aerosol size distribution at deck height on the basis of surface layer meteorological parameters. The radio sounding is subsequently used to characterize the boundary layer. NOVAM handles three types: almost well-mixed (one inversion), weak convection (two inversions) and free convection (no inversion). For each of these types of boundary layers, aerosol gradient relations are defined that allow mixing the initial NAM size distribution upwards. These relations are in part physical, based on the dynamical processes affecting the production, mixing, deposition and size of the aerosol within the marine atmosphere, and in part based on experimental observations. The upper limit of the NOVAM domain is of the order of 2-5 km.

4. THE COMBINATION OF AEROSOL MODELS AND SATELLITE DATA

4.1 From AOT to extinction parameter *α*

Propagation models such as EOSTAR compute the aerosol transmission losses along a (horizontal) optical path, which requires knowledge of the aerosol extinction α as a function of height. It is however not straightforward to combine satellite data with aerosol models like ANAM that are used by EOSTAR. Whereas NAM provides an estimate of the extinction at a single height (deck height or 10 meters), ANAM and NOVAM provide extinction as function of height. When considering complementing ANAM with satellite data, it should be kept in mind that the prime property retrieved by the satellite component is the Aerosol Optical Thickness (AOT), which is a measure for the total amount of aerosols in the atmospheric column between surface and satellite sensor. Note that the extinction α is defined as the transmission loss per unit distance, normally as km^{-1}.

The computed pixel AOT is a parameter that represents the integrated extinction along the (vertical) columnar path for each satellite sensor pixel. At first sight it appears that no information on the aerosol variability in the column or the height of the mixing layer is given in the retrieved AOT, which would be essential for estimation of extinction α at one specific height. However, a few reasonable assumptions can be made. First, it can be assumed that a substantial amount of the aerosols is contained in the boundary layer, i.e., the lower troposphere up to two kilometers from the surface. This is reasonably valid for sea salt and anthropogenic aerosols, but there are well-known exceptions on this rule of thumb, such as desert aerosols (i.e. generated in large storms over desert regions and advected at heights of 3 to 5 km) and volcanic ash aerosols (generated in exceptional eruption events and advected at heights of 6 to 8 km). For the aerosols in the boundary layer, a second assumption can be made concerning their vertical distribution. [*Toba*, 1965][11] showed that, to first order, the particle concentration in the (lower part of the) boundary layer decreases exponentially with height. More elaborate models have shown this assumption to be reasonably valid, except for very large aerosols with diameters in excess of 10-20 microns [*Van Eijk et al*., 2001][14].

The assumptions mentioned above are included in the look-up tables of the (satellite) retrieval procedure. First, the iterative fitting procedure yields the (two component) aerosol mixture that best matches the measured satellite data. Since these aerosol components are associated (in the LUT) with a particular vertical distribution, it is then relatively straightforward to find the extinction at a certain height by back calculation. In this contribution we assume that no desert aerosols are present and we assume an aerosol layer height of 2 km. This aerosol layer decreases exponentially in density in the upward direction.

4.2 Data fusion

The methods outlined above to convert the aerosol optical thickness (in the column) to extinction α at a particular height necessitate certain assumptions. The retrieval of extinction may become more reliable when additional information is added, such as the height of the boundary layer or a specific mixing scheme. From an operational perspective, it is important that such additional information is readily available or can be calculated with minimal computational needs. In this respect, the release of a radiosonde or the use of a simple model such as NOVAM may be preferred over the use of a dynamic mesoscale meteorological model, even though the latter is probably more precise.

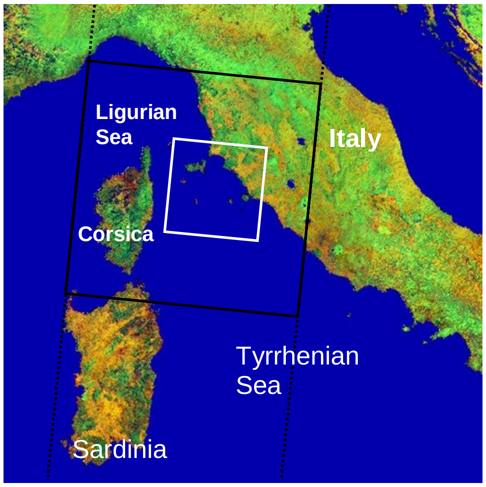
The concept of providing additional information to the retrieval algorithm can be expanded to data fusion. As discussed in previous sections, the ANAM is reasonably successful in providing an estimate of the concentration of marine aerosols on the basis of simple meteorological parameters. This estimate could be used as an input in the retrieval algorithm in the step of determining the mixture of sea spray aerosols and another (continental) aerosol component.

A powerful feature of space-based data is the spatial variability of the measured quantities. Satellite retrieval with AATSR data yields the distribution of the aerosol properties for each generic hi-res pixel of 1 x 1 km. One AATSR scene thus contains over 250,000 individual data points covering 512 x 512 km^2, which corresponds to a typical operational area in the coastal zone. The drawback of the AATSR instrument is that the temporal coverage is limited – the satellite has one overpass every three days. A mesoscale meteorological and aerosol model would thus be required for the assessment of the (prognostic) temporal evolution of the aerosol distribution. Nevertheless, the potential of satellites suggests that the electro-optical propagation models should be extended to the 3D-domain. EOSTAR now only considers vertical inhomogeneity of the atmosphere and thus assumes horizontal homogeneity. Consequently, only a single vertical profile of meteorological parameters, refractivity, aerosol extinction, etc. is required by the model. The spatial distribution of the satellite retrieved aerosol extinction data allows for horizontal inhomogeneity in EOSTAR, and thus directionally dependent propagation predictions.

5. TEST CASE RESULTS: 23 APRIL 2007 DURING MREA/BP'07

5.1 TNO and Maritime REA/Battlespace Preparation 2007

The MREA/BP'07 sea-trial was a multidisciplinary experimental initiative to address the battlespace preparation concept. The time frame of this trial was 20 April 2007 – 5 May 2007 and the location was south of the island Elba along the west coast of Italy, see Figure 5.1. The ultimate goal of the trial was the conception of an integrated 4D Recognized Environmental Picture (REP) of a shallow-water environment in order to support Anti-Submarine Warfare (ASW) and amphibious landing operations. Technologies from disciplines like geophysics, underwater acoustics, electro-optics and physical oceanography where combined for the acquisition, processing and assimilation of data from remote sensing, in-situ and autonomous sensors. The BP'07 trial is part of a broader Maritime REA effort that NATO Underwater Research Centre (NURC) is coordinating in the Ligurian Sea in 2007. During MREA/BP'07 TNO was involved in oceanic, radar, and electro-optical measurements in collaboration with the Royal Netherlands Navy (RNLN). The Hr. Ms. Snellius – a vessel from the Hydrography Service of the RNLN – operated as the platform for TNO personnel to conduct the measurements. The electro-optics part covered the provision of in-situ aerosol and meteo measurements accompanied with remote sensing data (aerosol optical thickness and sea water temperature) from AATSR. In-situ measurements where performed by TNO personnel on board Hr. Mr. Snellius.



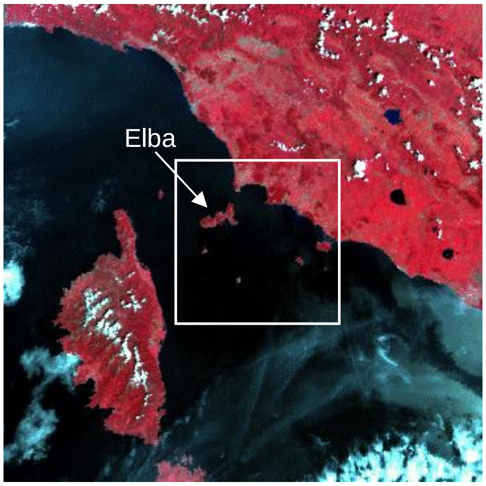


Figure 5.1. (a) Part of the AATSR track with scene (black) with the MREA/BP'07 trial area in the Mediterranean Sea along the west coast of Italy. Image by courtesy of ESA. **(b)** RGB image (0.67 µm) for part of the AATSR scene on 23 April 2007 with trial area. South of Elba are the waters of the BP'07 trial with some additional small islands. The area extends to approx. 100 x 100 km^2. The pixel resolution is 1 x 1 km^2.

5.2 Aerosol optical depth from AATSR and sun photometer measurements

The AATSR instrument covers the complete Earth surface every three days due to the sun-synchronous orbit of the ENVISAT satellite. This type of orbit implies that the satellite flies over any spot on Earth at local standard time between 10:00 and 11:00 A.M. (10:30 A.M. descending the equator). For the MREA/BP'07 trial area – which has a size of approx. 100 x 100 km^2 – the temporal coverage is limited to five overpasses between 20 April and 5 May. For proper retrievals the weather for these days should be such that the trial area is cloudless or has minimal clouds. The 23rd of April 2007 was a day with minimal clouds and proper conditions for the region.

In Figure 5.1(b) an image of the trial area is shown for the visible 0.67 µm channel of AATSR. One can see that the sky over the trial area is almost free from clouds and for the pixels in the trial area (white square) retrieval of accurate aerosol optical thickness is appropriate. The retrieval result is shown in Figure 5.2(a) and (b).

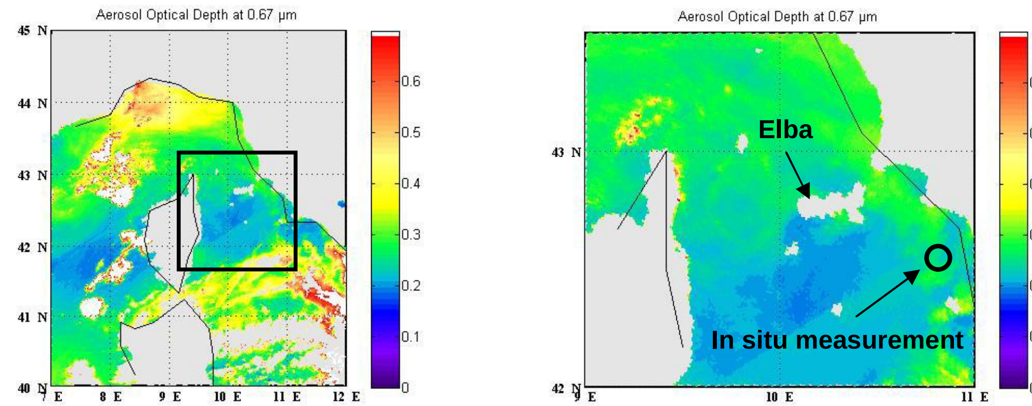


Figure 5.2. (a) Satellite aerosol optical thickness at 0.67 µm for the trial area with the in situ measurement at coordinate [42.638N, 10.871E]. **(b)** Zoom in on the black square.

The sun photometer AOT has been obtained on board Hr. Ms. Snellius by aiming the apparatus directly to the sun under cloudless conditions – between 10.00 and 11.00 A.M. This AOT is necessary for validation of the satellite retrieved AOT. If the sun photometer AOT agrees within certain limits with the satellite retrieved AOT in the pixel where the vessel resides, then the satellite retrieved AOT for the whole scene, i.e. the whole trial region, can be considered accurate. The sun photometer AOT was measured for a collection of wavelengths. Just the AOT at 0.67 µm was necessary in order to validate the 0.67 µm AATSR AOT. The pixel where the sun photometer measurement took place has coordinate [42.638N, 10.871E]. The satellite retrieved optical thickness for this pixel is AOT(0.67) = 0.22. In Figure 5.3 a graph is shown for the sun photometer measurements done.

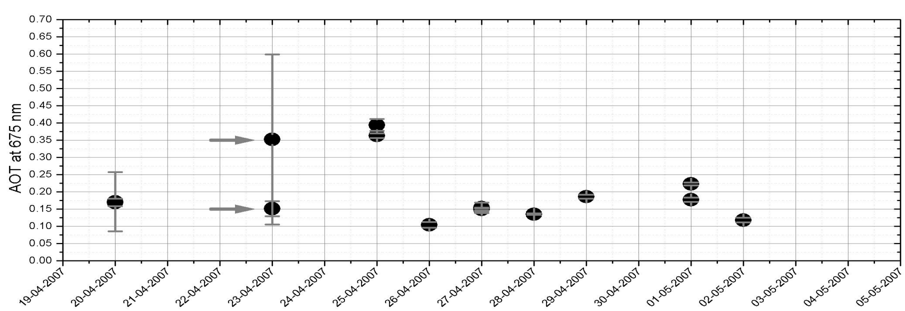


Figure 5.3. Sun photometer measurements for the AOT at 0.67 µm. For 23 April 2007 two measurements are shown. One measurement has a large uncertainty and its value of $AOT_{sp}(0.67) = 0.35$ is considered unreliable. The other measurement, $AOT_{sp}(0.67) = 0.15$, is accurate though and is used as validation for the satellite retrieved value for the pixels in the vicinity of the ship.

From Figure 5.2(b) the satellite retrieved AOT for the location of the ship at the time of the sun photometer measurement is retrieved as 0.22, while the uncertainty of aerosol retrieval over ocean with AATSR is 0.04 (see

[*Robles Gonzàlez*, 2003][9]), so that $AOT_{sat}(0.67) = 0.22 \pm 0.04$. This satellite derived value is higher than the sun photometer value of $AOT_{sp}(0.67) = 0.15$, yet is of the same order and we may assume the other satellite retrieved AOT pixels in the trial area as reliable.

Next to the sun photometer, a PMS aerosol spectrometer was in operation to count the number of particles for several sizes. From these PMS measurements the local extinction parameter can be obtained.

5.3 Conversion to extinction coefficients

Now that the validated $AOT_{sat}(0.67)$ for every pixel in the domain has been retrieved, the extinction coefficients are to be computed for a predefined path at deck height in the trial area. Five test cases are presented. The first test case assumes an aerosol layer with fixed height of h = 1000 m and modeled as exponential decreasing with height (Test case 1a) and a layer constant with height (Test case 1b) – confer Subsection 4.1. Test case 2 does not assume a specific height for the MBL but rather uses the in situ measurement of the extinction coefficient as a valid number for the complete path. The third test case also lacks an assumed specific height but uses the ANAM model value for the extinction according to the proper meteorological parameters for the same location and time as the other cases. Finally, the last two cases cover test cases 2 and 3 combined with satellite retrieved AOT in order to capture the non-uniformity of the aerosol distribution and the accompanying aerosol extinction coefficients.

► Test case 1a & 1b: In order to convert the column integrated extinction to an extinction coefficient for a certain height the following expression for the satellite retrieved aerosol optical thickness – for each pixel – is required:

$$AOT_{sat}(\lambda) = \int_0^{TOA} \alpha(\lambda, z)\, dz \,. \qquad \text{(Eq. 5.1)}$$

Here *TOA* is the top-of-the-atmosphere and α is the extinction coefficient along the vertical path. A description of the distribution of the aerosol in the layer (and implicitly of the aerosol extinction) is required as well as the height of the layer. With an exponentially decreasing aerosol distribution with height h the aerosol extinction coefficient at every height between 0 and h along the vertical path can be modeled – for each pixel – as

$$\alpha(\lambda, z) = \alpha_{\lambda,0}(1 - z/h)\, e^{-(z/h)}\,, \qquad \text{(Eq. 5.2)}$$

where h is the height of the aerosol marine boundary layer (MBL) and $\alpha(\lambda,0) = \alpha_{\lambda,0}$ is the aerosol extinction at the surface. For $z > h$ it is assumed that no aerosols are present, and hence the integral vanishes for the vertical path from h to *TOA*. Equation 5.1 now becomes

$$AOT_{sat}(\lambda) = \alpha_{\lambda,0} \int_0^{h} (1 - z/h)\, e^{-z/h}\, dz = \frac{\alpha_{\lambda,0} h}{e}\,, \qquad \text{(Eq. 5.3)}$$

and gives the $\alpha_{\lambda,0}$ if h and the AOT_{sat} are known for every pixel. This value of $\alpha_{\lambda,0}$ then can be substituted into Eq. 5.2 which gives the extinction at every height z.

For an aerosol distribution that is constant up to height h the extinction coefficient becomes

$$\alpha(\lambda, z) = \alpha_{\lambda,0}\,, \qquad \text{(Eq. 5.4)}$$

whereas the integral of Equation 5.1 now yields:

$$AOT_{sat}(\lambda) = \alpha_{\lambda,0} \int_0^{h} dz = \alpha_{\lambda,0} h\,. \qquad \text{(Eq.5.5)}$$

In Figure 5.4 this situation is schematized.

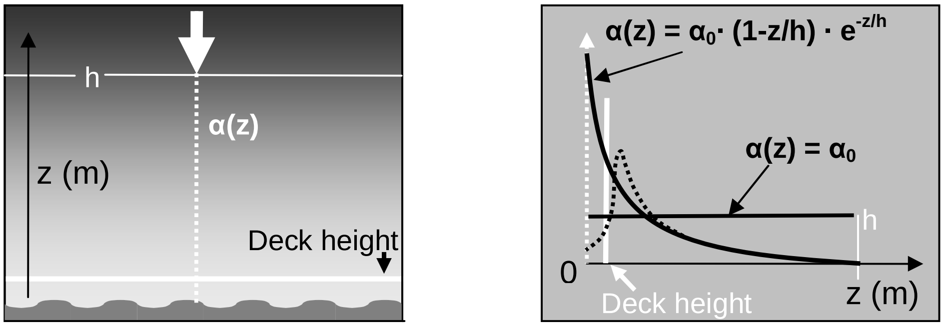


Figure 5.4. The aerosol distribution is modeled as an exponentially decreasing distribution up to the height h of the marine boundary layer or as a constant distribution of aerosol particles. For this study the deck height is 10 m above sea level. It is assumed for this test case that no aerosols are present higher than h and hence the aerosol extinction $\alpha = 0$ for $z > h$. Note that in the right panel the black dotted curve indicates an alternative distribution – see 6. Conclusions and outlook.

The height is taken to be h = 1000 m. The $AOT_{sat}(0.67)$ = 0.22 for the pixel that incorporates the coordinate [42.638N, 10.871E]. For case 1a the extinction at ground level $\alpha_{0.67,0}$ = 0.598 km^{-1} and at deck height the extinction is computed as $\alpha(0.67,10) = 0.598 \times (1 - 10/1000) \times \exp(-10/1000) = 0.586$ km^{-1}. For case 1b the extinction at ground level is identical to the extinction anywhere in the layer up to h and is $\alpha_{0.67,0} \equiv \alpha(0.67,10) = 0.22$ km^{-1}. For both cases the results are shown in Figure 5.5 below, where the modeled layer is representative for the whole satellite scene. ◄

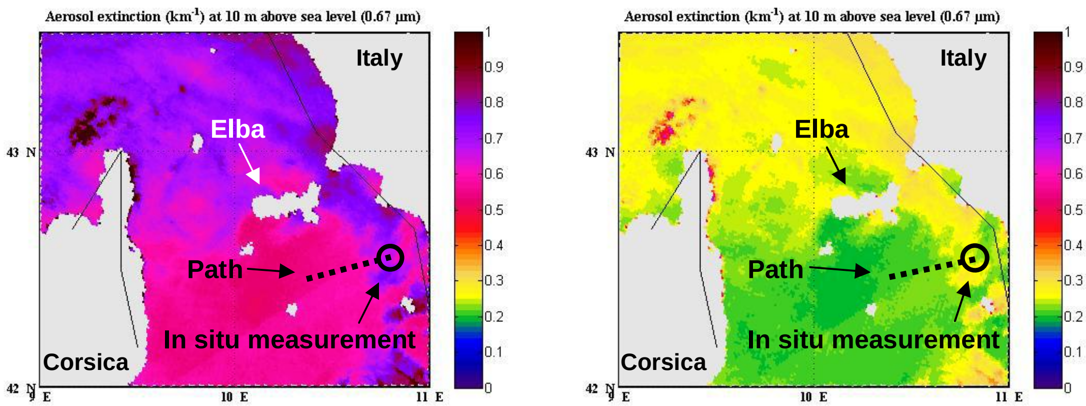


Figure 5.5. (a) The aerosol extinction coefficients for an exponentially decreasing aerosol boundary layer with h = 1000 m for Test case 1a. **(b)** The aerosol extinction coefficients for the constant aerosol density layer of Test case 1b.

► Test case 2: The in situ PMS measurements have a rate of once every fifteen minutes during the day. The average of five values is taken for the time slot between 10.00 and 11.00 A.M. The computed value for $\alpha_{probe}(0.67)$ at deck height at local time is $\alpha_{probe}(0.67)$ = 0.044 km^{-1}. No information on the (probable) non-uniformity of the aerosol distribution is applied, hence this value is used for each kilometer along a 20 km long path. ◄

► Test case 3: The ANAM computed value for the extinction at the same location as in Test case 2 is based on the local meteorological parameters concerning wind speed and air temperature at deck height. These parameters are known from 15 minute interval measurements. The computed value for $\alpha_{probe}(0.67)$ at deck height at local time is $\alpha_{probe}(0.67)$ = 0.18 km^{-1}. Like in Test case 2 there is no information on the (probable) non-uniformity of the aerosol distribution in the area. ◄

In order to capture the inhomogeneity of the aerosol layer, two additional cases have been analyzed that make use of the measured and computed value (cases 2 and 3) respectively. The extinction coefficients for the other pixels of the path are based on this one computed value in combination with the satellite retrieved aerosol optical depth for the other pixels in the path. By means of extrapolation the other extinction values can be computed. For the in situ case, e.g., the [AOT, α] = [0.22, 0.044] is a starting pair for the location of the in situ measurement. An identical scenario applies to the ANAM case with [AOT, α] = [0.22, 0.180] as a starting combination. In Figure 5.6 the aerosol extinction coefficient distribution is shown for the whole area with the path included for the two additional cases.

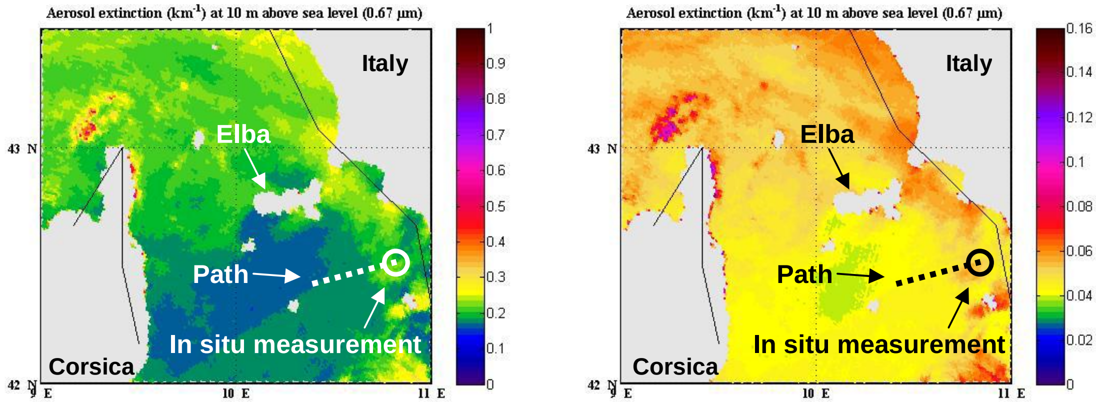


Figure 5.6. (a) The aerosol extinction coefficients based on the ANAM computation combined with satellite data. **(b)** The aerosol extinction coefficients – with different scale - based on the in situ measurement combined with the satellite retrievals.

5.4 Transmission loss along a path

An appropriate path is chosen perpendicular to the coast starting on the coordinate [42.638N, 10.871E] at 10:30 A.M. From Figure 5.2(b) it can be seen that the aerosol optical thickness is higher closer to the coast. This path makes a possible distinction between near coastal and open ocean conditions. For all cases in the former paragraph all extinction coefficients in the path are computed and tabulated in Table 5.1. The satellite retrieved path extinctions $\alpha_{\text{satellite}}$ are based on ten values for the AOT, i.e. [0.22, 0.21, 0.205, 0.2, 0.198, 0.196, 0.194, 0.192, 0.191, 0.19] with 0.22 as the value nearest to the coast. Each value represents 2 km of the path. The total transmission loss can be calculated by multiplying the transmission for each *i*. The loss for the 20 km path is:

$$1 - T = 1 - \prod_{i=\{1,\dots,10\}} \exp(-\alpha_{satellite,\,i} \cdot L_i)\,. \qquad \text{(Eq. 5.6)}$$

Here T is the total transmission – the ratio of outgoing radiation I to incoming radiation I_0 through an atmosphere with length L_i.

Table 5.1. Comparisons between in-situ, modeled (ANAM) and satellite retrieved transmission losses along the 20 km path. Note that each slot represents a length of 2 km along the path. The most left extinction value refers to the location of the Hr. Ms. Snellius at the time of measurement, i.e. the location closest to the coast.

Test case	Extinction coefficient α in km^{-1} (Transmission loss) < to coast									to open ocean >	$1 - I / I_0$
1a: Satellite	**0.586 (69.0%)**	**0.570 (68.0%)**	**0.557 (67.1%)**	**0.544 (66.3%)**	**0.538 (65.9%)**	**0.533 (65.6%)**	**0.527 (65.1%)**	**0.522 (64.8%)**	**0.519 (64.6%)**	**0.516 (64.4%)**	**~100%**
1b: Satellite	**0.220 (35.6%)**	**0.210 (34.3%)**	**0.205 (33.6%)**	**0.200 (33.0%)**	**0.198 (32.7%)**	**0.196 (32.4%)**	**0.194 (32.1%)**	**0.192 (31.9%)**	**0.191 (31.8%)**	**0.190 (31.6%)**	**98.1%**
2: In-situ	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**0.044 (8.4%)**	**58.5%**
3: ANAM	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**0.180 (30.2%)**	**97.3%**
In situ + Satellite	0.044 (8.4%)	0.042 (8.1%)	0.041 (7.8%)	0.040 (7.7%)	0.039 (7.5%)	0.039 (7.5%)	0.039 (7.5%)	0.038 (7.4%)	0.038 (7.4%)	0.038 (7.4%)	55.0%
ANAM + Satellite	0.180 (30.2%)	0.172 (29.1%)	0.168 (28.5%)	0.164 (27.9%)	0.162 (27.7%)	0.160 (27.4%)	0.159 (27.2%)	0.157 (27.0%)	0.156 (26.8%)	0.155 (26.7%)	96.2%

The aerosol extinction coefficient obtained from the point measurement (Test case 2) and from the ANAM computation (Test case 3) is representative for the whole path for the particular time slot. The transmission loss along the predefined path is then computed as $1 - T = 1 - I / I_0 = 1 - \exp(-\alpha_{probe} \cdot L)$. Here L is the total path length of L = 20 km. For the additional two cases in which Test case 2 and Test case 3 are combined with the satellite retrieval results expression Eq. 5.6 is used.

In Table 5.1 one can see the large differences for the total transmission loss. The total loss based on the satellite retrieved extinction coefficients for the two modeled layers shows a complete loss for the exponential layer and a more realistic loss for the constant layer. In case of the ANAM computed value, the total transmission loss for the path is 97.3%. However, using the ANAM coefficient in combination with the satellite information for the other pixels in the path, the loss is 96.2%. The difference is 1.1% for the total loss over the 20 km path for an AOT change of 0.3 (0.22 – 0.19) along the path. The in situ measurement on the other hand shows other values that are much lower and different losses are computed for each 2 km with a difference in total transmission loss of 3.5%.

6. CONCLUSIVE REMARKS

It has been shown through the retrieval of the aerosol optical depth that the spatial and temporal variation of the aerosol layer in the coastal environment of the trial area under consideration is non-uniform. This paper demonstrates that satellite retrieved aerosol extinction coefficients result in different transmission values along a horizontal path for an inhomogeneous aerosol field compared to current methods that use only one value for the same domain. The crucial step to convert the AOT – which was validated and considered accurate within certain limits – into extinction coefficients is not trivial and premises are required that give the necessary information on the boundary layer under consideration. The modeled aerosol layers that were opted – confer Subsection 4.1 – resulted in very different values for the extinction coefficients. In case of the applied exponential layer the AOT should have been lower in order to get reasonable values for the extinction at deck height. While the AOT is considered accurate, it is concluded that the exponential layer yields unrealistic results for the extinction – for this particular case. The layer with a constant density on the other hand resulted in more reasonable values for the extinction; although it can be argued that a constant layer of 1 km thickness is not very realistic either. A third aerosol layer was drawn (black dotted) in Figure 5.4 (right panel) that shows an inversion layer. Although such a layer was not modeled here, it is speculated that such layers do exist in coastal environments. Moreover, in the trial case it signifies the necessary realistic value for the AOT, i.e. enough particles in the column, and in the meantime a very low value for the extinction (note the in situ value) at deck height just under the inversion layer where the density is highest.

One can observe that the ANAM value differs significantly from the in situ value at the location of the vessel and starting point of the predefined path. Parametric aerosol models such as the ANAM are less reliable, especially due to uncertainties in the estimate of aerosol composition. On the other hand, extraction of the aerosol extinction from PMS in situ measurements depends on Mie calculations with specific input for the aerosol properties, which are based on assumptions as well.

It is not trivial to get a handle on the vertical composition for the topical situation. Locally generated aerosols do not necessarily mix efficiently in the vertical, resulting in strong concentration gradients in the lower parts of the boundary layer. Mixing layers could be defined on the basis of vertical aerosol models, such as NOVAM, which would constitute a refinement of the simple exponential or constant vertical distribution. Another refinement could consist of a retrieval algorithm that takes the height of the boundary layer as an input variable. This height could be provided by a mesoscale meteorological model or a radiosonde that is released at the site of interest (confer Subsection 4.2 for these matters). This paper does show, however, the difference in transmission values that occur when applying more realistic scenarios for the horizontal aerosol distribution. Future work will address a more accurate quantification of the vertical layer in order to match the satellite retrieved extinction coefficients properly with the in situ and/or ANAM modeled extinction coefficients for the problem at hand.

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