Combining ANAM with satellite data to determine the EOSTAR aerosol component

R.M. Schoemaker*, G. de Leeuw, and A.M.J. van Eijk
TNO Defence, Security and Safety, P.O. Box 96864, 2509 JG, The Hague, The Netherlands

ABSTRACT

The detection of targets at low levels above the sea surface by electro-optical (EO) sensors is affected by the atmosphere. Models have been developed to describe the electro-optical propagation in the marine atmospheric surface layer as a function of meteorological parameters. EOSTAR is 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 favorable results in open ocean conditions where the aerosols predominantly consist of sea salt particles, the model lacks accuracy in coastal zones due to the presence of aerosols from a variety of other sources. 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. In principle, ANAM can be extended with the various aerosol types that may occur in the coastal zone, but to correctly handle their effect on EO propagation, information is required on the actual aerosol mixture over the range of interest. In this contribution we explore the potential of satellite instruments to provide this information. 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. Input into this retrieval is a model describing the aerosol mixture in varying ratio, e.g. a mixture of continental and marine aerosol. While the marine component can be constrained by ANAM using local meteorological input parameters, the continental component can be retrieved and used as input to determine the fine particle distribution in ANAM.

Keywords: ANAM, satellite retrieval, aerosol, EOSTAR, coastal zones

1. INTRODUCTION

Electro-optic and infrared (EO/IR) systems represent a critical Navy technology for the detection, tracking and neutralization of high-precision and low-signature anti-ship missiles. An example 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. [*De Leeuw et al*. 1995][3] 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. 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

* Tel: +31 70 374 0571, Fax: +31 70 374 0654, E-mail: robin.schoemaker@tno.nl

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of electro-optical radiation. For engineering purposes, the most used model is the extensive MODTRAN code [Kneizys *et al*., 1996][10], which has been developed by the US Air Force. The introduction of the NAM (Navy Aerosol Model [*Gathman*, 1983][5]) and NOVAM (Navy Oceanic Vertical Aerosol Model, [*Gathman et al*., 1989][7]) models in MODTRAN has improved the description of marine aerosols in the boundary layer above deck height. For the near-surface region below deck height, efforts are underway to develop ANAM (Advanced Navy Aerosol Model [*Gathman et al*., 1998][8], [*Van Eijk et al*., 2002][18]. The ANAM code is currently not available in MODTRAN. Several engineering tools provide an extension to the MODTRAN code for the assessment of electro-optical effects, e.g. IRBLEM [*Dion and Schwering*, 1996][4] and EOSTAR/ARTEAM [*Kunz et al*., 2004][11]. The latter, EOSTAR (Electro-Optical Signal Transmission and Ranging) / ARTEAM (Advanced Ray Tracing in the Earth's Atmosphere), 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 (A)NAM 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 (A)NAM, 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 (A)NAM, it is also necessary to assess the concentrations of the individual aerosol types.

The uncertainty in the ratio of marine and continental particles and the uncertainty in the chemical composition of continental particles are both accountable to the inaccuracy of predictions by the models in this coastal zone. The exact concentration and composition of the aerosol mixture depends on a multitude of (meteorological) parameters, such as wind speed and wind direction, and the distance to the various sources. Due to the relatively rapid changes in meteorological conditions in the coastal zone, and due to the fact that many over-land sources are highly localized, the aerosol mixture is spatially and temporally inhomogeneous. A successful description of this mixture requires not only the local meteorological parameters, but also the distance to individual sources and mesoscale meteorological conditions that have governed the dispersion from these sources. This implies that any model aiming at describing the aerosol composition in the coastal zone requires a large footprint, the inclusion of local sources and advection processes. An example of such an extensive model is NAAPS (Navy Aerosol Analysis and Prediction System) by NRL Monterey. For practical purposes, however, it may be worthwhile to have a simpler, stand-alone and fast model available to obtain a zero-order estimate of the aerosol extinction in the coastal zone. When (A)NAM is considered for this purpose, it is evident that a parameter must be introduced that governs at least part of the aerosol variability in the coastal zone. [*Piazzola et al*. 2000][14] and [*Piazzola et al.* 2004][15] have shown that the introduction of fetch (the distance an air mass has traveled over water) in (A)NAM leads to reasonable estimates of the aerosol extinction in the coastal zone. This concept is currently being exploited and will be reported elsewhere.

In this contribution we focus on another route to obtain information about the aerosol variability in the coastal zone, i.e. the exploitation of satellite data. Rather than the extensive modeling as done by NAAPS, we consider the possibility of retrieving information about the aerosol mixture from experimental data. These data may be introduced directly in models such as EOSTAR describing aerosol effects on EO-propagation, or alternatively, may be used to complement the model predictions by (A)NAM. 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. Many 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 (ATSR-2 and AATSR) with a sensor pixel resolution of 1 x 1 km^2, and this offers a high potential for detailed aerosol assessments in coastal waters. 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.

2. MARINE AEROSOL MODELS

2.1 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 part (mode radius adjusted according to humidity) and a non-hygroscopic part (fixed centre radius of 0.03 µm). 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 (radius > 5 microns) marine aerosols [*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][19]). (A)NAM 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][13] show that considerable aerosol production takes place in this region. The development of a coastal version of ANAM may remedy these shortcomings.

2.2 NOVAM

The Naval Oceanic Vertical Aerosol Model (NOVAM) ([*Gathman and Davidson*, 1993][6]) 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.

3. AEROSOL RETRIEVAL FROM SATELLITE DATA

3.1 Instrumentation

The satellite radiometers of interest in this pilot study are the ATSR-2 instrument onboard the European ERS-2 (European Remote Sensing) satellite and the AATSR instrument onboard ENVISAT (Environmental Satellite), both orbiting the Earth at a height of approx. 800 km. (A)ATSR stands for (Advanced) Along-Track Scanning Radiometer and both instruments are actual identical with the difference that the Advanced version is modified for the ENVISAT platform and has a higher data rate. (A)ATSR 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. First, the radiometer views the surface along the direction of the orbit track at an incidence angle of 55° as it flies toward the scene. Then, some 150 seconds later, it records a second observation of the scene at an angle close to the nadir view. The spatial resolution is 1 x 1 km^2 at nadir and the swath width is 512 km. This 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 water surface these corrections are straightforward and a single view observation suffices. Land pixels however show very bright surface reflectances. For single view remote sensing of aerosol properties over land information is required on the reflective nature of the surface. By combining the two views of (A)ATSR it is possible to eliminate the surface reflectance and surface albedo leaving only atmospheric corrections. The multi-viewing capability of the satellite sensor constitutes an improvement over data obtained from single view measurements, and made it possible to develop an algorithm to retrieve aerosol properties over land surfaces in a rather accurate and unique way, see e.g. [*Veefkind et al*., 2000][21] and [*Robles Gonzàlez*, 2003][16]. One of these properties is the Aerosol Optical Dept (AOD), which is a measure of the amount of scattering and/or absorbing aerosol in the atmospheric column.

3.2 Retrieval procedure

At TNO aerosol properties are retrieved from (A)ATSR 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 a fast and efficient algorithm that allows for near real-time processing and that is suitable for semi-operational use. The algorithm includes all necessary corrections for surface and atmospheric effects including fully automated cloud screening procedures. Cloud-free pixels are essential for a proper retrieval of aerosol properties, hence three tests for the presence of clouds are used based on cloud detection routines developed by [*Koelemeijer et al*., 2001][9]. Subsequently, corrections for ozone, surface contributions (ocean) and atmospheric (Rayleigh) contributions are involved. The final product of this procedure is the corrected measured TOA (top of the atmosphere) reflectance at the satellite sensor.

The algorithm includes an integral aerosol part that allows for the modelling of an external mixture of two aerosol types. This is achieved by means of a look-up table approach. The aerosol types have to be specified a priori, the two types can be anthropogenic aerosol (sulphate/nitrate water soluble) and sea salt for example. A Mie scattering code and a Radiative Transfer Model are used for the generation of look-up tables (LUT's) containing - for the three visible wavelengths and the 1.6 μm wavelength - the TOA reflectances, TOA AOD values, transmission, single scattering albedo, Stokes parameters, reflectance at the surface, sun-satellite geometry, and a few other parameters. Each LUT contains a large number of possible aerosol atmospheres for one aerosol type for the complete sun-satellite geometry. The core part of 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 AOD for the four mentioned (A)ATSR wavelengths. See Fig. 1 for a schematic overview of the retrieval procedure.

The AOD is the column integrated extinction at the top of the atmosphere. The AOD is zero when no aerosols are present in the atmospheric column. A value larger than zero gives a measure of the amount of scattering and/or absorbing aerosols in the atmospheric column. In most instances, yet depending on the wavelength, the AOD is between 0 and 1.5. For values larger than 1.5 the amount of aerosols in the column is extreme. A second important retrieved property is the Ångström coefficient α, which is an indicator for the size distribution of the mixture. This coefficient can be determined through the wavelength dependence of the AOD (and hence TOA reflectance). A small value for the Ångström coefficient α, i.e. in the range 0.0 – 1.0 implies coarse particles. Larger values, say 1.0 – 1.5, specify in most cases an external mixture of coarse and smaller particles. Largest values in the range 1.5 – 2.5 indicate very small particles for the retrieval. A third retrieval result is the mixture type, a number that shows the relative contribution of each of two aerosol types for each pixel.

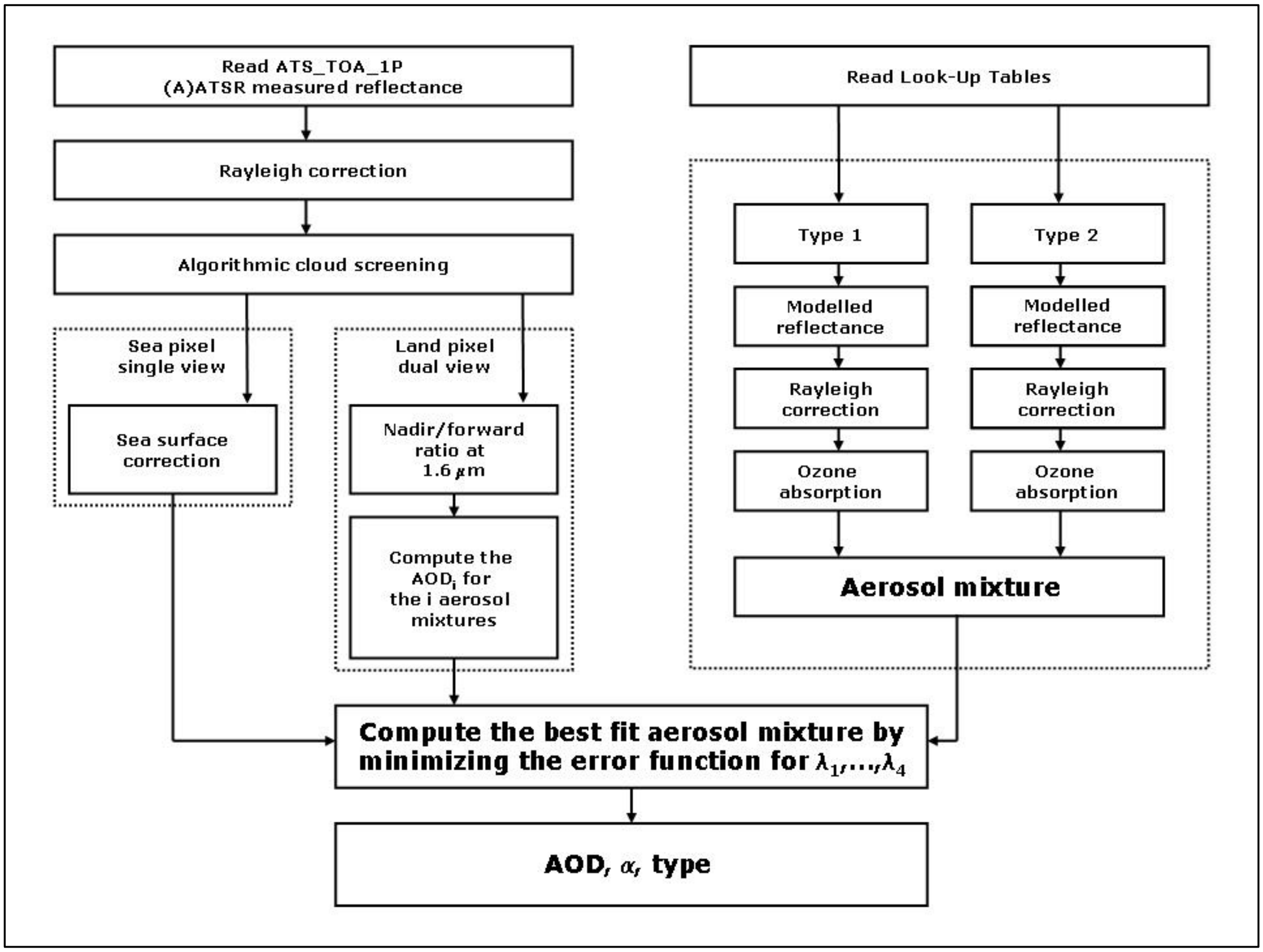
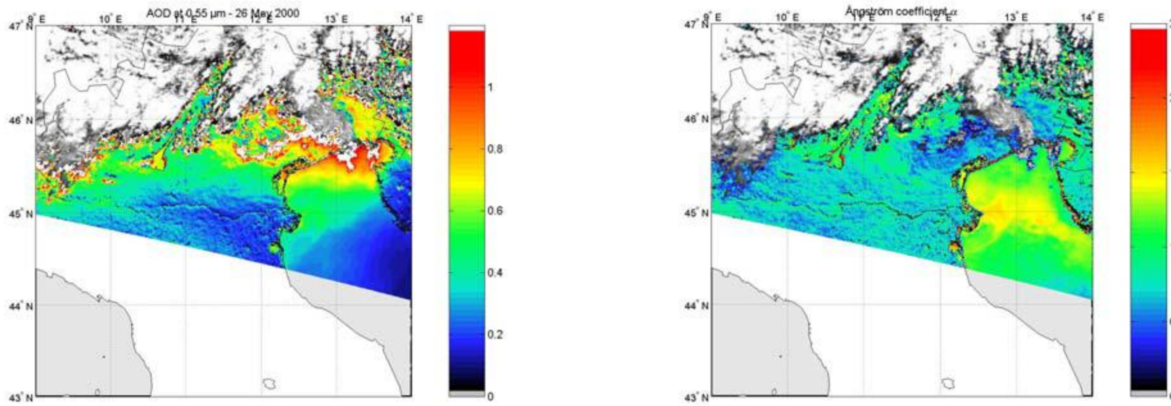


Fig. 1. Retrieval procedure schematic. A retrieval yields AOD (Aerosol Optical Depth), α (the wavelength dependent Ångström coefficient; an indicator for the size distribution), and the mixture type (relative contribution of the two modelled aerosol types).

A retrieval example is shown in Fig. 2. The two pictures show the AOD (Fig. 2a) and the Ångström coefficient α (Fig. 2b). The two aerosol types that have been used in the pre-modelling are a small anthropogenic water soluble particle with a monomodal size distribution and a mode radius of 0.10 μm [*Volz*, 1972][22] and a biomass burning particle, with a bimodal size distribution, and with a small mode radius of 0.15 μm and a large mode radius of 1.5 μm. The retrieval shows the retrieved properties for one ATSR-2 scene above part of Italy and the Adriatic Sea in the generic high resolution of 1 x 1 km^2. It is an example to show the variability of AOD and α in a coastal environment. The Po Basin in Northern Italy is a prime example of extreme poor air quality.



(a) (b)

Fig. 2. (a) Retrieval over part of Italy and the Adriatic Sea in the year 2000. The AOD is shown for the 0.55 µm channel for one scene of 512 x 512 km^2. (b) The Ångström coefficient for the same scene.

4. COMBINING SATELLITE DATA AND AEROSOL MODELS

It is not straightforward to combine satellite data with aerosol models like (A)NAM that are used by propagation codes such as EOSTAR. Propagation codes calculate aerosol transmission losses along the optical path, which requires knowledge of the aerosol extinction as function of height. 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 to complement (A)NAM with satellite data, it should be kept in mind that the prime property retrieved by the satellite component is the Aerosol Optical Depth (AOD), which is a measure for the total amount of aerosols in the atmospheric column between surface and satellite sensor.

The AOD is computed as the integrated extinction along the columnar path for each 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 AOD, which would be essential for estimation of extinction 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][17] 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 to 20 microns [*Van Eijk et al*., 2001][20].

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. Although based on assumptions, this method is efficient and interesting for further statistical analysis.

From a satellite retrieval perspective, it is certainly possible to extend and refine the LUT with other mixing schemes for a particular aerosol component or mixture. As an example, in the coastal environment, close to the land-sea interface, both locally generated aerosols (surf, sand) mix with aerosols (sea salt, continental aerosols) generated elsewhere and advected to the shoreline. It has been shown [*Kunz et al*, 2002][12], [*De Leeuw et al*., 2002][2] that these locally generated aerosols do not necessarily mix efficiently in the vertical, resulting in strong concentration gradients in the lower parts of the boundary layer. This knowledge could be used to generate (pre-modelled) mixing layers in the satellite retrieval procedure for specific conditions and aerosol mixtures. Mixing layers could also be defined on the basis of vertical aerosol models, such as NOVAM, which would constitute a refinement of the simple exponential 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.

The methods outlined above to convert the aerosol optical depth (in the column) to extinction 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 (A)NAM 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 (A)ATSR data yields the distribution of the aerosol properties for each generic hi-res pixel of 1 x 1 km. One (A)ATSR scene thus contains over 25,000 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. CONCLUDING REMARKS AND FUTURE WORK

In this paper we have made an inventory of pathways to apply satellite retrieved aerosol properties to electro-optical propagation models such as EOSTAR. The spatial coverage of the satellite image and the resolution of the order of 1 kilometer of modern satellite instruments, suggest that the assumption of aerosol horizontal homogeneity, which is often made in propagation models, could be relaxed when satellite data is passed to these models. Such a relaxation implies that EOSTAR should be expanded with a third dimension (XYZ instead of XZ), but this expansion seems rather straightforward at this time.

For marine applications, such an expansion would only be meaningful in a region where strong horizontal inhomogeneity in the aerosol concentration and composition is expected, i.e., the coastal zone. It is also here that parametric aerosol models such as the (Advanced) Navy Aerosol Model are less reliable, especially due to uncertainties in the estimate of aerosol composition. Present-day satellite retrieval algorithms, such as outlined in this paper, allow estimating the relative concentration of multiple aerosol species, which potentially leads to a better prediction of the aerosol extinction.

The satellite retrieval algorithm yields a column-integrated property, aerosol optical depth, which is not readily converted into the aerosol extinction at a specific height. However, a number of assumptions allow making reasonable estimates. These estimates can probably be improved by providing additional information to the retrieval algorithm, such as the height of the boundary layer or the presence of a specific mixing layer of aerosols. It might also be possible to estimate the concentration of the marine aerosol component from another model such as ANAM and use this information in the retrieval algorithm.

The above pathways are deliberately kept simple. From an operational point of view, they require (apart from the satellite images) only readily available meteorological parameters and the product (aerosol extinction) can be made available with simple means and in a short time. We realize that the resulting estimates of the aerosol extinction are probably less reliable as those resulting from the use of mesoscale dynamical models, but such models are possibly less interesting from an operational point of view.

It is our intention to explore these pathways in order to find out if the inclusion of satellite data constitutes an improvement in assessing the aerosol extinction over the parametric models such as (A)NAM that are currently used in electro-optical propagation codes. To this end, we will combine satellite data with in-situ aerosol measurements in a coastal region. A potential data source may be an experiment over San Diego Bay that is currently being conducted (August 2005).

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REFERENCES

1. G. De Leeuw, K.L. Davidson, S.G. Gathman and R.V. Noonkester. *Modelling of aerosols in the marine mixed-layer*. SPIE Proc. 1115, 27-1 to 27-8, 1989.
2. G. De Leeuw, G.J. Kunz, G. Buzorius, and C. O'Dowd, *Meteorological influences on coastal new particle formation*, J. Geophys. Res., Vol. 107, No. D19, 2002
3. G. De Leeuw, P.B.W. Schwering, P.J. Fritz and A.N. De Jong, *Long-range IR propagation measurements over the North Sea*. AGARD electromagnetic wave propagation panel 55th specialists' meeting on "Propagation assessment in coastal environments", Bremerhaven, Germany, 19-23 September, 1994. AGARD CP 567, paper 14 (published 1995).
4. D. Dion and Schwering, P., *On the analysis of atmospheric effects on electro-optical sensors in the marine surface layer*, IRIS conference UK, 1996.
5. S.G. Gathman, *Optical properties of the marine aerosol as predicted by the Navy Aerosol Model*, Opt. Eng., 22, 57, 1983.
6. S.G. Gathman and K.L. Davidson, *The Navy Oceanic Vertical Aerosol Model*, NraD Technical Report 1634, San Diego, 1993.
7. S.G. Gathman, G. De Leeuw, K.L. Davidson and D.R. Jensen, *The Navy Oceanic Vertical Aerosol Model: progress report*, AGARD conference proceedings 454, paper17, 1989.
8. S.G. Gathman, A.M.J. Van Eijk and L.H. Cohen, *Characterizing large aerosols in the lowest levels of the marine atmosphere*, SPIE Proceedings 3433, 41-52, 1998.
9. R.B.A. Koelemeijer, P. Stammes, J.W. Hovenier, and J.D. De Haan, *A fast method for retrieval of cloud parameters using oxygen-A band measurements from the Global Ozone Measurement Instrument*, J. Geophys. Res., 106, pp. 3475-3490, 2001.

10. F.X. Kneizys, L.W. Abreu, G.P. Anderson, J.H. Chetwynd, E.P. Shettle, A. Berk, L.S. Bernstein, D.C. Robertson, P. Acharya, L.S. Rothman, J.E.A. Selby, W.O. Gallery and S.A. Clough, *The Modtran 2/3 report and Lowtran 7 model*, Philips Laboratory PL/GPOS, Hanscom AFB, MA, 1996.
11. G.J. Kunz, SPIE Gran Canaria 2004
12. G.J. Kunz, G. De Leeuw, E. Becker and C.D. O'Dowd, *LIDAR observations of atmospheric boundary layer structure and sea spray aerosol plumes generation and transport at Mace Head, Ireland (PARFORCE experiment)*, J. Geophys. Res., Vol 107, No. D19, 2002.
13. F.P. Neele, G. De Leeuw, M. Jansen and M. Stive, *Qualitative assessment of surf-produced sea spray aerosol*, SPIE Proceedings, 3433, 53-62, 1998.
14. J. Piazzola, A.M.J. Van Eijk and G. De Leeuw. *An extension of the Navy Aerosol Model to coastal areas*. Opt.Eng. 39, 1620-1631, 2000.
15. J. Piazzola, G. Kaloshin, G. De Leeuw and A.M.J. Van Eijk. *Aerosol extinction in coastal zone*. SPIE con-ference on Optics in atmospheric propagation and adaptive systems VII, 13-17 September, Maspalomas, Gran Canaria, Spain, 2004.
16. C. Robles González. *Retrieval of Aerosol Properties using ATSR-2 Observations and Their Interpretation*, Ph. D Thesis, Utrecht University, Utrecht, The Netherlands, 2003.
17. Y. Toba, *On the giant sea-salt particles in the Atmosphere. II. Theory of the vertical distribution in the 10-m layer over the ocean*, *Tellus 17,* 365-382, 1965.
18. A.M.J. Van Eijk, L.H. Cohen, L.J. Navarro and G. De Leeuw, *Near-surface aerosol transmission in the marine environment*. SPIE Proceedings 4884, 160-169, 2002.
19. A.M.J. Van Eijk and G. De Leeuw. *Atmospheric effects on IR propagation at sea*. SPIE Conf. San Diego, 11-16 July 1993. Infrared Technology XIX. B. Anderson and F.D. Shepherd (Eds.), Proceedings SPIE 2020, pp. 196-206, 1993.
20. A.M.J. Van Eijk, B.J.S. Tranchant and P.G. Mestayer, *SeaCluse: numerical simulation of evaporating sea spray droplets*. Journal of Geophysical Research (Oceans), 106 (C2), 2573-2588, 2001.
21. J.P. Veefkind, G. De Leeuw, P. Stammes, and R.B.A. Koelemeijer, *Regional Distribution of Aerosol over Land, Derived from ATSR-2 and GOME*, Rem. Sens. Of the Env., 74, pp. 377-386, 2000.
22. F.E. Volz, *Infrared refractive index of atmospheric aerosol substances*, Applied Optics, 11, pp. 755-759, 1972