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ARTEAM

Advanced Ray Tracing with Earth Atmospheric Models

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ABSTRACT

The Advanced Ray Tracing with Earth Atmospheric Models (ARTEAM) aims at a description of the electro-optical propagation environment in the marine atmospheric surface layer. For given meteorological conditions, the model evaluates height- and range-resolved transmission losses, refraction and turbulence effects. These results are subsequently applied to an electro-optical sensor with given specifications to evaluate the effective range and performance of the sensor under the prevailing meteorological conditions. Finally, for specified sensor-target geometry, the model calculates characteristic parameters for geometrical and spectral intensity, scintillation, blur and image distortion. ARTEAM is developed with an extensive Graphical User Interface (GUI) for Windows environments.

Keywords: Refraction, transmission, turbulence, ray-tracing, sensor performance, electro-optical, marine surface layer

1. INTRODUCTION

Electro-optical systems are becoming increasingly important for surveillance applications in the marine environment. Over the years, the technical capabilities of such systems has increased considerably, resulting in larger detection, classification and identification ranges. Electro-optical systems provide a useful complement to radar systems and since they are passive systems, their use may be preferred over active radar systems in certain situations. The range of electro-optical systems is usually shorter than that of radar systems. Interestingly, the range of state-of-the-art electro-optical systems in the marine environment is generally no longer limited by system design, but by the prevailing meteorological conditions.

The atmosphere thus has an important effect on the propagation of electro-optical radiation. Molecules and aerosols in the atmosphere scatter and absorb radiation resulting in transmission losses, and hence a reduced range. In the marine environment, absorption by water vapor is a key process in range assessment for the long-wave IR band (8-12 μm). Aerosols predominantly scatter radiation and are most pertinent to transmission in the short-wave IR band (3-5 μm), near-IR or visible bands. Compared to molecules, the concentration (and the composition in coastal environment) of aerosols is a highly fluctuating quantity, which makes it difficult to assess their contribution to the transmission losses.

The second phenomenon affecting the propagation of electro-optical radiation is refraction. Refraction effects arise from variations in the vertical profiles of meteorological parameters such as humidity and temperature. A distinction is made between long-term, large-scale variations and short-term, small-scale variations. The latter variations are associated with turbulence in the atmosphere, and the resulting refraction effects are generally referred to as scintillation (intensity fluctuations) and blur (image distortion). The term 'refraction effects' is usually reserved for the effects of the long-term, large-scale variations of meteorological parameters, which often are much more drastic than scintillation and blur. Over a range of several kilometers, the large-scale refraction effects may cause significant deviations (ray-bending) of the propagation path as compared to situations where the refractive index of the air is invariant with height (straight line). In this manner, the optical horizon (maximum unobstructed range of sensor) may become smaller than the geometrical horizon (expected maximum unobstructed range without refraction effects), which results in a delayed threat detection. The opposite is also possible resulting in earlier threat detection. In the radar community, such conditions are generally referred to as ducting. Since refraction effects are height-dependent, severe image deformation may occur for extended (not point source) targets. This obviously hampers the classification and identification process. The most dramatic manifestation of refraction effects is the presence of a secondary image (mirage) of a target on the

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detector while in reality there is only a single target. These mirages increase the false alarm rate of surveillance systems and hamper tracking of targets.

The effective detection, classification and identification ranges of electro-optical surveillance systems in a given meteorological scenario are important parameters in the assessment of both the vulnerability of a military platform, as well as its strike capacity. To make this assessment, a tool is required that ideally has now- and forecasting capabilities of the electro-optical propagation environment. From the discussion above, it is evident that such a tool must integrate a variety of modules that describe transmission, refraction and turbulence. Over the years, many of such modules have been developed and presented in literature. An extensive overview and bibliography of these modules is outside the scope of this contribution, but representative examples will be given in the next section. While the individual modules are abundant, few integrated tools are presently available. For electro-optical applications, one of the most complete tools to evaluate atmospheric propagation conditions is provided by the Canadian IRBLEM model.¹ However, this model focuses on scientific applications and is less suited for operational applications.

In view of the relatively few tools available, the TNO Physics and Electronics Laboratory has initiated the development of the Advanced Ray Tracing with Earth Atmospheric Models (ARTEAM). The core of ARTEAM is a flexible structure of modules to characterize the propagation environment, allowing for future additions or upgrades of individual modules. This core is embedded in a Windows-based Graphical User Interface (GUI), which controls both input and output handling. This design allows for input at various levels (e.g. explicit specification of input parameters or selection from predefined databases), as well as output at various levels (e.g., general presentation in coverage diagrams for sensor performance assessment or detailed presentations for analysis of camera data). The next two sections detail the core and GUI of ARTEAM, respectively. A general discussion of the present model and some future prospects conclude this contribution.

2. MODEL DESCRIPTION

2.1 Marine atmospheric surface layer

An important aspect of any propagation model concerns the description of the environment. The initial version of ARTEAM focuses on the lower region of the marine atmosphere, i.e., the marine atmospheric surface layer (MASL). Frictional and convective processes at the surface characterize the MASL. Their effects typically extend to a few tenths of meters above the wave surface. In this surface layer, scaling parameters can be defined which describe the (mean) vertical profiles of wind speed, water vapor and temperature, but also the fluctuations in these quantities due to turbulence. A micrometeorological bulk model evaluates these scaling parameters on the basis of the macroscopic (bulk) input parameters, such as wind speed at a given height. For more information, the reader is referred to the pioneering efforts of *Monin and Obukhov*², the textbook by *Panofsky and Dutton*³ and one of the first bulk models implemented by *Liu, Katsaros and Businger*⁴.

One of the requirements for ARTEAM is that the model can be driven with meteorological parameters that are readily available onboard a ship, such as wind speed, temperature and humidity, each at a single height, and the sea surface temperature. With this in mind, the choice for a micrometeorological bulk model is obvious. ARTEAM applies the Turbulence And Refraction Modeling Over the Sea (TARMOS) model⁵. TARMOS can be used in two modes: with an assumed relation for z_{0m} , the roughness length for momentum,⁶ or with an assumed relation for C_{DN} , the drag coefficient under neutral conditions.⁷ In the latter case, we use the relation for open ocean as given by *Smith*.⁶ The output of TARMOS consists of the (logarithmic) vertical profiles of wind speed, temperature and water vapor, as well as characteristic turbulence (micrometeorological) quantities.

The micrometeorological model does not yield a pressure profile. For the MASL, such a profile is calculated separately from the hydrostatic equation and the reference pressure at a given height. This approach is considered to be sufficiently accurate over the small altitude interval of the MASL.

2.2 Transmission losses

The transmission losses due to molecular constituents of the atmosphere are calculated using the well-known MODTRAN code (version 3.7).⁸ For a general MASL, the concentration of most molecules may be considered constant with height except for the water vapor concentration. As mentioned in the previous sections, this quantity varies

logarithmically with altitude and has a pronounced impact on the IR transmission. It is thus necessary to provide for a height-dependent water vapor concentration in MODTRAN. To this end, MODTRAN is run with a user-defined atmosphere that consists of a number of levels (10) between the surface and the maximum height of interest in a logarithmic spacing. No aerosol or cloud model is selected. At each level, the values of temperature and humidity as calculated by TARMOS are specified, as well as other input parameters that are available. At each of the levels, a horizontal path transmission calculation is made over a selected range. The transmission values are subsequently converted into extinction coefficients to remove the range dependency. This process requires a careful selection of the range for the MODTRAN calculations, since transmission losses over that range should be between 0% or 100% and preferably not peg at either limit. The final output of the module consists of a database of molecular extinction coefficients as function of wavelength and height.

Transmission losses due to aerosol are more difficult to assess due to their highly variable concentration. At the wavelengths of interest to ARTEAM (visible and IR), the aerosol transmission losses mainly arise from Mie scattering. Therefore, the calculation of the aerosol extinction not only requires the absolute number of particles and their composition (which would be sufficient to assess absorption effects), but also size information. This information is generally presented in the Particle Size Distribution (PSD), a plot of the number density versus size. The first step in the assessment of the aerosol extinction therefore consists of a model for the PSD. The well-known Navy Aerosol Model⁹ (NAM) assumes that the PSD can be represented as the sum of 3 log-normal curves (mode). The mode for the larger particles (nominally centered at 2 μm) corresponds to aerosols freshly produced by wind-wave interaction and is related to (instantaneous) wind speed. The middle mode corresponds to aerosols that have spent some time in the atmosphere, and adjusted to the ambient humidity by evaporation (thus reducing their size). They were produced earlier and are related to the average wind speed over the last 24 hours. Finally, the mode corresponding to the smallest particles is considered a background that may also contain particles produced over land and advected out to sea. This mode is most difficult to characterize and utilizes a so-called air-mass parameter related to visibility. To calculate the aerosol extinction, NAM assigns a refractive index to each mode representative for the type of aerosol in the mode, and a Mie calculation is performed over the PSD.

The NAM is a generalized model and aims at providing an estimate for the aerosol extinction at deck height (typically 10 meters). In oceanic environment and at the height specified, NAM performs quite well as evidenced by numerous studies. However, it has been suggested¹⁰ that the NAM underestimates the concentration of larger aerosols (radii in excess of 5 μm) resulting in an estimate of the (IR) extinction that is too low. If so, the NAM calculation will fail even more below deck height, since turbulence is less efficient in transporting these relatively heavy aerosols upward from the sea surface resulting in a relative steep vertical concentration gradient. The Advanced Navy Aerosol Model¹¹ (ANAM) aims at resolving this deficiency in NAM by the introduction of a large particle log-normal mode (4th mode). The 4th mode is assumed to consist of freshly produced particles (hence its amplitude is governed by the instantaneous wind speed) and height dependent. The height dependence is not only governed by altitude, but also by instantaneous wind speed that is a measure for the efficiency of turbulent mixing.

The preliminary version of ANAM¹¹ is being developed on the basis of vertical profiles of aerosol concentration as measured by the Rotorod device.^{12,13} Due to the sparse amount of experimental data available, the development is complemented by numerical simulations of aerosol dispersion in the MASL to establish trends in the concentration of 4th mode aerosols as function of meteorological conditions. The present version of the ANAM is not yet validated and therefore, not yet definitive. However, it is implemented in ARTEAM as an extension of NAM to provide a first estimate of the height-dependent aerosol extinction. To this end, ANAM is used to calculate the aerosol extinction coefficients as function of wavelength at a number of altitudes (10), logarithmically spaced between 0 and 20 meters height. Above that last height, the 4th mode of ANAM yields an almost constant aerosol concentration with height. It is noted that this is probably not correct and the use of ANAM is not recommended above 20-30 meters.

2.3 Refractive index

The long-term, large-scale refraction effects are calculated by a ray tracer based on Snell's law for spherically layered structures, which calculates the actual trajectory of electro-optical radiation propagating through the atmosphere. The basic parameter of the ray tracer is the index of refraction n of the atmosphere, which is wavelength dependent. More often the refractivity $N = (n-1) \cdot 10^6$ is used, since the variations of n in the atmosphere are quite small. Many authors

have reported (approximate) relations to infer the refractivity as function of atmospheric conditions. For visible and infrared radiation, *Eddén*^{14,15} has made pioneering efforts, resulting in the following model¹⁶:

$$N(\nu) = A(\nu) \cdot \frac{P}{P_0} \cdot \frac{(T_0 + 15)}{T} - C(\nu) \cdot \frac{P_w}{P_0} \quad (1)$$

where $P_0 = 1013.35$ hPa, $T_0 = 273.15$ K and

$$A(\nu) = \left[83.42 + \frac{185.08}{1 - (\nu / 1.14 \cdot 10^5)^2} + \frac{4.11}{1 - (\nu / 6.24 \cdot 10^4)^2} \right] ; \quad C(\nu) = \left[43.49 - \left(\frac{\nu}{1.7 \cdot 10^4} \right)^2 \right] \quad (2)$$

The variables in eq.(1) are: ν the frequency in $[\text{cm}^{-1}]$, T the air temperature in $[\text{K}]$ and P_w the water vapor pressure in $[\text{hPa}]$. The latter quantity can be obtained from the temperature and the (absolute or relative) humidity. A sensitivity analysis of eq.(1) shows that $N(\nu)$ is mainly dependent on air temperature and pressure, and that water vapor plays a relatively small role at visible and infrared wavelengths. Other models can easily be incorporated in the model.

2.4 Ray tracer

Ray trajectories in the Earth' atmosphere can basically be constructed from successive application of Snell's law on the interface of two layers, each with their own index of refraction. However, this approach requires extra steps due to the curvature of the Earth. Alternatively, the spherically layered structure can be transformed to a horizontally layered one in which the refractive index transforms to the so-called *modified refractivity*, which is a function of the refractive index and the radius of the Earth curvature. A third and direct approach, which we use in our ray tracer, is the application of Snell's law for spherically layered structures¹⁷, which is given by:

$$n_1 R_1 \sin(\varphi_1) = n_2 R_2 \sin(\varphi_2) \quad (3)$$

With equation (3), the variation in ray direction can be expressed in terms of the first derivative of the refractive index with height and the ray can be constructed relative to the center of the Earth.

The trajectory of a ray is ended when it hits the surface. In the marine environment, the surface consists of waves and their amplitude must be taken into account when evaluating the ray trajectory. The ray tracer accomplishes this by applying a cut-off factor m , as suggested by other authors.¹⁸ Each ray that descends below $m \cdot H_0$, where H_0 is the wave amplitude (trough to crest), is ended. In operational context, the wave amplitude is often not precisely known: it is estimated by an observer or expressed as a sea state. In a scientific experimental context, the wave height is generally expressed as a significant wave height, i.e., the average height of one third of the highest waves, known as $H_{1/3}$. Adopting this value for H_0 , the value of m should be slightly higher than 0.5 to assure "capture" of the rays by the highest waves. Following other authors^{18,19} who tuned m to experimental data, we have set $m = 0.65$ and accounted for the wavy surface. However, this is subject in future versions of ARTEAM.

2.5 Turbulence effects

Optical turbulence is caused by variations of the refractive index due to complex spatial and temporal atmospheric variations. The variations are caused by wind shear and/or by convective process due to vertical gradients in wind speed, temperature and humidity. Therefore, optical and infrared turbulence are closely related to atmospheric turbulence. The driving parameter for the calculation of turbulence effects is the refractive index structure parameter defined as:

$$C_n^2 = \left(\frac{\partial n}{\partial T} \right)^2 C_T^2 + \left(\frac{\partial n}{\partial q} \right)^2 C_q^2 + 2 \left(\frac{\partial n}{\partial T} \frac{\partial n}{\partial q} \right) C_{Tq} \quad (4)$$

This equation describes the relation between the atmospheric structure function parameters C_T^2 , C_Q^2 and C_{TQ} , provided by the bulk model, and the optical structure parameter C_n^2 . The latter is the driving parameter for describing optical turbulence effects in the atmosphere. The temperature and humidity dependence of the refractive index can directly be calculated from Edlén's equation. Scintillation and blur are calculated from special functions²⁰ of C_n^2 integrated over the path of interest.

3. GRAPHICAL USER INTERFACE

The previous section describes the core modules of ARTEAM. In this section, we will concentrate on the input and output of the model, which is controlled by a flexible Graphical User Interface (GUI). In developing the GUI, it was recognized that the (potential) user community of ARTEAM will exploit the model with different goals in mind. For example, users who study the propagation conditions and utilize ARTEAM to analyze experimental data need full control of all input parameters and the most detailed information available. On the other hand, in an operational context, input should be preferably automated and output must be presented in a concise, but informative manner. The GUI offers this variety of options, and can be customized for a specific user.

A meteorological module allows specification of the atmospheric conditions. For full control, the user may specify all input parameters manually. Alternatively, the user can select from an (editable) database with predefined meteorological scenarios of interest, or enter a geographical position to access the climatological database containing monthly averaged meteorological data for the seas and oceans of the world. For nowcasting, ARTEAM may be connected to an automated meteorological station to provide it with actual data.

While ARTEAM is primarily intended to assess the electro-optical propagation environment, such an assessment is not very meaningful without information about the sensor system and potential targets. The required information consists of both geometry specifications (e.g., height, field-of-view, observation direction) and system parameters (e.g., wavelength band, number of pixels on detector, sensitivity, noise). ARTEAM allows full specification of sensor and target parameters, or selection from predefined (editable) databases. It is important that these databases are editable, since most users will prefer to supply their own parameters of sensors and targets. ARTEAM accepts both point-targets and extended targets.

The center of ARTEAM is formed by the ray tracer, which brings together all input and processing modules. For a given sensor geometry and specifications, the ray tracer calculates the spatial coverage of the sensor, i.e., the ranges and heights at which a target can potentially be detected. This calculation provides all information required to generate the output of the model of interest to the user.

Figure 1: Coverage diagram showing potential mirage areas

Figure 2: Ray-trace diagram showing detailed information

Two (customized) examples of ARTEAM output for operational and scientific applications will now be discussed. For surveillance operations, the customer is most interested in a spatial coverage diagram that shows the actual range of the sensor. In this application, ARTEAM presents two output screens. The first provides the intensity on the detector that a (specified) target would have at a particular range and height and can be used for threat analysis. The second output screen is presented in Figure 1, and provides information on the occurrence and locations of mirage images. The three-color figure shows the regions where a target is not seen, (potentially) visible, or generates two images on the detector. This screen can be used for false alarm analyses.

Figure 2 provides an example of more detailed output. For a given sensor system and a given meteorological condition, ARTEAM provides the ray-trace pattern for the sensor, the image deformation function, the possible occurrence of mirages, the spectral transmission losses including geometrical effects as well as the direction and distance of the geometrical and optical horizons. For further analysis, the user may dynamically position a (point) target at a given range and height. Primary parameters describing the propagation path, possible mirages, transmission, image transfer function, blur and scintillation are identified and presented immediately. Additional graphs present the spectral transmission and scintillation of the target as function of range at the specified height, or alternatively, as function of height at the specified range.

Figure 3: Infrared image of a commercial ship used as test target for ARTEAM.

Figure 4: Geometrically distorted long range infrared image of Figure 3, calculated by ARTEAM. Transmission and scintillation effects are not activated in this example.

While the parameters above describe all relevant processes, a visualization process is helpful to understand the full implications. Therefore, a module has been added to ARTEAM that calculates the actual image of an (extended) target as seen by the sensor. Figures 3 and 4 show an example of an infrared image of a ship at short range and at long range (scaled to the same size), respectively. The figure shows at a glance the dramatic effects of refraction only (noise, scintillation, transmission losses and scatter are not activated in this example).

Although ARTEAM is primarily a propagation module, the requirement of sensor and target information raise the question as to ARTEAM can remain as a stand-alone module. In a typical use of ARTEAM to generate a coverage diagram of detection probabilities, more information is required than the propagation environment alone. A signature model would be needed to calculate the actual irradiance of the target at the position of the observer, whereas a background model is called for to calculate the contrast of the target in a scene. It is thus anticipated that ARTEAM will eventually be included in Tactical Decision Aid (TDA), which brings together sensor, target and atmosphere modules, as well as possible camouflage and/or countermeasures.

4. DISCUSSION

The modules described in the previous sections define the framework of ARTEAM. It is emphasized that the model can be driven by standard meteorological information that is generally available at marine platforms. In its present state, the model assesses the performance of electro-optical surveillance systems in the Marine Atmospheric Surface Layer (MASL). Both now- and forecasting is supported, which allows the assessment of platform vulnerability against sea-

skimming missiles. This assessment against these threats is of primary importance due to the short reaction times available for defensive actions.

The micrometeorological module of ARTEAM utilizes relations that are only valid in the MASL. This limits the use of ARTEAM in ground-to-air operations. Limitations also exist for near-surface applications, since the height of the MASL varies considerably as function of atmospheric stability. In very stable conditions (often encountered before dawn), the MASL may not exist at all and the micrometeorological models based on surface layer scaling will fail to give a solution in these cases. It is then necessary to apply a model for the Marine Atmospheric Boundary Layer (MABL). The introduction of a dynamical MABL model seems not feasible for computational reasons, but suitable parameterizations²¹ driven by low-altitude bulk observations are considered for introduction in ARTEAM.

The extension of the vertical domain is likely to violate the requirement that ARTEAM can be driven by the standard shipboard meteorological information. From a meteorological point of view, there is little, if any, relation between the surface conditions and the conditions above the MABL. Thus, additional information in the form of radio-sondes would be required for ground-to-air scenarios. This information would also be required for the calculation of transmission losses by MODTRAN and e.g., the Navy Oceanic Vertical Aerosol Model (NOVAM)²².

Work also remains to be done on the lower boundary of the ARTEAM domain, i.e., the wave surface. As discussed above, the ray tracer now ends each trajectory that descends below the wave crests, since the ray is then considered to hit the water surface. A problem exists here as to the exact cut-off height, since no two waves have the same amplitude. A recent study²³ has shown that certain results of ARTEAM (such as the location of the mirage zone) are very sensitive to the exact cut-off height and suggests that more detailed information about the wave field is required.

The presence of waves also affects the airflow in the near-surface region (typically up to 5-10 meters above the wave crests). This is not taken into account by the micro-meteorological models, which assume a flat surface. Hence, there is a bias in the low-altitude refraction profile resulting in erroneous in the ray trajectories. Experimental evidence also demonstrates the break-down of ray tracing algorithms near the sea surface.¹⁸ Beaulieu²⁴ was one of the first to recognize this problem and to propose a solution consisting of averaging individual refraction profiles over one wave length. After incorporating this idea in a ray-tracer²⁵, more correct results were obtained than with traditional flat-surface algorithms, although the results appeared not conclusive.¹⁸ Other models exist to take the wave influence on the airflow into account. The SeaCluse model²⁶ averages individual profiles of water vapor and temperature over one wave, and then applies turbulent mixing to these scalar quantities throughout the MASL and MABL. Using these profiles as input for the ray tracer, better results than with standard meteorological models were obtained in some cases.²³ Clearly, this topic requires additional attention.

Another issue concerns horizontal homogeneity. ARTEAM assumes a horizontally homogeneous atmosphere, which is a simplification that could be acceptable in open ocean but probably not in coastal regions, today's operational areas. Close to the coast and with off-shore winds, the atmospheric and surface conditions may change considerably over the typical ranges of 20-40 km as considered by ARTEAM. It is difficult to improve ARTEAM for these conditions: it would require a coastal atmospheric model (e.g., capable of handling internal boundary layers), a module for wave growth, and a module for aerosol dispersion. While such modules have been developed, their implementation in ARTEAM is not obvious and may not lead to the desired result. For example, an aerosol dispersion module is meaningless without knowledge about local and regional aerosol sources. One of the possible solutions here is to enlarge the input data for ARTEAM by satellite observations and/or onboard lidar measurements.

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