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EOSPEC: A complementary toolbox for MODTRAN calculations

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ABSTRACT

For more than a decade, Defence Research & Development Canada (DRDC) has been developing a Library of computer models for the calculations of atmospheric effects on EO-IR sensor performances. The Library, called EOSPEC-LIB (EO-IR Sensor PErformance Computation LIBrary) has been designed as a complement to MODTRAN™, the radiative transfer code developed by the Air Force Research Laboratory and Spectral Science Inc. in the USA. The Library comprises modules for the definition of the atmospheric conditions, including aerosols, and provides modules for the calculation of turbulence and fine refraction effects. SMART (Suite for Multi-resolution Atmospheric Radiative Transfer), a key component of EOSPEC, allows one to perform fast computations of transmittances and radiances using MODTRAN through a wide-band correlated-k computational approach. In its most recent version, EOSPEC includes a MODTRAN toolbox whose functions help generate in a format compatible to MODTRAN 5 and 6 atmospheric and aerosol profiles, user-defined refracted optical paths and inputs for configuring the MODTRAN sea radiance (BRDF) model. The paper gives an overall description of the EOSPEC features and capacities. EOSPEC provides augmented capabilities for computations in the lower atmosphere, and for computations in maritime environments.

Keywords: radiative transfer, EO-IR propagation, atmospheric refraction effects, atmospheric turbulence effects

1. INTRODUCTION

MODTRAN, a worldwide reference in the field of atmospheric radiative transfer, has been historically designed by the US Air Force for calculations in altitude (including space) or for addressing relatively steep slant paths to/from ground. Severe MODTRAN limitations were reported for many decades by users dealing with calculations near the surface. In particular, in computations at horizon ranges, MODTRAN ray-tracing often failed, and the MODTRAN atmospheric layering was regrettably too coarse to handle fine variations of refraction and of atmospheric constituents (molecular species and aerosols). MODTRAN 5 [1], released several years ago (hereafter denoted as MOD5), featured a series of improvements and utilities that contributed to alleviate many of the shortcomings. Among the new MOD 5 features, let us mention the new flexible way to define aerosol vertical profiles and the capability to handle user-defined refracted paths, both in new user input files. Furthermore, of great interest for computations in maritime environments, MODTRAN now incorporates a sea radiance model. However, settings of these new MODTRAN capabilities can prove somewhat tricky, with rules that may restrain their use.

For the last decades, DRDC Valcartier has been developing a Library of functions that provide capabilities complementary to MODTRAN. The Library, called EOSPEC-LIB (EO-IR Sensor PErformance Computation LIBrary), is composed of a suite of C/C++ functions and its architecture has been designed as an Application Programming Interface (API). EOSPEC was built up upon the IR Boundary Layer Effects Model (IRBLEM) developed by DRDC in the early 90's [2]. EOSPEC contains modules that are especially useful for calculations at low altitude and for calculations in the maritime environment. The most recent version of EOSPEC features a MODTRAN toolbox whose aim is to facilitate exploitation of new capacities in MOD5.

EOSPEC is presented in Section 2, while Section 3 briefly introduces the new MODTRAN toolbox.

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2. EOSPEC-LIB

In the early 90's, DRDC Valcartier developed IRBLEM to provide capacities not included in MODTRAN for the computation of near-surface propagation effects. Among the main capacities brought up by IRBLEM we can mention:

- Efficient and stable ray-tracing for high precision line-of-sight calculations
- Computation of anomalous refraction effects
- Computation of turbulence effects
- Models of maritime aerosols other than NAM (the Navy Maritime Model contained in MODTRAN).

Figure 1 shows the IRBLEM block-diagram and Figure 2 shows a comparison between computations of Signal-to-Noise Ratio obtained with IRBLEM combined with the German TRP model and IR measurements collected during a ship tracking experiment [3].

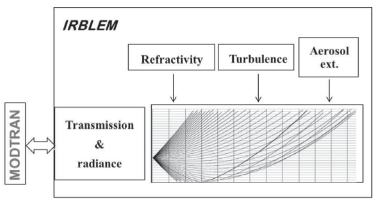

Figure 1. IRBLEM block diagram

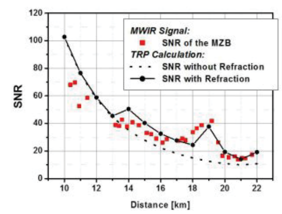

Figure 2. IRBLEM-TRP calculations against measurements (excerpt from [3])

A major shortcoming of IRBLEM was the uncoupling of calculations of atmospheric effects in and above the surface layer. Uncoupling of layers hampers computations of transmission across atmospheric layers. In particular, it invalidates computations of atmospheric and background radiances, which necessitate reliable computations of energy fluxes transport throughout all atmospheric layers, from space to ground.

In the last decade, bilateral efforts between Canada and the US led to new significant capacities in MODTRAN improving calculations at low altitudes. The number and thickness of layers can now be easily defined by users with very minor restrictions. In addition, MOD5 featured a very flexible means to define aerosol contents of atmospheric layers through the use of the SAP user input files (see MOD5 user's manual). Furthermore, MOD5 can handle user refracted optical paths saved in files (the pth files)[1].

Concurrent to the MOD5 development in the US, DRDC undertook to put together a library of functions to complement and assist MODTRAN computations, building up on IRBLEM principles. The library, called EOSPEC, has been structured for Advance Programming Interfacing (API) to facilitate integration of functions into user c/c++ applications. The library provides Integrated Development Environments (IDEs) supporting development of WINDOWS applications using Visual Studio and Linux applications using Code::Block.

EOSPEC functions can be broken down in two categories, providing tools for environmental characterization and for propagation effects computation, respectively.

2.1 Environmental characterization with EOSPEC

EOSPEC comprises a suite of core modules aimed at characterizing the environmental conditions in preparation of calculations of atmospheric effects on sensors. The suite comprises functions for the modeling of thermodynamic profiles, and for the calculations of profiles of index of refraction (refractivity) and turbulence. EOSPEC also contains a module for the modeling of aerosol profiles in maritime environments. The EOPSEC core environmental profiles comprise two stratified regions: the surface and the upper-air regions. This is illustrated in Figure 3, taking the air temperature as an example.

[1] Although ray-tracing has been improved in MOD5, erratic outputs may still occur in situations requiring fine layers and high angular resolution. The code is nevertheless more robust than before and exits more gracefully upon failure.

2.1.1 - **Modeling of thermodynamic profiles**

Thermodynamic profiles near the surface are modeled based on the Monin-Obukhov Similarity (MOS) theory with module MslMc (MainSurfaceLayerModelc). The MOS model used in EOSPEC is described in Appendix of Ref [4]. Validity of MOS profiles is generally accepted to be limited to about 2-3 times the Monin-Obukhov scaling length (e.g. stability length), and it rarely extends beyond 30 m. For the definition of profiles in the upper-air region, a selection of options is provided by module MetProf (Meteorological Profile). One of the six MODTRAN standard atmospheres can be selected or alternatively one can use measured profiles. Various file formats are supported including TEMP, widely used among meteorologists.

In a final process, profiles in the surface and upper-air regions are linked (blended) in a way to ensure physical consistency of the resulting temperature and moisture profiles. A fitness factor is generated as output to quantify the quality of the blending. To support applications involving both EO-IR and RADAR sensors, MetProf provides options that allow ones to minimize - if required - impacts on the RF surface duct heights, a key parameter characterizing RF propagation. Figure 4 shows a blending example of temperature and moisture profiles.

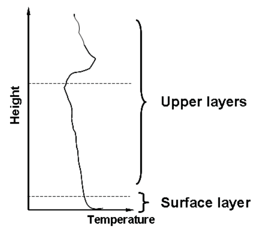

Figure 3. The two atmospheric regions considered by EOSPEC core functions.

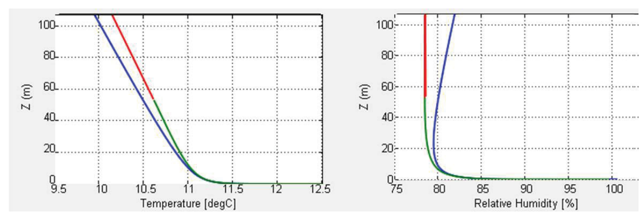

Figure 4. Example of surface and upper-air profile blending with MetProf.

2.1.2 – Computation of refractivity and turbulence (Cn2) profiles

EOSPEC provides different ways to get the refraction profiles. Module RefProf contains functions written in C and C++ using as input thermodynamic profiles obtained from MetProf or from other sources. Alternatively, within user applications, it may prove more convenient to exploit directly the dedicated SMART C++ object (see section 2.2.2 on SMART).

Cn2 profiles can be calculated using the EOSPEC core module Cn2Prof. Profiles near the surface are modeled after Potvin et al. [4]. The model was built upon the conventional expression for Cn2 derived from MOS theory. A new term is added to account for flux nonuniformities along the propagation path. Furthermore, for propagation above sea, a modified expression was developed to account for the alleged variation of the Monin-Obukhov *fluctuation* length caused by the air-sea interaction. Figures 5 and 6 shows comparisons between calculations with the conventional and maritime Cn2 expressions, respectively, against Cn2 derived from scintillation measurements collected by the Space and Naval System Warfare Command Center, in the San Diego Bay. Above the surface region, Cn2 profiles obey the Kukharets-Tsvang formulation [5] as modified by Murphy [6].

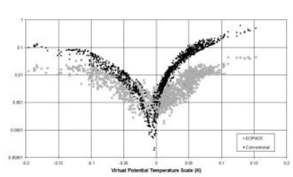

Figure 5. Comparison between measured Cn2 over sea and calculations using the conventional (land) model.

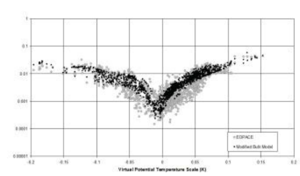

Figure 6. Comparison between measured Cn2 over sea and calculations using the EOSPEC "sea" model.

2.1.3 – Definition of hydrometeors and maritime aerosols properties

EOSPEC core module AeroProc can be invoked for determining properties of hydrometeors (e.g. fog, rain, snow) and maritime aerosols. The AeroProc standard output comprises vertical profiles of the total spectral extinction coefficient, the spectral scattering coefficients and of the normalized phase function.

Hydrometeor extinction coefficients are derived from the visibility when given as input. If not, fog extinction is evaluated using the fog liquid water content using different expressions for the advective and radiative fog. Rain extinction is calculated considering Marchall-Palmar distributions for strati-form rain, or Laws-Parson distributions for convective rain. Snow extinction is calculated based a DRDC model developed a few years ago [7]. In this model, extinction depends on the crystal type. If not specified as input, the crystal type is inferred by the model based on temperature and humidity.

AeroProc provides several alternatives to the Navy Aerosol Model (NAM, incorporated in MODTRAN) for the modeling of aerosols in the marine surface region. Like in NAM, the models in AeroProc are based on a sum of log-normal distributions, characterizing the different modes/sources of aerosols into play. The AeroProc default model is an improved version of WKDAERX developed by Low and Loeb [8]. This is a three-mode model wherein mode 2 and 3 (characterizing the concentration of sea water droplets) are made dependent upon both the current and the 24 hr-average wind speeds. With WKDAERX, amplitude of mode 1 (for the background particles) can be inferred from the input visibility, thereby eliminating the inconvenience of the Air Mass Parameter in NAM/MODTRAN. WKDAERX also models the vertical variation of the extinction in the surface region. As an alternative, AeroProc includes MEDEX [9], a model that incorporates a 4^{th} mode for the characterization of the giant water droplets (> 10 microns). An interesting feature of MEDEX is its dependence upon the *fetch* (the distance over which the wind blows over sea). Accounting for the fetch has been demonstrated to be important especially for calculations in littoral environments. Figure 7 exhibits calculations of WKDAERX and MEDEX surface profiles compared to NAM for the same input condition. Validity of WKDAERX and MEDEX is addressed in Ref [10] wherein predictions are compared against transmission measurements.

With AeroProc, profiles of aerosols in the upper-air region are computed using a revised version of NOVAM. The later had to be revisited to alleviate instabilities and to comply with the 4-mode models. For all surface models, modal radii's vary with the relative humidity, and thus with elevation.

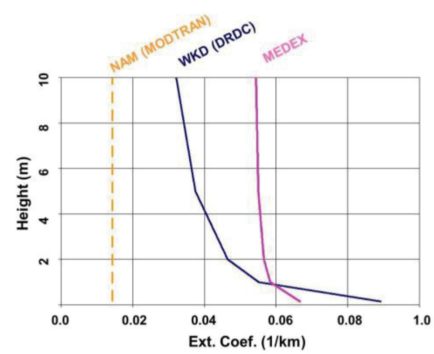

Figure 7. Surface profiles of aerosol extinction coefficients obtained from the main models included in EOSPEC .

2.2 Computations of propagation effects EOSPEC

2.2.1 – Core propagation effect modules

EOSPEC core module RefPath contains functions for the calculation of optical ray-path and raw refractance, using as input a vertical refractivity profile, while module RefPlane allows one to calculate for a given sensor Field-Of-View the full ray pattern in a given distance-elevation plane. As done by IRBLEM, RefPlane outputs the Maximum Inter-Vision Range versus height and the target height-looking-angle relationship at a range specified as input.

EOSPEC also provides a module for the calculations of parameters characterizing effects of turbulence on target images. The module calculates: the coherence length needed for the modeling of the atmospheric modulation transfer function and the variance of image displacement. Furthermore, the variance of intensity fluctuation can be calculated using an improved model which allows one to account for both the size of the target and the sensor aperture [11].

2.2.2 – SMART

A key module of EOSPEC is SMART (Suite for Multi-resolution Atmospheric Radiative Transfer) which provides an alternate high-performance radiative transfer solution throughout an advanced exploitation of MODTRAN. Through an efficient wideband correlated-k (CK) approach, SMART can perform very fast computations of transmittance and radiance for wideband sensors. For a given setting of atmospheric condition, initialization of MODTRAN is performed just once for computations required in the entire propagation space. After initialization, calculations for an entire sensor band can be many orders of magnitude faster than traditional radiative transfer computations, while maintaining fairly good accuracy. Details on SMART and examples of large performance gains are exposed in Ref.[12] .

Being mindfully linked to the EOSPEC core modules, the SMART module makes use of the EOSPEC atmospheric characterization capacity, and accounts for refraction with great efficacy alleviating constraints in MODTRAN.

3. THE EOSPEC MODTRAN TOOLBOX

A MODTRAN toolbox was recently added to EOSPEC to facilitate exploitation of the MOD5 capacities discussed in Section 1 and 2. The use of the MOD5 new options are somewhat tricky, especially regarding the stringent rules that must be followed for the creation of the SAP and PTH files. The toolbox functions provide assistance for the setting of the inputs.

The toolbox currently contains four modules providing support for running MODTRAN with:

- User-defined atmospheric profiles
- User-defined Spectral Aerosol Profiles
- User-defined Refracted Paths
- The Ross-Dion sea Bi-directional Reflectivity Distribution Function (BRDF) contained in MODTRAN [13][14].

The four modules provide both C / C++ functions/objects to assist edition of the tape5 MODTRAN input file. The produced tape5's are compatible with both version 4 and 5 of MODTRAN. The Spectral Aerosol Profile and Refracted Path modules contain in addition procedures for generating respectively the *.sap* and *.pth* files required for the MODTRAN calculations. The modules assure consistency among the various inputs generated for MODTRAN. Furthermore, each module contains examples showing how to use the toolbox functions/objects. Note that the examples do not provide assistance for the overall tape5 edition. In the examples toolbox functions are used to write the cards required by the selected options considering a default tape5 initialization. Besides, the toolbox contains stand-alone applications (.exe) designed as flexible tools for the generation of cards considering user inputs saved in ASCII files.

Moreover, the toolbox also contains methods/objects to support computations using the MODTRAN 6 API. Running MOD6 through the API is much more convenient than through the legacy mode, which requires complying with tape5 or JSON file formats. Each of the four modules of the EOSPEC toolbox contains C and C++ examples of calculation using the API.

4. CONCLUSION

As a follow-on of the IRBLEM development in the 90's, DRDC Valcartier undertook at the start of the new century the development of EOSPEC, a C/C++ library providing modeling capabilities not included in MODTRAN. The library core modules comprise functions for the calculations of fine refraction and turbulence effects, and for the modeling of aerosols in maritime environments. SMART, a key EOSPEC sub-library, provides an high-performance radiative transfer solution for wideband systems, through an advanced interaction with MODTRAN. An overall description of the EOSPEC main capacities was given in this paper. A MODTRAN toolbox, recently added to EOSPEC, facilitates exploitation of some of the new capabilities of MODTRAN 5. Information on EOSPEC distribution and licensing can be obtained by contacting the Author.

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For more than a decade, Defence Research and Development Canada (DRDC) has been developing a Library of computer models for the calculations of atmospheric effects on EO-IR sensor performances. The Library, called EOSPEC-LIB (EO-IR Sensor PErformance Computation LIBrary) has been designed as a complement to MODTRAN, the radiative transfer code developed by the Air Force Research Laboratory and Spectral Science Inc. in the USA. The Library comprises modules for the definition of the atmospheric conditions, including aerosols, and provides modules for the calculation of turbulence and fine refraction effects. SMART (Suite for Multi-resolution Atmospheric Radiative Transfer), a key component of EOSPEC, allows one to perform fast computations of transmittances and radiances using MODTRAN through a wide-band correlated-k computational approach. In its most recent version, EOSPEC includes a MODTRAN toolbox whose functions help generate in a format compatible to MODTRAN 5 and 6 atmospheric and aerosol profiles, user-defined refracted optical paths and inputs for configuring the MODTRAN sea radiance (BRDF) model. The paper gives an overall description of the EOSPEC features and capacities. EOSPEC provides augmented capabilities for computations in the lower atmosphere, and for computations in maritime environments.