# MATISSE: version 1.2 and future developments

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*Abstract -* **This paper presents the MATISSE-v1.2 code which computes spectral or integrated natural background radiance images. The spectral bandwidth extends from 765 to 3300 cm$^{-1}$ (3 to 13 µm) with a 5 cm$^{-1}$ resolution. Natural backgrounds include the atmosphere, low altitude clouds, sea and land. The most particular functionality of the code is to take into account atmospheric spatial variability quantities (temperatures, mixing ratio, etc) along each line of sight of the image. In addition to image generation capability, the code computes atmospheric radiance and transmission along a line of sight with the same spectral characteristics as in imaging mode. In this case atmospheric refraction effects and radiation from high or low altitude clouds are taken into account. A high spectral resolution mode is also available to propagate radiation from a high temperature medium in the same atmospheric state as that used for the image generation. Finally, the code is developed with a modular architecture in order to facilitate its use in conjunction with external codes .**

**This paper describes the range of functionalities of Matisse-v1.2. Computation results and comparisons with results from other codes are presented, along with future developments : Matisse-v1.3 containing an improved refraction model, Matisse-v1.4 allowing computation in the marine boundary layer and Matisse-v2.0 whose main purpose is to modelize sea radiance images with a 1 meter spatial resolution.**

## 1 INTRODUCTION

MATISSE (Advanced Modeling of the Earth for the Imagery and the Simulation of the Scenes and their Environment) is an infrared background scene generator. It was developed in order to meet the requirements of natural background radiance images and radiative quantities (local illumination, spectral transmission, …), expressed by DGA (French MOD) and French Defense companies.

Unlike most other image simulators, which favorize computation speed to the detriment of physical realism, MATISSE was developed to generate reference images using methods efficient in terms of accuracy and computation time. MATISSE-v1.2 contains the functionalities of MATISSE-v1.1 [ 1], [ 2], incorporating improvements from first users feedback and adding new functionalities, in particular, a line of sight (LOS) mode which computes spectral radiance and transmission along a LOS taking into account atmospheric refraction. The code architecture is designed for image generation, but this approach is unadapted to a LOS mode. A modification of the architecture is planned to optimize this mode.

During the code's development, new requirements appeared which led to further upgrades. These new upgrades, still ongoing, are presented at the end of this article.

## 2 DESCRIPTION OF MATISSE-v1.2

The mission of MATISSE-v1.2 is twofold – firstly, to provide spectral radiance and transmission images of natural backgrounds and secondly, to propagate radiation resulting from a high temperature target in the same thermodynamic environment as that of the images. The architecture is adapted for these functionalities. However, during development of the code, the need emerged to compute radiation along a LOS with the same atmospheric environment and spectral features as those of the generated images. To this end, a LOS mode was added, with slightly different functionalities from those of the imaging mode. These functionalities are described in the paragraph on LOS mode.

### *2.1 Functionalities of imaging mode*

The aim of imaging mode is to generate spectral radiance images such as seen by an observer, defined by the observer's position in geocentric coordinates, its altitude, the viewing geometry and the characteristic image parameters (field of view, number of pixels). The computed image is a radiance image, i.e. each pixel of the image corresponds to a unique radiance along the LOS. In this case, the sensor's field of view (FOV) is used only to determine the area seen by the observer. No angular integration is performed on pixel FOV.

### *A. Molecular absorption model*

The spectral bandwidth extends from 765 to 3300 cm$^{-1}$ (3 to 13µm) with a 5 cm$^{-1}$ computation step and a 5 cm-1 spectral resolution. Code outputs are spectral radiance images and spectral transmission images.

With regards to molecular absorption, the code uses a Correlated K (CK) model developed by ONERA [ 3]. In addition to the benefit of this kind of model for computing atmospheric propagation (accuracy/computation time efficiency, molecular absorption/scattering coupling), the choice of this method fully addresses one of the functional requirements for MATISSE, ie. the ability to generate a series of images without systematically computing the whole of the radiative scene parameters. To do so, these radiative parameters (atmospheric source functions, extinction coefficients, background radiance) are computed for the whole of the area for each of the 17 CK parameters and subsequently stored in files. Image generation then consists in reading these files and, for each pixel on the image, propagating the source terms corrected by molecular absorption. Expression (1) illustrates this point. The left term is the average radiance seen by the observer in the spectral interval $\Delta\sigma$ and the $\theta$, $\varphi$ direction. The first term on the right represents the surface background radiance (land, sea or cloud) propagated through the atmosphere. The second term on the right represents the contribution of atmospheric source functions. Once computed, the $L_S^i(\theta, \varphi)$ and $J^i(s,\theta,\varphi)$ terms are stored in files. Radiance computation then consists in reading these radiative quantities and propagating them with the CK model along the path from the background to the observer.

$$\overline{L}_{obs}^{\Delta\sigma}(\theta,\varphi)=\sum_{i=1}^{N} w_i L_S^i(\theta,\varphi) e^{-\int_{S_0}^{obs} k_i^{ext}(s')ds'} + \sum_{i=1}^{N} w_i \int_{S_0}^{obs} e^{-\int_{s}^{obs} k_i^{ext}(s')ds'} J^i(s,\theta,\varphi) k_i^{ext}(s) ds \quad (1)$$

where

- $N$ is the number of quadrature points,
- $w_i$ is the $i^{th}$ quadrature weight,
- $L_S^i(\theta, \varphi)$ is the background surface radiance in the $\theta$, $\varphi$ direction when the radiative transfer equation is resolved with the $i^{th}$ value of the CK parameters,
- $J^i(s,\theta,\varphi)$ is the atmospheric source function, at the location $s$ and in the $\theta$, $\varphi$ direction when the radiative transfer equation is resolved with the $i^{th}$ value of the CK parameters,
- $k_i^{ext}(s)$ is the $i^{th}$ value of the CK parameters at position $s$.

With the use of a CK model, we are able to use Beer's law in the MATISSE architecture. Of the various models describing molecular absorption in the infrared with average spectral resolution (typically a few cm$^{-1}$), only CK approach allows the use of Beer's law. The model comprises 17 quadrature points on each 5 cm$^{-1}$ interval. To limit computation times during code execution, all the thermodynamic profiles contained in MATISSE databases are converted into CK profiles, ie. each vector containing all thermodynamic data at a given altitude is replaced by the 17 K values. To do so, the absorption coefficients are initially computed for each spectral element using a line by line model. They are subsequently sorted by increasing value of K. CK coefficients are then evaluated at the quadrature points. To preserve the layer to layer spectral correlation, CK weights are identical on the entire atmospheric column from 0 to 100 km of altitude. The profiles are then stored in a CK database.

### *B. Modeled backgrounds*

Modeled backgrounds in MATISSE are land, sea, clouds and the atmospheric background.

#### Atmospheric background

Atmospheric background comes from thermal emission along the LOS, direct solar illumination and solar radiation scattered by aerosols and molecules.

Thermal emission is computed with the assumption of Local Thermodynamic Equilibrium (LTE) from the ground to the top of the atmosphere. This assumption is justified for the major parts of the observation geometries used in imaging. This would not be the case for high altitude limb viewing for certain spectral bands [ 4]. With regards to atmospheric scattering, MATISSE includes the discrete ordinates RTRN21 code [ 5] for the multiple scattering term, also providing the local sphere of illumination in each discretization point of the atmosphere.

In most atmospheric radiative transfer codes or scene generators, the atmospheric thermodynamic quantities (pressure, temperature, mixing ratios) vary with altitude but are horizontally homogeneous. This assumes that, on a horizontal LOS of several hundred kilometers, the thermodynamic profile remains unchanged. One of the functionalities of MATISSE is that it can take into account this spatial variability along each LOS of the image. The code architecture models the atmosphere on a grid. To each node are associated thermodynamic parameters (pressure, temperature, mixing ratios,…) and all the computed radiative parameters (atmospheric source functions, sphere of illumination, extinction coefficients,…). Input data can be either weather forecast output codes providing a collection of atmospheric profiles on a given zone and horizontal sampling (Europe sampled to 0.25°x0.25° for EUROC25 scenes from MétéoFrance, the French weather bureau), or user-defined 1D profiles used to construct a 3D scene. For aerosols, MATISSE contains the 5°x5° sampled GADS climatology database with global coverage [ 6]. Scattered radiation is then computed using RTRN21 code applied to each aerosol climatology sample. This results in a pseudo-3D computation of atmospheric scattering. Once the radiative quantities have been computed and stored on nodes of the atmospheric grid, the radiation is propagated using Beer's law.

Atmospheric data comprise thermodynamic profiles and aerosol optical properties. The thermodynamic profiles are divided into three categories according to their spatial extension :

- 1D profiles are used over the whole computed scene. 1765 atmospheric profiles are available. These include 1761 radiosounding measured over the whole of Earth (TIGR database [ 7]) and a further 4 of the standard AFRL [ 8] profiles (US Standard, Midlatitude summer/winter, Tropical),

- 2D profiles come from a climatology [ 10] providing the average thermodynamic profile on each latitude band with a 10° sampling and for 8 seasons of 45 days,
- 3D scenes contain a collection of profiles with a spatial resolution of 0.25°x 0.25° (EUROC25 scenes from Météo France); currently, a scene of extension of part of France is available.

The 1D profiles resulting from measurements and the 3D profiles from weather forecast output codes are generally available only for a maximum altitude of 10 km. These profiles are then extrapolated to the top of the atmosphere to be directly usable in the code (use of PRFL model [ 9]). These data are then stored in databases.

Likewise, the aerosol data are divided into two categories :

- horizontally uniform aerosol data on the whole scene. This includes part of the AFRL aerosol data (rural, urban, maritime and tropospheric) [ 11]
- 3D data from GADS climatology [ 6] providing all the optical parameters on a grid of global coverage with a 5°x5° spatial resolution over two seasons.

*Land and sea background*

Land is geometrically modeled by triangular facets using a digital model of elevation with reference to Mean Sea Level (MSL). Two spatial resolutions are currently available in MATISSE databases. One spatial resolution represents a 30 arc-second at the equator (900m) with a global coverage [ 12]. The other spatial resolution represents a 3 arc-second at the equator and is limited to part of Europe and North Africa. Access to this database is restricted and requires authorization from the French military cartography department.

Land thermo-optical properties are stored in a database. A land use selected from 17 IGBP (International Geosphere-Biosphere Program) categories (forests, savanna, agricultural zone,…) is associated to each element of the 30 arc-second resolution DTED (Digital Terrain Elevation Data). Spectral reflectivity and an effusivity are associated to each category of land use (currently the spectral reflectivity stored in the database is assumed to be Lambertian but the code architecture was designed to take into account possible directional effects).

The code also comprises a thermal model to compute the temperature of each facet of the land. This model supposes absence of heat transfer between facets and periodical temporal evolution of radiative energy deposit on the ground. Under these conditions, surface temperature temporal variation can be obtained by a Fourier Transform model [ 13]. Deposited radiative flux comprises direct and scattered radiative energy. Scattered energy is computed with a 2-stream model using the local atmospheric profile. A total cover of standard stratocumulus or cirrus clouds can also be taken into account.

The sea is geometrically modeled by facets with a 30 arc-second resolution (as for the global coverage DTED) with the WGS84 ellipsoid as reference. The radiation resulting from each facet takes into account both the thermal emission and the reflection of the local sphere of illumination. There is currently no specular reflection effect and the sea temperature is taken from ASST climatology (Averaged Sea Surface Temperature [ 14], spatial resolution is 0,5°x0,5°) derived from ATSR (Along Track Scanning Radiometer) satellite measurements.

Lastly, a texture model was included into the code to artificially introduce ground radiance spatial variability. This model is based on Power Spectral Density (PSD) derived from specific images acquired during measurement campaigns.

*Cloud radiation*

The code uses two different approaches. The first yields images containing a partial coverage of stratocumulus resulting in cloud radiance spatial variability (sampled to 500 m). The second approach yields a total coverage of stratocumulus or cirrus clouds, horizontally homogeneous over all the image. This latter approach has been developed mainly for the LOS mode as it does not introduce radiance spatial variability but only a homogeneous cirrus cloud to the image.

In the first approach, the clouds are modeled by faceted objects to which surface properties (BRDF, BTDF and emissivity) are applied. These three quantities are precomputed with RTRN21 code then included into MATISSE as a database. From the user-defined input data (coverage rate, minimal cloudbase altitude, maximum cloud thickness, spatial sampling), a cloud coverage generator computes the spatial distribution of the stratocumulus within the image. The cloud surface is subsequently generated as facets to which the previously computed surface properties are associated. The radiation is then computed from the radiative environment in the vicinity of the cloud, and the local temperature. This method, called Independent Pixel Approximation [ 15], assumes that radiation from each cloud facet is independent from the contribution of all other facets. It is justified on condition that the facet size is sufficiently large and that the solar angle and observation angle are sufficiently far removed from the horizontal).

As in land background treatment, a texture model increases radiance spatial variability on each facet. Moreover, the cloud shadows projected onto the ground can be taken into account. The direct solar illumination of the hidden facets is zero, however the local sphere of illumination does not take the cloud into account. This limits the validity of the approach.

In the second modeling type, the cloud coverage is systematically global. Cloud parameters are assumed to be horizontally homogeneous, however they are dependant on altitude. Radiation is computed during code execution by adding a layer containing the cloud’s optical parameters (phase function, extinction and scattering coefficients,…) to the atmospheric quantities. This computation approach is similar to that applied to aerosols. The clouds modeled in this mode are stratocumulus or cirrus.

### *C. Code architecture*

MATISSE is executed in two successive phases: an initialization phase and a rendering phase.

In the first phase, all the radiative quantities (atmospheric source functions, extinction coefficients, grounds and clouds radiances) are computed in all directions and for the whole of the spectral band required by the user, and stored in binary files.

These files are then read in the rendering phase, so that only background radiance and atmospheric source functions propagation is computed. This allows determination of radiation at observer level for various possible geometries. This phase uses the 3D OpenGL version 1.2 Library, which constructs the image at observer level from the scene facets by eliminating the hidden parts.

### 2.2 *Line of sight mode*

This mode computes radiance and transmission along a single LOS. Part of the functionalities of the imaging mode are used. Some modifications have been made, these will be described below.

The spectral characteristics and the absorption model are identical to those of imaging mode: spectral band 3 – 13 µm, 5 $cm^{-1}$ computation step and spectral resolution, CK model. The outputs are spectral radiance and transmission. These two quantities can also be integrated by a user-defined spectral response of the sensor. The observer is defined by its position in geocentric coordinates and its altitude with respect to the reference ellipsoid. Radiance propagation is performed either by considering the straight optical path from the background to the observer, or by taking into account atmospheric refraction effects. In this latter case, the observer position and the observation angles are imposed. The code then computes the path from the observer and stops when the path exits the atmosphere, or reaches the ground or a user-defined distance.

The ground is no longer modeled by a DTE but is assumed to be uniform and geometrically described by the reference ellipsoid (WGS84) with a user-defined temperature and albedo.

Radiation from clouds is computed with the assumption of a uniform horizontally infinite layer. The clouds considered are stratocumulus (2 microphysics available) and cirrus.

Atmospheric features (thermodynamic profiles, aerosols, models) are identical to those in imaging mode.

### 2.3 *High spectral resolution computation*

This mode computes thermal radiance (no scattering) and transmission using a line by line model [16]. This functionality computes high spectral resolution propagation along a single LOS with the same atmospheric characteristics as those in imaging mode. This allows computation of radiation from a high temperature target in an image.

Radiance and transmission are computed on the spectral band from 765 to 3300 $cm^{-1}$ with a resolution ranging from 0.1 to 0.005 $cm^{-1}$ (automatic computation according to thermodynamic conditions) along the LOS. Refraction can be included in the computation. There is no background nor aerosols in this mode. On the other hand all the thermodynamic profiles in imaging mode and 3D atmospheric scenes can be used.

### 2.4 *Validation*

Most of the code functionalities were validated in the previous version of MATISSE (version 1.1). This present validation concerned only new functionalities and performed tests of non-regression vis-a-vis MATISSE-v1.1.

The validations compared the results of MATISSE-v1.2 with those of other codes: LBLRTM [17] for high spectral resolution mode and MODTRAN4 [18] for the LOS mode. In both cases, results are in agreement for equivalent functionalities (no 3D atmosphere) and for identical atmospheric parameters. To satisfy atmospheric parameter validation, certain MODTRAN data were inserted into MATISSE for the test duration to evaluate purely algorithmic behavior. This approach leads to a satisfactory comparative agreement of the models.

One specific point should be noted namely the discrepancies appearing in water vapor bands during line by line model validation. These discrepancies are due to the fact that different modelings were used for water vapor continuum, on the one hand modelised by LBLRTM code (use of model CKD [19]) and on the other hand by the MATISSE line by line model which uses the continuum models developed by the "Laboratoire de PhotoPhysique Moléculaire" (CNRS) [20] designed for the line by line model. Experimental validation will be necessary to evaluate the respective performances of these models.

For imaging mode, propagation computations were self-validated by comparing radiance obtained on the central pixel with the radiance computed in the LOS mode.

### 2.5 *Results*

Below are two results obtained with MATISSE-v1.2. The first result is in imaging mode. The second result is in LOS mode.

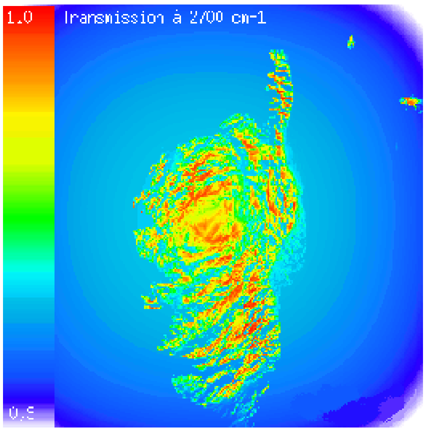

Figure 1 : imaging mode - transmission image

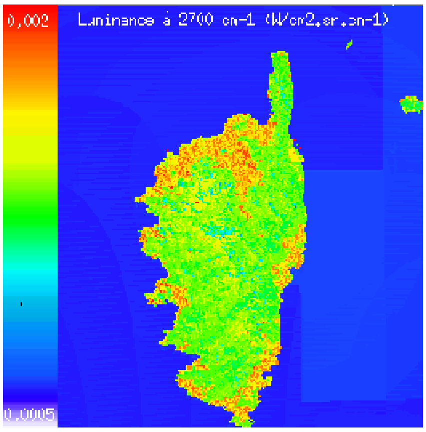

Figure 2 : imaging mode - radiance image

Figure 1 represents a transmission image. The observer is located above Corsica (9° E/42.3°N) at an altitude of 90 km and at 12h00, local time. The number of pixels is 200 X 200, the total field of view is 80° and the wavenumber is equal to 2700 $cm^{-1}$ (3.7 µm). This wavenumber corresponds to an atmospheric transmission window, confirmed by the values appearing on the color scale to the left of the figure (between 0.9 and 1). In the center of the image we can see that the highest transmission values correspond to the mountain ranges in Corsica (the shortest distance from the observer) and that the minimum transmission value is located at the corners of the image corresponding to the field of view effect.

Figure 2 represents the radiance ($W/m^2.sr.cm^{-1}$) obtained with the same configuration as that of the previous image. We can see the radiance spatial variability on the land background, due to temperature variations and to the reflected radiation induced in both cases by different land uses, the local ground orientation and differing altitudes. On the sea background we can see the appearance of “tiles” due to the lower spatial resolution of the ASST database (which is only 0,5°x0,5°).

The results below are taken from a study performed within the framework of the AIREW project (Airborne Infrared Early Warning**)** [ 21**]** funded by the DGA**.** In this project, radiance fluctuations induced by atmospheric variability along the horizontal optical path were to be estimated. MATISSE was thus used to evaluate the impact of the thermodynamic profile variations along the LOS over radiance variations. A 3D scene was generated with three atmospheric profiles selected from the MATISSE database (profiles 58, 105 and 267).

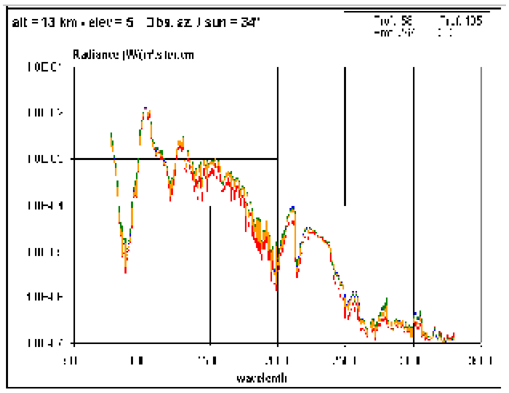

Figure 3 : LOS mode - radiance computed in 4 different atmospheric conditions

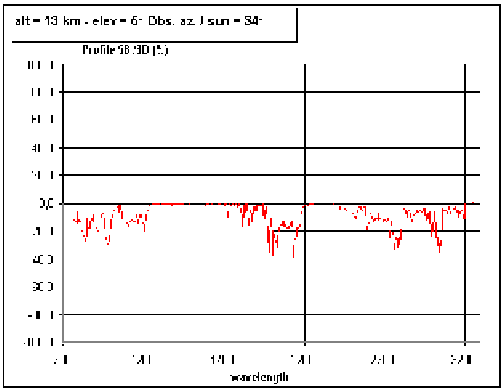

Figure 4 : LOS mode - radiance relative differences

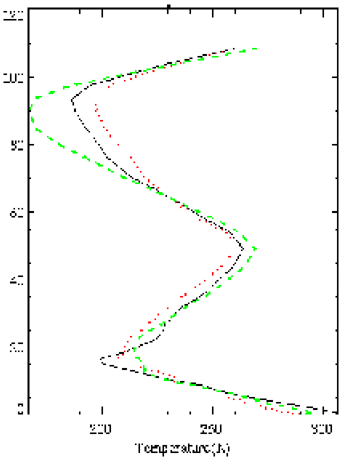

Figure 5 : temperature profiles selected for the study

Figure 3 shows the radiances computed along a LOS for four different atmospheric configurations. The observer is located at 16° North and 6° East, at an altitude of 13 km. The path length is approximately 1000 km and elevation is equal to 5° (zenith angle 85°). The difference between the solar azimuth and the observational azimuth is 34°. The observation takes place at 12h00 local time on June 21.

On Figure 3, the blue curve represents the radiance computed assuming that profile 58 is identical along all the LOS. The green curve makes the same assumption with profile 267. Similarly for the red curve with profile 105. The temperatures associated with these profiles are presented on Figure 5. The orange curve represents radiance by assuming that the path goes through the three profiles consecutively, the first profile being profile 58, the last being profile 105. We can see radiance variability between the configurations. Figure 4 represents the difference between the radiance obtained in the 3D case and the radiance obtained using profile 58 (closer to the observer) along all the LOS. We can see differences in radiances reaching almost 30%. This information can be critical for the development of optronic systems.

### *2.6 Code distribution*

Currently the code is distributed to the French defense industry. This initially addressed the request by the DGA. It is also distributed to state run establishments under MOD supervision (Celar, SHOM). The DRDC (Defense Research and Development for Canada) in Valcartier, Quebec, also uses the code within the framework of a specific French-Canadian agreement (AS20).

The code is designed to function on a SUN-type workstation running with Solaris 2.8 or and IBM-type worksatation running with AIX4.3. MATISSE databases require 20 Gb of disk space for optimum use. The code can operate with reduced data but in this case some functionalities are lost.

A new streamlined and more widely accessible version of MATISSE is being considered. It will run on any system and will be downloadable from Internet.

An Internet page dedicated to MATISSE (http://matisse.onera.fr) is under construction. This page contains a presentation of the code and its functionalities, registration facilities and access to descriptive documentation (user's manual). Registered users will have access to reserved information, FAQs, a forum, and downloadable previous versions of MATISSE.

## 3 FUTURE VERSIONS

### *3.1 MATISSE-v1.3*

This new version, operational in September 2005, has a new functionality for computing refraction in LOS mode. In version 1.2, when the user wants to compute radiance or transmission along a LOS, the position of the observer and the observation angles are imposed. The program then automatically computes the geometry of the refracted path from the observer. Propagation stops as soon as the path exits the atmosphere, or if the path reaches the ground or a user-defined distance. The new functionality, under development, authorizes the user to set both the observer and the target positions in the same computation. The observation angles and the observer/target distance is then determined by finding the shortest optical path between the two extremities. Localization error evaluation on ground level, represented by the difference between the refracted path and the straight line path, is available to the user.

### *3.2 MATISSE-v1.4*

MATISSE-v1.4 is being developed in collaboration with the DRDC (Defense Research and Development for Canada) in Valcartier, Quebec. The objective is to compute radiance propagated along a LOS in the maritime boundary layer. Two tasks are to be addressed. The first task is to modelize input data. The second task is to develop a fine geometrical module to allow determination of multiple paths (possibility of several refracted paths).

Input data comprise thermodynamic profiles and aerosol data. Thermodynamic profiles are obtained using a Bulk model on an altitude of 0 to 10 m, extended by local radiosounding data, subsequently extrapolated to the top of the atmosphere by program PRFL [ 9] (cf). Aerosol data are taken from three sources. The first, the AP (Aerosols Profile) model, developed by the DRDC, provides areosol data to an altitude of 30 m. The second, the NOVAM model [ 22], provides data from 30 m to 3 km. The third, the AFRL's models, are used to extend the profile to the top of the atmosphere. The geometric module is taken from a module contained in IRBLEM code [ 23] adapted for integration into MATISSE.

This release is scheduled for the end of year 2005.

### *3.3 MATISSE-v2.0*

The latest version under development requires a major architectural modification. This modification justifies a change of classification. In Version 1.2, the computed resolution of land background radiance spatial variability was not finer than the DTE (30 arc-second at the equator, which represents about 700m at our latitudes).

MATISSE-v2.0 introduces a 1 meter scale spatial variability on background. Although the requirements are for all background types (grounds, sea, cloud, atmosphere), MATISSE v2.0 will include only sea variability. Nevertheless studies on land background spatial variability are currently ongoing at ONERA, and the code architecture will be adapted to incorporate the resulting models in a future version.

MATISSE-v2.0 will be able to generate irradiance images of the sea, taking into account the effects of solar glint, with a finest resolution of 1 meter. Sub-pixelic variability will be included. The requirement to compute images of any observational geometry implies development of a multi-scale model to generate images in grazing view geometry (multiresolution in the field). The user can thus zoom in on the images.

Obviously, all the functionalities of previous versions will be included to ensure non-regression. MATISSE-v2.0 should be available in fall of the year 2008.

## 4 CONCLUSION

All the functionalities of MATISSE-v1.2 have been presented in this article. Spectral or integrated radiance and transmission images, ground radiation with ground temperature computation, sea radiation, stratocumulus cloud radiation and high temperature radiation propagation. The code can also be used to perform computations along a LOS taking into account atmospheric refraction.

New versions are under development: version 1.3 for computing target/observer refraction, version 1.4 for computing in the maritime boundary layer. Finally, version 2.0 will generate images from sea backgrounds containing spatial radiance variability to a finest resolution of 1 meter and taking into account solar glint.

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