Automatic Temperature Computation for Realistic IR Simulation

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ABSTRACT

Polygon temperature computation in 3D virtual scenes is fundamental for IR image simulation. This article describes in detail the temperature calculation software and its current extensions, briefly presented in [1]. This software, called MURET, is used by the simulation workshop CHORALE of the French DGA. MURET is a one-dimensional thermal software, which accurately takes into account the material thermal attributes of the three-dimensional scene and the variation of the environment characteristics (atmosphere) as a function of the time. Concerning the environment, absorbed incident fluxes are computed wavelength by wavelength, for each half an hour, during 24 hours before the time of the simulation. For each polygon, incident fluxes are composed of : direct solar fluxes, sky illumination (including diffuse solar fluxes). Concerning the materials, classical thermal attributes are associated to several layers, such as conductivity, absorption, spectral emissivity, density, specific heat, thickness and convection coefficients are taken into account. In the future, MURET will be able to simulate permeable natural materials (water influence) and vegetation natural materials (woods). This model of thermal attributes induces a very accurate polygon temperature computation for the complex 3D databases often found in CHORALE simulations.

The kernel of MURET consists of an efficient ray tracer allowing to compute the history (over 24 hours) of the shadowed parts of the 3D scene and a library, responsible for the thermal computations.

The great originality concerns the way the heating fluxes are computed. Using ray tracing, the flux received in each 3D point of the scene accurately takes into account the masking (hidden surfaces) between objects.

By the way, this library supplies other thermal modules such as a thermal shadow computation tool.

Keywords: simulation, thermal computation, infrared, battlefield, realism.

1. INTRODUCTION

Due to the increasing costs of current and future weapons systems validation and qualification trials, both government services and industrial companies opted to use simulation.

Intelligent systems have better accuracy of sensors and associated signal processing devices. In these cases, realistic simulations, thanks to processors growing computation power, are quite useful.

Realistic visualization in the infrared spectrum requires accurate temperature knowledge on the surface of the polygons in the 3D scene used in the simulation, thus justifying the use of a thermal program.

For these reasons, CHORALE, an OKTAL product recently acquired by French DGA, is enhanced with MURET thermal software, a product of French ONERA Research Center .

2. OVERVIEW OF CHORALE

2.1. Presentation

CHORALE is a specialized IR visualization system. The problem particularly tackled by CHORALE is the evaluation of weapons detection systems in study or in development. There are several domains of applications: missiles, intelligent ammunitions, gunnery systems; search and fire control systems; target furtivity and self-protection; satellite reconnoitering.

The first step for using CHORALE is defining a 3D virtual scene where the simulation will take place. This scene reproduces a realistic environment containing one or more weapon systems with IR sensors. The second step, is the computation of physical data, as accurate as possible, to be perceived by the sensors operating in the scene.

Moreover, to a better accomplishment of these objectives, CHORALE is also delivered as a library with a comprehensive API, enabling to build transverse applications. System performance is not strongly sensitive to scene complexity, number of polygons or number of textures.

2.2. Components

CHORALE does not supply any 3D modeling tools. GAIA IR module can be used to create physical attributes (to add or edit temperatures, spectral physical material description and thermal complementary information). PTT (Photoshop texture Tool) module enables producing IR textures from a physical material database.

Atmospheric data are pre-computed with ATC (Atmospheric Tool Compiler) module that uses LOWTRAN. Interfaces to MOSART will be soon available. SPECRAY module is the kernel of CHORALE containing a spectral ray tracing and a physical model for radiance exchanges. Antialiasing algorithms are implemented for both geometry and radiometry. The main window is useful to process scenarios by defining a set of moving or static objects, a set of sensors, an atmospheric file, a horizon/sky model file, and by activating the calculation of an image or a sequence of images. SPECRAY can also deal with 3D textures, decoys and flares models, and even 3D cloud representations (voxels). At last, the VISUSPS module enables to show and analyze spectral images computed by SPECRAY. For each pixel, it can indicate the radiance in each spectral band, the code of the object displayed in the pixel and the distance to the sensor.

Other optional tools can be supplied (i.e. 3D clouds model creation) but are not considered as belonging to the CHORALE workshop.

3. MAIN FUNCTIONNALITIES OF THE THERMAL LIBRARY

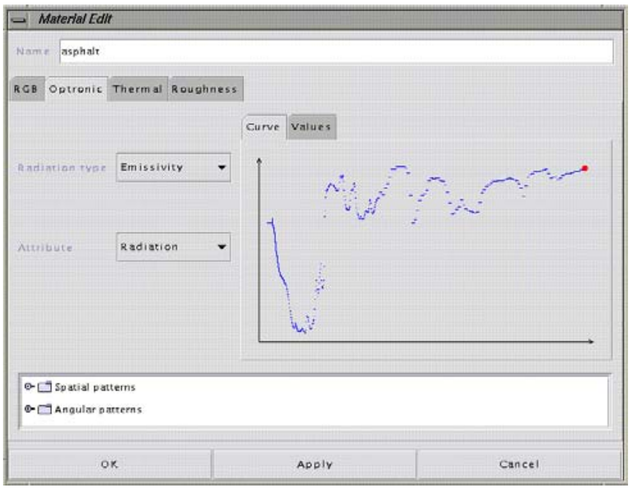
The thermal library calculates polygon temperature according to:

- ➔ polygon geometry (normal vector, height, …),
- ➔ the temporal evolutions during a period of 24 hours of the absorbed flux and external air temperature,
- ➔ material thermal attributes (conductivity, specific heat, density, absorptivity, thickness, composition, …),
- ➔ internal temperature of the air (in the case of a wall).

3.1. Geometry model

CHORALE is based on the SDM format, which is an ASCII format for 3D databases representation, and the SDM++ format which is the extended file format (with extensions for physical data).

In the SDM format, polygons are classically described by a list of vertices. Each vertex is represented by its X,Y,Z coordinates in an absolute coordinate system. Each polygon has its own temperature and is "colored" by an element of a material database. Each material can be shared by many polygons in the database.

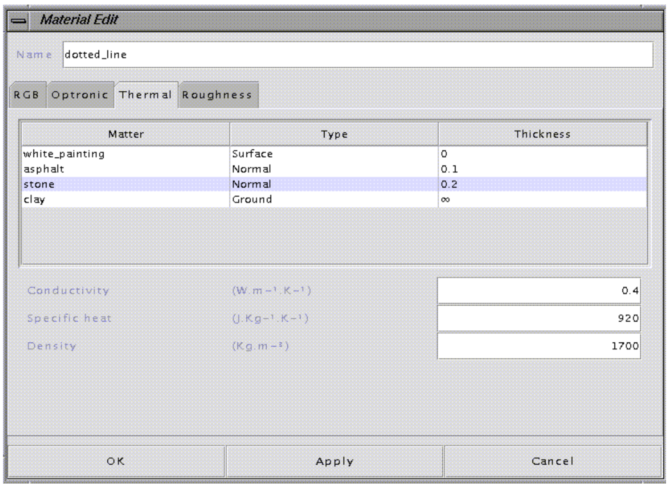


Name: asphalt

Radiation type: Emissivity

Attribute: Radiation

GAIA IR GUI for the edition of material physical attributes



Name: dotted_line

Matter	Type	Thickness
white_painting	Surface	0
asphalt	Normal	0.1
stone	Normal	0.2
clay	Ground	∞

Conductivity ($W.m^{-1}.K^{-1}$) 0.4

Specific heat ($J.Kg^{-1}.K^{-1}$) 920

Density ($Kg.m^{-3}$) 1700

GAIA IR GUI for the edition of material thermal attributes

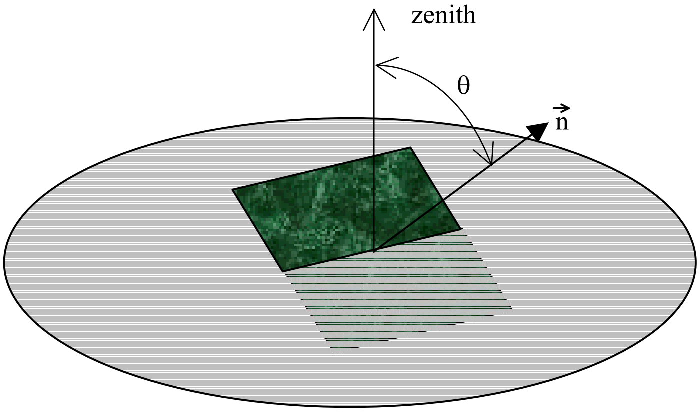
In SDM++ format, a material can be extended with :

- ➔ spectral physical attributes (BRDF(λ), emissivity ε(λ), …),
- ➔ thermal attributes (conductivity Λ, specific heat C_p, …),
- ➔ the composition for multi layers material

Modeling tool GAIA IR of the CHORALE workshop is used to create or enhance the material database.

3.2. Absorbed fluxes

Absorbed fluxes are calculated for each polygon in the 3D database. This computation takes into account the orientation of the polygon. Let $\vec{n}$ be its normal vector, and G its geometrical center. Zenith angle θ is the angle between the zenith and the normal vector.



Absorbed fluxes are computed for each ½ hour during 24 hours before the simulation time t for the polygon temperature computation. Incident fluxes is composed of sun irradiance and sky irradiance (at the moment, irradiance due to the ground is not considered). The data to compute sun and sky irradiance are stored in atmospheric propagation files (.atm files).

3.2.1. Atmospheric propagation file description

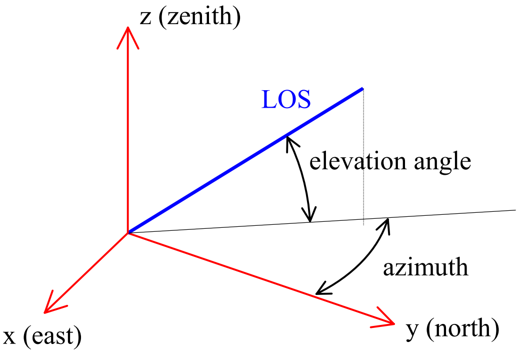
An atmospheric propagation file is valid for a specific world position, a specific day of the year, a specific time of day and a specific atmospheric condition. These files are pre-computed before the temperature calculation and contain the following information:

⇨ sun irradiance : $\frac{dE_{sun}}{d\lambda}[\lambda_i][h_j]$, for :

- ⇒ a list of wavelengths (λ_0, λ_1, …, λ_i, …, λ_I),
- ⇒ and a list of heights (h_0, h_1, …, h_j, …, h_J)

⇨ atmospheric attenuation: $\tau[\lambda_i]\,[h_j][d_k][s_m]$, for :

- ⇒ a list of wavelengths (λ_0, λ_1, …, λ_i, …, λ_I),
- ⇒ a list of heights (h_0, h_1, …, h_j, …, h_J),
- ⇒ a list of ranges (d_0, d_1, …, d_k, …, d_K)
- ⇒ and a list of elevation angles (s_0, s_1, …, s_m, …, s_M)



⇨ sky radiance $\dfrac{dL_{sky}}{d\lambda}$ $[\lambda_i]$ $[h_j][d_k]$ $[s_m][g_n]$, for :

- ⇒ a list of wavelengths (λ_0, λ_1, …, λ_i, …, λ_I),
- ⇒ a list of altitudes (h_0, h_1, …, h_j, …, h_J),
- ⇒ a list of ranges (d_0, d_1, …, d_k, …, d_K),
- ⇒ a list of elevation angles (s_0, s_1, …, s_m, …, s_M)
- ⇒ and a list of azimuths (g_0, g_1, …, g_n, …, g_N)

Typically, the list of wavelengths covers the spectral domain from 0.3 to 30 µm.
Atmospheric propagation files can be generated using atmospheric propagation software such as LOWTRAN, MODTRAN, MOSART

3.2.2. Incident fluxes

The polygon is illuminated by :

➔ the irradiance of the sun:

A ray is cast from G towards the Sun. Sun position is given by ephemeris data of the associated atmospheric data file. To perform this ray casting, the 3D database is, first of all, voxelised by an efficient and powerful algorithm of SPECRAY library. After the ray is cast and the returned result indicates if the point G is in shadow or not. If the point G is illuminated by the sun, attenuation τ_n (λ) along the Line Of Sight (LOS) towards the sun is also given. This attenuation does not include atmospheric attenuation because it is already included in the solar irradiance $E(h_G,t,\lambda)$.

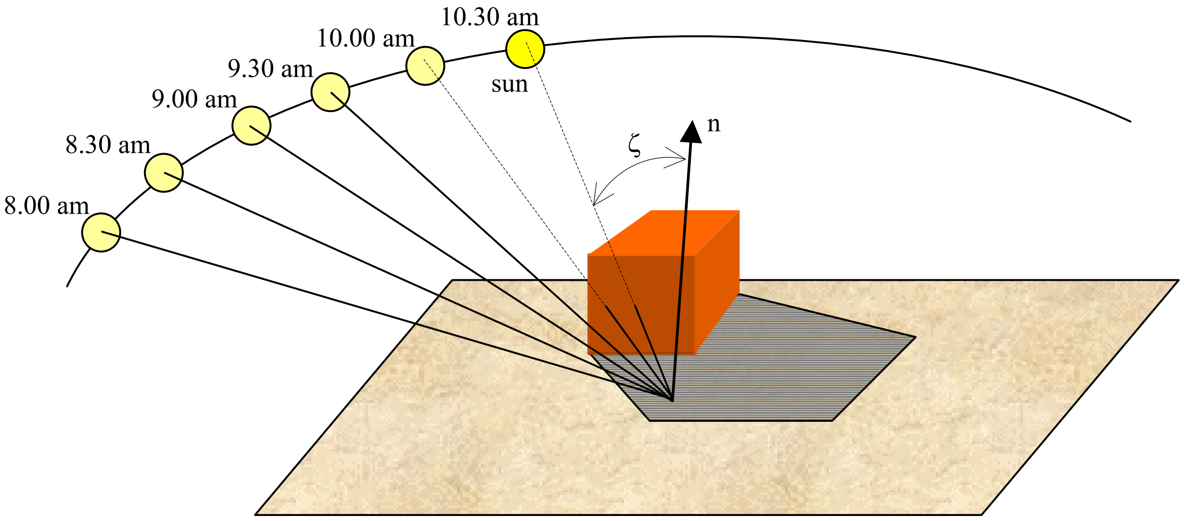
⇨ if G is in shadow (opaque body), irradiance due to the sun is $\Phi'_s(t,\lambda) = 0$.

⇨ if G is illuminated by the sun, irradiance due to the sun is : $\Phi'_s(t,\lambda) = E'(h_G,t,\lambda).\cos(\zeta).\tau_n(\lambda)$

with $E'(h_G,t,\lambda)$: spectral irradiance of the sun (given by atmospheric propagation file .atm for the time of day t)

ζ : incident angle of the sun

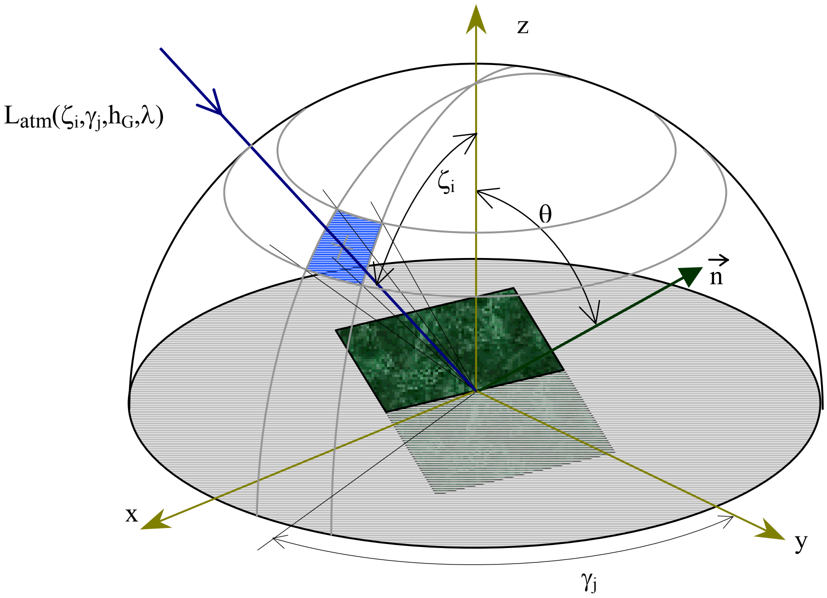
$\tau_n(\lambda)$: attenuation (if no mask then $\tau_n(\lambda) = 1$ else $\tau_n(\lambda) = 0$)



➔ the irradiance of the sky :

To accurately compute the fluxes from the sky and to take into account the hidden parts is a problem of radiosity which need to be solved by casting many rays from G towards many directions of the sky. At the moment, this solution has been dropped out because of its high computational cost.

The chosen solution consists in taking into account only the portion of the sky that illuminates (without making shadows) the polygon. The sky is tessellated in discrete solid angles defined using elevation and azimuth angles. As the sky is not isotropic, some directions are defined and radiance is calculated along these directions. Radiance is considered constant for all the directions in the associated solid angle.



Irradiance due to the sky is equal to the integral over the solid angle of the sky seen from the polygon :

$$\Phi'_c(t) = \int_\Omega L'_{atm}(\theta_{in},\varphi_{in},\lambda,t).\cos(\theta_{in}).d\omega_{in}$$

$$= \sum_\Omega L'_{atm}(\zeta_i,\gamma_j,\lambda,t)\cos(\theta_{in}).\Delta\omega_{ij}$$

with $L'_{atm}(\zeta_i,\gamma_j,\lambda,t)$: spectral sky radiance in the direction ζ_i,γ_j (time of day = t)

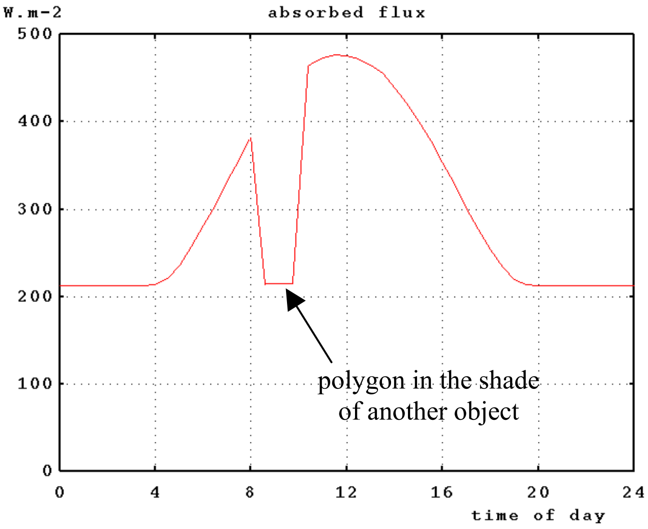
Ω : solid angle of the sky seen from the polygon

$\Delta\omega_{ij}$: elementary solid angle in the direction ζ_i,γ_j

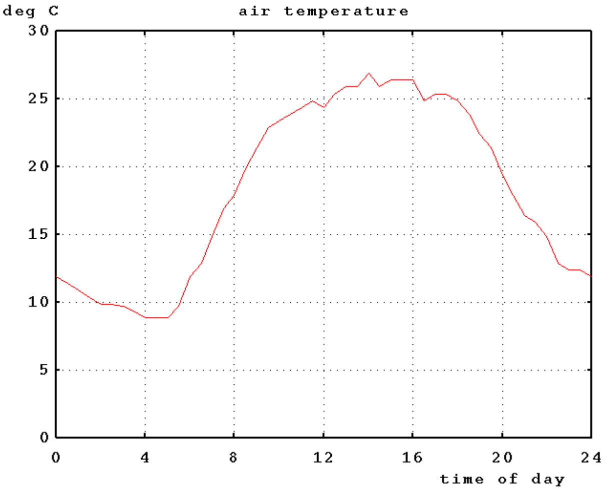
θ_{in} : angle between the polygon normal vector and the direction ζ_i,γ_j

The absorbed flux is therefore given by :

$$\Phi_a(t) = \int_{0.3\mu m}^{3\mu m} \alpha(\lambda)\cdot\Phi'_s(\lambda,t)\cdot d\lambda + \int_{0.3\mu m}^{30\mu m} \alpha(\lambda)\cdot\Phi'_c(\lambda,t)\cdot d\lambda$$



Example of absorbed flux according to the time of day for an horizontal polygon



Example of external air temperature according to the time of day

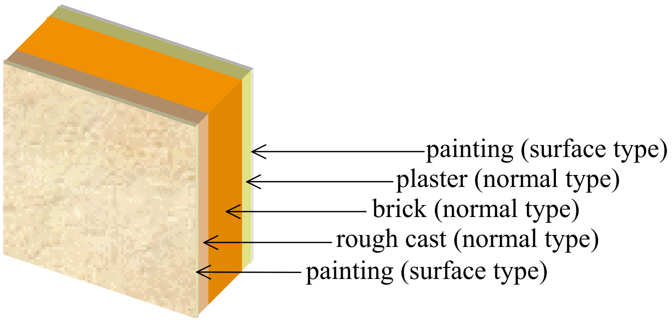
3.3. Thermal attributes

Thermal attributes are associated to the polygon material. A material is characterized by a list of layers. Each layer has its own thermal attributes. There are three types of layers :

- ⇨ "surface": for layers of very small thickness (e.g.: painting, …)
- ⇨ "infinite": for layers of infinite thickness (e.g.: the ground)
- ⇨ "normal": for others layers

These types of layers can be associated of many ways.

For example, the characterization of a wall is :



A "surface" type layer is characterized by:

- ⇨ its spectral absorptivity $\alpha(\lambda)$,
- ⇨ its spectral emissivity $\varepsilon(\lambda)$,
- ⇨ and its natural convection coefficient h,
- ⇨ no thickness,
- ⇨ no thermal inertia.

A “normal” or “infinite” type layer is characterized by:

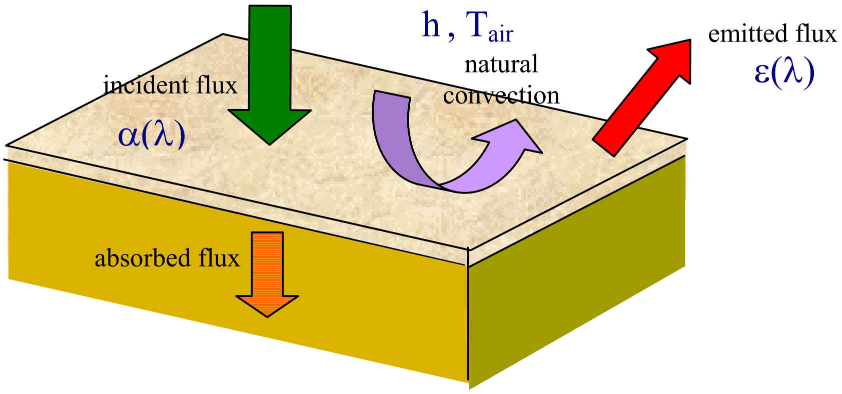
- ⇨ its conductivity Λ,
- ⇨ its specific heat C_p,
- ⇨ its density ρ,
- ⇨ its spectral absorptivity α(λ),
- ⇨ its spectral emissivity ε(λ),
- ⇨ its natural convection coefficient h,
- ⇨ and a thickness $e \neq 0$

} (if there is no surface layer upon)

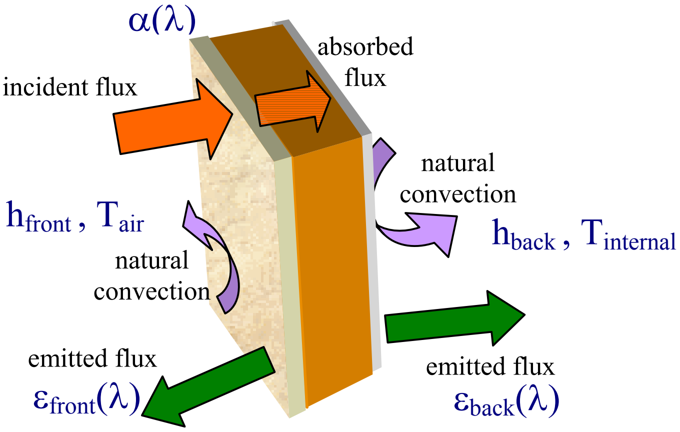
3.4. Solution of the heat equation

For the thermal software, there are 2 kinds of materials :

➔ “ground” type materials (if the last layer is an “infinite” type layer):



➔ “wall” type materials (if the last layer is a “surface” or “normal” type layer):



Each layer is defined by its thermal attributes (thermal conductivity, specific heat and density) and its thickness. For ground type polygons, the thickness of the last layer is calculated according to penetration thickness over a circadian cycle.
Convection fluxes are calculated according to analytical evaluation of the natural convection coefficient based on the temperature gradient between air and polygon. Radiative losses on both sides of the polygon (walls only) are simulated using the Stephan-Boltzmann law, according to a constant and average value of emissivity in band III.

Spatial initialization of temperature is obtained by a method based on a steady state analytical solution. This method allows quick convergence of the numeric solution and a computation with only one circadian cycle.
The principle of the thermal solving is based on the mono-dimensional and non-stationary solving of the heat equation by a finite difference method in each layer of the polygon :

$$\frac{d^2T(x,t)}{dx^2} = \frac{1}{a} \cdot \frac{dT(x,t)}{dt}$$

with a : thermal diffusivity $a = \frac{\Lambda}{\rho \cdot C_p}$ *(m^2/s)*

Λ : thermal conductivity *(J/s/m/K)*

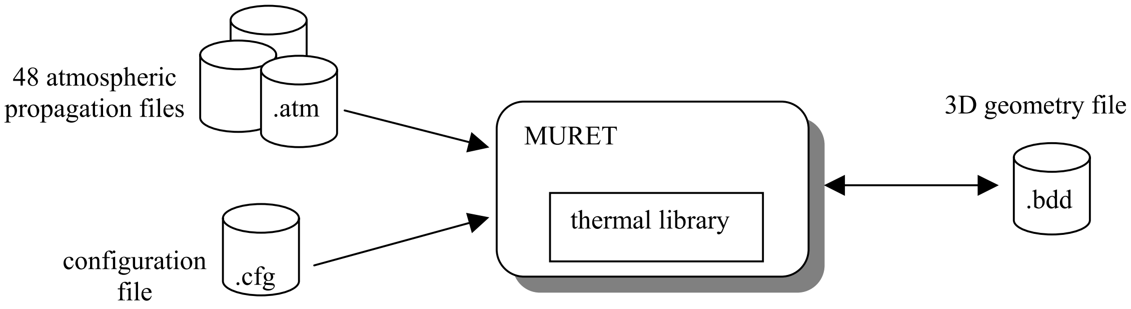
ρ : density *(kg/m^3)*

C_p : specific heat *(J/kg/K)*

Each layer of the material is supposed homogeneous, isotropic and impermeable. The numeric solution is of implicit type.

4. MURET : A THERMAL SOFTWARE WHICH USES THE THERMAL LIBRARY

MURET is the thermal software based on the thermal library. It needs a set of 48 atmospheric propagation files representative of the atmospheric conditions 24 hours before the simulation time of day t, a configuration file (which contain the list of these atmospheric propagation files and the associated external air temperatures).
MURET reads a SDM file (3D geometry file) with physical and thermal extensions and computes polygon temperatures of each polygon and stores the result in a SDM file.



3 options are allowed :

- ➔ normal calculation : MURET takes into account the masks of the others objects of the 3D scene,
- ➔ calculation without masks : on the other hand, MURET takes into account the masks of the others objects of the 3D scene,
- ➔ calculation without direct sunlight irradiance.

The second option is used with the TSC software described below.

5. TSC: THERMAL SHADOW COMPILER

In the infrared domain the thermal transfers generate particular shadow effects. A surface that has been exposed to solar heat for a long period of time shows up brighter than surfaces less exposed to the sun. This phenomenon is fundamental for infrared vision (in band II as well as in band III, but not in the visible spectrum), particularly for missile guidance based on infrared recognition. For certain missiles the targets are usually urban, where shadow phenomena most often occur. Thus, it becomes important to simulate thermal shadow effects accurately. This is the aim of TSC, Thermal Shadow Compiler.

This software calculates the thermal emissions of a terrain after 24 hours of continuous exposition to the sun and sky irradiance. Because of these emissions the terrain becomes more or less "visible" in the infrared frequencies. This visibility depends on the meteorological conditions of the day that dictates the amount of solar exposition. It also depends on the materials as well as on the geometry of the terrain because certain parts of it are less exposed to the sun than others. So, it becomes very important to determine which parts have been in shadow with respect to the sun and for how long. TSC attacks these problems with an original implementation of shadow textures that allows to determine the temperature of a certain point taking in consideration the different positions of the sun in the day and the shadows corresponding to those positions. TSC generates a shadow object in SDM format that can be rendered by SPECRAY or real time synthetic image generators (for example: SensorVision).

5.1. Functional Description

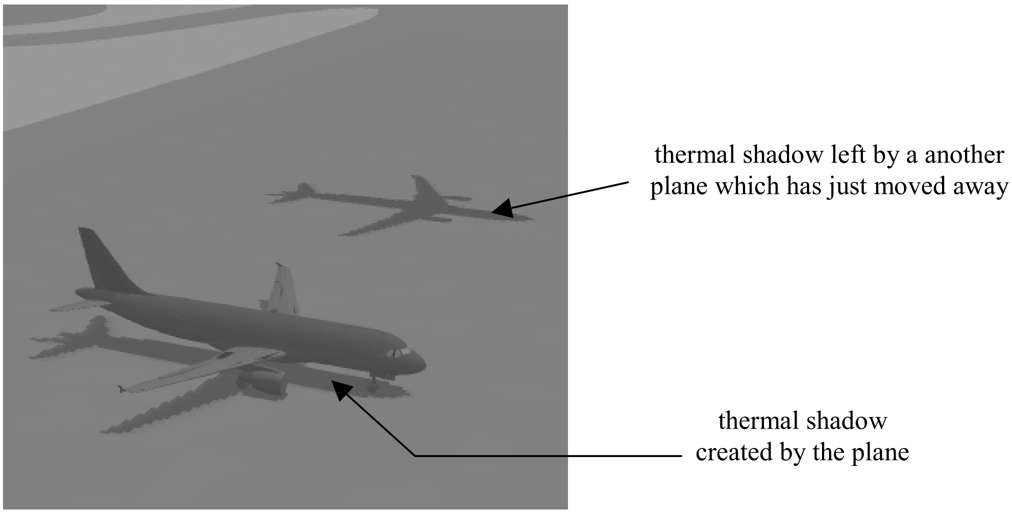
The polygons are read from a database without shadows. These polygons are cut according to a grid defined in the three planes perpendicular to the co-ordinate axes. The resulting polygons serve to hold the shadow textures. Each pixel of the alpha plane of a texture will have the transparency factor calculated by the quotient between the radiance emitted by a black body at the temperatures not taking and taking into account the shadows for the given wavelength interval (Band II by default or given by a parameter when calling the program). The temperatures are calculated by MURET. MURET can receive up to 48 sun positions, sampled at each half an hour for the 24 hours preceding the simulation, to calculate the temperature. The thermal shadows are calculated by shooting one ray for each sun position, using Ray Tracing, to verify possible shadows of objects blocking the sun. The sun positions where obstructions were detected are not considered for the temperature calculation when taking the shadows into account.

Once all the temperatures are determined and stored in textures associated with the clipped polygons, the new database is saved. However, if all transparency values are zero (or if the maximum value is under a given threshold) in a cell of the grid, the texture and the associated polygons are discarded. Likewise, if inside a certain clipped polygon the maximum transparency value is too low (zero or below a given threshold), it is also discarded.

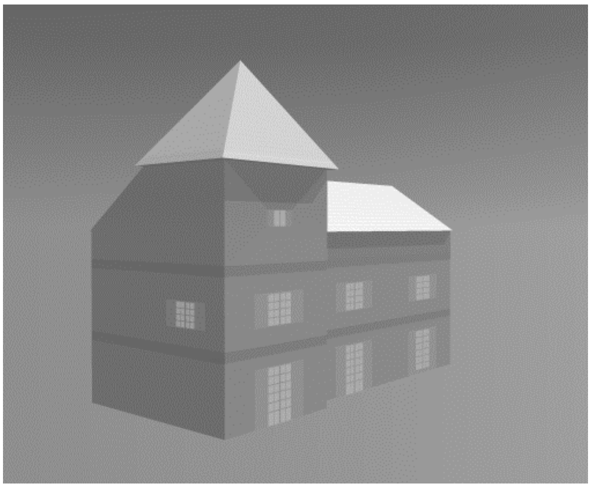
6. RESULTS

Examples of images obtained using the ray tracer SPECRAY of the CHORALE workshop and the thermal library.

1. This first image shows thermal shadows (band II). The upper thermal shadow is left by a plane which has just moved away (plane not in the field of view). The other thermal shadow is created by the immobile plane.


thermal shadow left by a another plane which has just moved away
thermal shadow created by the plane

2. The second image represents an image generated by SPECRAY (band II) of a house. All the polygon temperatures were calculated using MURET.



7. FUTURE EVOLUTIONS OF THE THERMAL LIBRARY

The future evolutions of the thermal library and the associated software are:

- better computation of absorbed fluxes by taking into account the irradiance of the ground,
- simulation of the internal heat sources,
- simulation of the forced natural convection due to the wind,
- link with an hybrid resolution model which will simulate the water concentration evolution of permeable grounds (for a better estimation of evaporation or condensation latent heat fluxes),

8. CONCLUSION

The thermal library of CHORALE and the associated software (MURET and TSC) allows a quick and accurate computation of temperature polygons of a 3D scene for realistic and physical simulations in the infrared domain. This software is specially fitted for temperature computation of “ground” and “building” type polygons. The future evolutions planed this year for CHORALE will allow a better temperature computation for permeable ground type polygons and for objects with internal heat sources (buried pipes, radiator behind a wall, …).

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