Improvement of the SE-WORKBENCH workshop for rendering targets

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ABSTRACT:

The SE-WORKBENCH workshop, also called CHORALE, is used by the French DGA to perform multi-sensors simulations. The SE-WORKBENCH enables the user to create virtual and realistic multi spectral 3D scenes that may contain several targets, and then generate the physical signal received by a sensor.

One of the main current interests for the DGA is to be able to compute the infrared (IR) signature of targets in their environment as accurately as possible, even if the targets are coated with a special paint for improving their stealthness. But for that the SE-WORKBENCH workshop needs to be improved as regard to the BRDF (Bi-directional Reflectance Distribution Function) modelling of the materials.

In this article, authors will focus on the following topics:

- Characterization of the materials: the aim is to be able to input the physical parameters of any kind of material, even multi-layered materials, as it is already done in the radio-frequency (RF) version of the SE-WORKBENCH, and to find a way to connect the different possibility to characterize a material.
- Characterization of the surface roughness: the challenge is to be able to model the micro level scale roughness (comparable to the wavelength and responsible for scattering) in such a way that it can be taken into account in the BRDF model.
- BRDF modelling: the challenge is to be able to connect the physical characterization of the materials and the surface roughness to a BRDF model that is relevant for complex reflectance effects. The paper will explain why the He-Torrance model has been selected for that purpose.

INTRODUCTION

Visible, infrared, electromagnetic or acoustic sensor systems are usually difficult to simulate due to the complexity of the required synthetic environment modelling. The OKTAL-SE suite of software (SE-WORKBENCH [4] [5] [6]) enables the creation of realistic multi-spectral synthetic environments. The priority of the software is to provide physically accurate 3D databases and databases of physical materials. The usage of ray tracing and 3D graphic board techniques for the scene analysis enables the generation of high quality scenes of complex scenarios.

In last years OKTAL-SE papers for ITBM&S, planned developments of SE-RAY-IR, the ray tracing kernel engine of the SE-WORKBENCH, were presented so that first preliminary results, especially in the frame of global illumination rendering ([2] [3] [6]) in both visible and infrared spectrum.
To perform these evolutions, the key point is to dispose of an accurate definition of the physical materials. Indeed, to efficiently cast photons (Photon Map method) or rays (Distributed ray tracing) it is necessary to “invert” the material reflection functions in order to trace photons or rays in the “good” directions. This paper focuses on the implementation of a new and sophisticated types of materials that inherits OKTAL-SE and ONERA experience in the field of RF simulation.

The current paper focuses on physical material definition, in correlation with SE-RAY-IR.

- Section 1 sums up the SE-WORKBENCH workshop main features.
- Section 2 gives a short description of the previous implementation of physical material.
- Section 3 gives a general description of the new way of defining physical materials.
- Section 4 focuses on the new way of radiative characterization of smooth dielectric physical materials.
- Section 5 focuses on the new way of surface state characterization for a physical materials.
- Section 7 gives some details on wavelet approach to compress and invert BRDF.
- Section 8 gives some details on correlated enhancements of SE-WORKBENCH tools GUI.

1 THE SE-WORKBENCH/CHORALE WORKSHOP MAIN FEATURES

The SE-WORKBENCH, also called CHORALE in France in the frame of DGA, is a full workbench that aims at simulating an E/O and/or RF synthetic environment. The SE-WORKBENCH both contains modelling tools for synthetic environment modelling (SE-AGETIM is a sophisticated terrain modelling tool including a full GIS) and tools for rendering. The rendering process is dual. Either using ray tracing for advanced but slow rendering. Either using 3D graphic boards new technology (shaders …) for fast rendering. The SE-WORKBENCH main advantage is its validation settlement. The advanced rendering has been validated in the frame of Defence programs with the support of several eminent research centres. The great originality of the SE-WORKBENCH is to be able to compute exactly the same image in real-time and non-real-time, sharing the same 3D database, the same physical materials, the same scenarios, the same atmospheric conditions and the same thermal definition. Comparison of such images is the best way to seriously quantify the limitation due to real-time approach.

According to this policy, OKTAL-SE pushes the ray tracing quality to limits. In this frame, the SE-WORKBENCH includes more and more sophisticated global illumination algorithms, taking advantage of complex definition of materials, atmosphere and thermal exchanges. Many details concerning the SE-WORKBENCH (including several white papers) can be found on the web site: http://www.oktal-se.com.

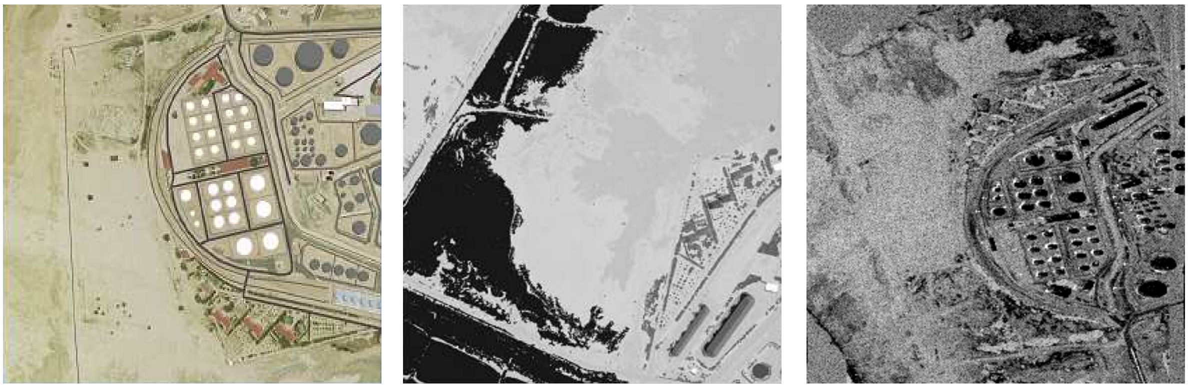


Figure 1: Illustration of the main principle of the SE-WORKBENCH: generation of multi-sensor images from the same 3D environment: Visible spectral domain (left), Infrared-EO domain (middle), radio-frequency SAR domain (right).

2 SHORT DESCRIPTION OF THE PREVIOUS IMPLEMENTATION OF PHYSICAL MATERIAL IN SE-WORKBENCH

The radiance reflected by a surface is :

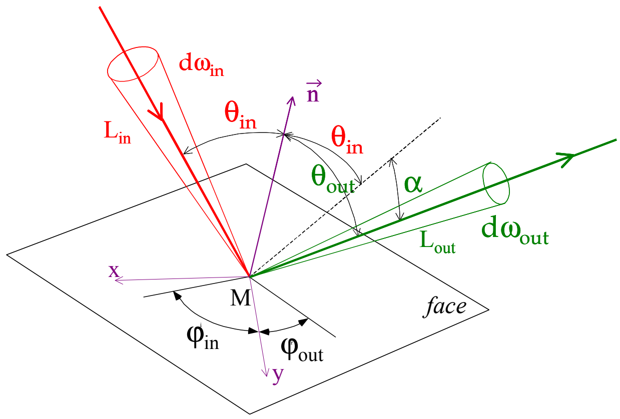
$$dL_{out}(\lambda,\theta_{out},\varphi_{out}) = f_r(\lambda,\theta_{in},\varphi_{in},\theta_{out},\varphi_{out}) \cdot L_{in}(\lambda,\theta_{in},\varphi_{in}) \cdot \cos(\theta_{in}) \cdot d\omega_{in}$$

θ_{in}, φ_{in} are the incident angles

θ_{out}, φ_{out} are the angles of the observation direction

$f_r(\lambda,\theta_{in},\varphi_{in},\theta_{out},\varphi_{out})$ or BRDF is the Bidirectional Reflection Distribution Factor

Figure 2: Schematic view of the expression of the reflected radiance as function of the incident flux.



The BRDF (Bi-directional Reflectance Distribution Function) is the only serious data that can be used in physical simulation. It is defined aside. Integration is performed on the solid angle $d\omega_i$ corresponding to the source visibility from the reflection point.

Diffuse and specular reflections: Artificially a “diffuse” part and a “specular” part can be distinguished. The diffuse component can be characterized by $BRDF_d(\lambda,\theta_{in},\varphi_{in})$ and the specular component can be characterized by $BRDF_s(\lambda,\theta_{in},\varphi_{in},\alpha)$ in which α is the angle between the ideal specular direction and the observation direction. The physical reflection model is based on an automatic function for factorization $BRDF(\lambda,\theta_{in},\varphi_{in},\theta_{out},\varphi_{out})$ into $BRDF_d(\lambda,\theta_{in},\varphi_{in})$ and $BRDF_s(\lambda,\theta_{in},\varphi_{in},\alpha)$ terms

The SE-RAY-IR software basic version, (the SE-WORKBENCH ray tracing kernel) implements a generalization of texture mapping. Classically, a texture is a sort of photo T(u,v) being mapped onto a polygon that creates a color spatial modulation of the polygon better than an uniform color. Texture mapping is a very clever mechanism to artificially improve the scene radiometric complexity.

The first extension concerns generalization of texture definition to any physical data (emissivity, BRDF, radiance ...). The second extension is a generalization of spatial “u,v” modulation to directional θ,ϕ modulation using texture. This second generalization of texture is useful to take into account the dependence on incidence and reflection angles of the physical materials. As a consequence SE-RAY-IR can simulate the variation of specular reflection factor with the observation angles. For instance using SE-RAY-IR a material can be diffuse for normal incidences and quite specular for tangential incidences.

The SE-PHYSICAL-MODELER tool, included in SE-WORKBENCH, is used for editing the physical materials.

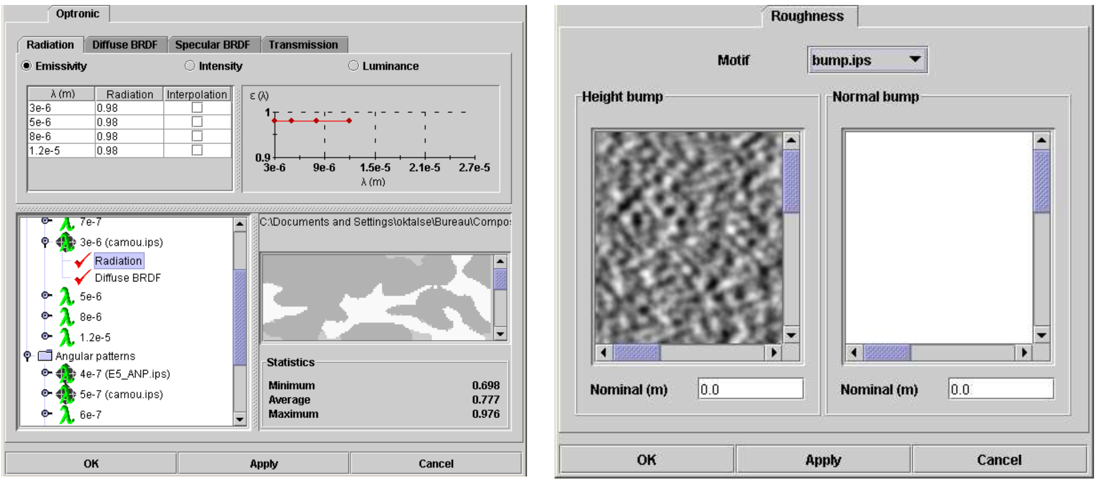


Figure 2: User interface of the SE-PHYSICAL-MODELER software: Schematic Infrared material physical properties edition (left), Surface state material properties edition (right).

Beyond that, texture has also been generalized to ”classification”. Classification is an abstraction that enables to store in the texture table the pointer of material rather than the material data themselves.
The SE-CLASSIFICATION tool, included in SE-WORKBENCH, is used for classifying texture of physical materials. The picture to be classified is decomposed in layers. For example, for a wall picture, one “roughcast” layer, one “window” layer and one “shutter” layer are created. For each layer, a material modulation is computed. For the “window” layer, brown pixels are associated with the “wood” material, and the others ones with the “glass” material.

The classification panel, taking advantage of photo-interpretation, enables to select a color by picking on the picture and then to associate it to a physical material. To check the spectral behavior of materials in use, and to get an idea of the result, a visualization panel enables the pre-view of the physical classification effect.

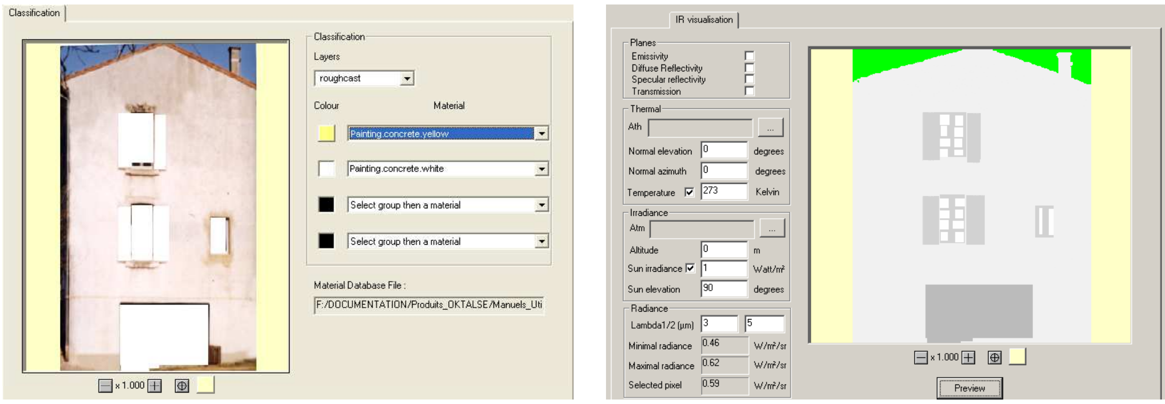


Figure 3: User interface of the SE-CLASSIFICATION software: Textures classification panel as function of a material library (left) and pre visualization window (right)

3 GENERAL DESCRIPTION OF THE NEW WAY OF DEFINING PHYSICAL MATERIALS IN SE-WORKBENCH

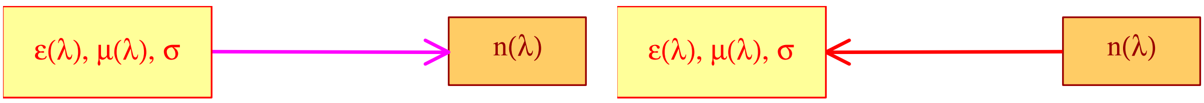
The new generation of SE-WORKBENCH physical materials enables to define smooth dielectric characteristics. There are basically two different ways to define the dielectric material:

- Fresnels approach, for smooth dielectric material,
- He Torrance [1] approach for rough dielectric materials.

The Fresnels approach admits two equivalent parameterisations:

1. The first one is based on complex number values for the refraction index. The refraction index $\underline{n}(\lambda)$ specifies the light celerity within the material. For an isotropic material, smooth with regard to the wavelength, $\underline{n}(\lambda)$ enables to compute complex reflection factors $\underline{\rho}_{\perp(\omega)}$ and $\underline{\rho}_{//(\omega)}$.
2. The second characterization uses fundamental physical constants required by Maxwell equations:
   $\underline{\varepsilon}(\lambda)$: complex electrical spectral permittivity,
   $\underline{\mu}(\lambda)$: complex magnetic spectral permittivity,
   $\sigma(\lambda)$: electrical spectral conductivity.
   Let us precise that $\underline{\varepsilon}(\lambda)$ and $\underline{\mu}(\lambda)$ are absolute values, but that the relatives components $\underline{\varepsilon}_r(\lambda)$ and $\underline{\mu}_r(\lambda)$ are actually manipulated.

Special converters have been developed that allow the transformation of these two equivalent definitions.



The He Torrance [1] approach is based on roughness definition and influence. Globally speaking, the model takes into account the surface roughness statistical feature in order to characterize the BRDF. The main parameters are the Root Mean Square (RMS) height and the Correlation Length, whose influence is summarized in the following figure:

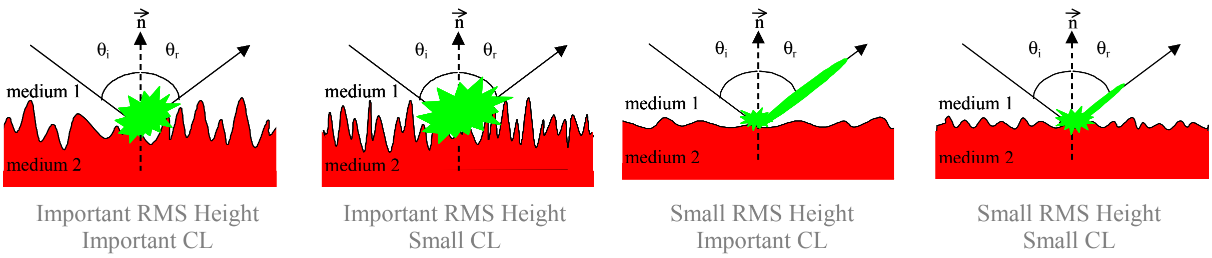


Figure 4: Illustration of the main principle and parameters of the He Torrance model.

4 NEW WAYS OF RADIATIVE CHARACTERIZATION OF SMOOTH DIELECTRIC PHYSICAL MATERIALS

In the frame of the SE-RAY-IR Validation Dossier, new tests have been implemented that show some results of new materials using the "Fresnel approach" compared with classical material implementation.

The scene is a plate classified using a texture of classification that distinguishes two different types of material. A punctual local source enlightens the plate. The pate is constructed as follow (Figure 5):

- RED colour is associated to a classical material definition. Its type is "<RADIATIVE_MODEL> MPS". Its emissivity is constant and equal to 0.9 between 0.4 et 12 µm. Diffuse BRDF is null. Specular BRDF value is given by $BRDF_{spec} = 1.62 \cos^{100}(\alpha)$. Its temperature is constant and equal to 293 K.

- GREEN colour is associated to a new Fresnel type material defined using a mean value of relative permittivity in band II given by: 1.75 + j 0.74, and by: 1.6 + j 0.087 in band III. Its type is "SMOOTH_DIELECTRIC". Its temperature is constant and equal to 323 K.

- Atmospheric propagation data correspond to a fine weather condition, at midday, with a solar site of 69.2° and a solar azimuth of 187.8

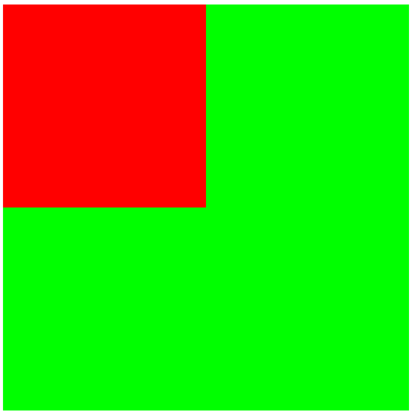


Figure 5: Definition of the new material for the tests and validation of the "Fresnel approach".

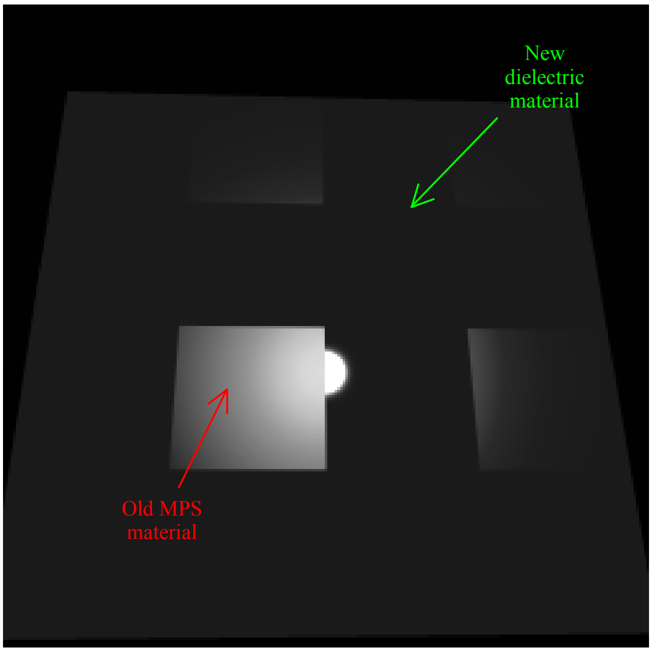


Figure 6: The SE-RAY-IR spectral image shows that it is possible to obtain new smooth dielectric with a much more specular behavior than classical "Open GL like" material using old materials. The source reflection effect is quite blurred for the old material, when very sharp for the new material.

Another example of test is given here, that shows the same phenomenon but without any local source. In that case, the scene is made of 3 objects:

- An horizontal plate
- A vertical rectangle textured using 2 different materials
- A horizontal rectangle that reflects onto the plate

The observer looks vertically at the plate.
The different materials involved in this test case are the following (Figure 7):

- The material for the rectangles is an old type material characterized by a constant radiance independent to wavelength.
- The material for the plate is a "`SMOOTH_DIELECTRIC`" type new material, whose permittivity in the visible spectrum is given by: 1.75 + j 0.74.

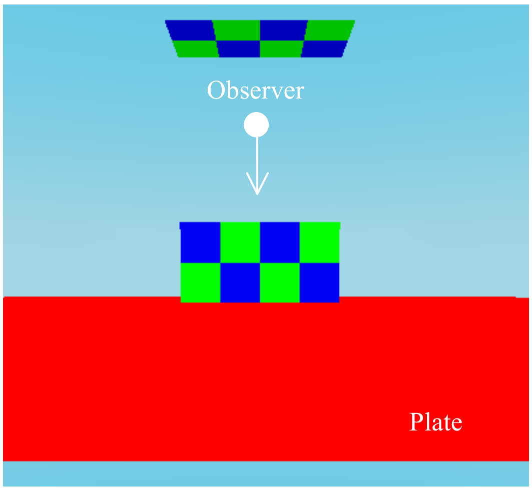


Figure 7: Definition of the set-up for the tests and validation of the "Fresnel approach" without external source.

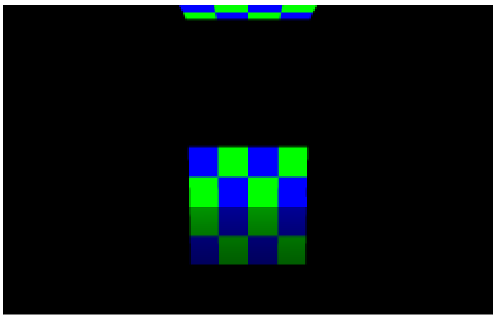


Figure 8: The resulting image shows the reflection effect on the plate, and the attenuation due to the dielectric characteristics. The BLUE and GREEN radiance of reflected rectangle can be measured and compared to theory.

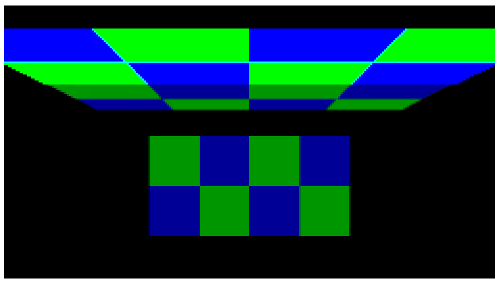


Figure 9: The point of view can be changed to grazing angles and we can observe and measure that the plate material reflects more energy than for normal incidence.

To conclude this session, let us consider the following example that shows the influence of texture classification. The scene is made of a single square mapped with a classified texture. The texture admits 3 zones:

- The RED zone with a "<RADIATIVE_MODEL > MPS" type using a constant emissivity of 0.1 between 3 et 12 µm, a null BRDF diffuse component, and a specular BRDF given by: $BRDF_{spec} = 14.6 \cos^{100}(\alpha)$. Its temperature is constant and equal to 433 K.
- The GREEN zone with a "`SMOOTH_DIELECTRIC`" type and using a mean value of relative permittivity in band II given by: 1.75 + j 0.74, and by: 1.6 + j 0.087 in band III. Its temperature is constant and equal to 293 K.

- The “GRADIENT” zone that corresponds to a linear combination of RED and GREEN materials.

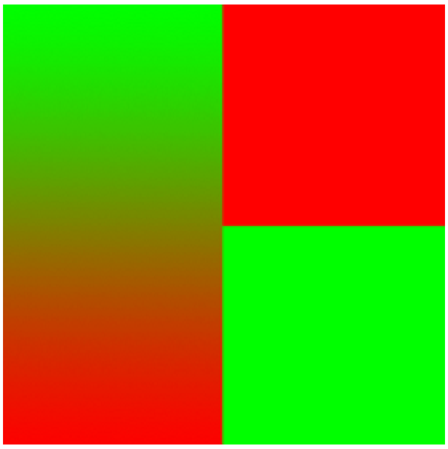


Figure 10: Definition of the new material for the tests of the influence of the classification.

A LWIR (Long Wave Infrared) sensor is looking vertically at the square, so that the specular reflection of sun is perceptible.

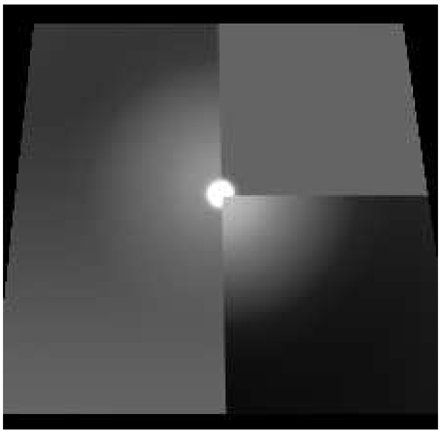


Figure 11: The resulting image allows to make different qualification trials.

5 NEW WAY OF SURFACE STATE/ROUGHNESS CHARACTERIZATION OF A PHYSICAL MATERIAL

Generally speaking, a surface state can be characterized by the local height of each of its points. Given the average plane of the surface (tessellated with polygons), the local height is given by the function “z = h(x,y)”. This function can be either continuous either discreet if there is no explicit definition available or in case of measurements.

There are a lot of different models available in literature. After a State of the Art achievement, with the support of French DGA, the He Torrance [1] model has been selected as the more adapted model with regards to roughness. The usefulness of this model is obvious under the assumption that it is much easier to measure (or gather existing measurements) surface states, rather than measure BRDF (or gather existing data), which are very dependent on environment. Besides this model is based on Physics, when most of competitive models are more empiric and even “cosmetic”.

Kirchhoff theory application allows to take into account wave polarization, interferences due to phase, directional Fresnel effects. Besides local shadowing and masking are modelled from the surface roughness characterization.
He Torrance model relies on Kirchhoff theory of diffraction (vector form) that enables to express the EM field scattered by a surface at one point in all scattered direction, knowing the incident field at that point. The local surface is approximated by its local tangent plane.

As previously said, the first hypothesis is that the surface roughness can be described as the realisation of a stochastic process, controlled by statistic moments.

Concerning the vertical variation, a Gaussian model is assumed that characterizes the height "h" of a point P(x,y), based on a probability function of $\langle h \rangle=0$ mean value and $\langle h^2 \rangle = \sigma^2$ variance, given by:

$$p(h) = \frac{1}{\sigma.\sqrt{2\pi}}.\exp\left(-\frac{h^2}{2\sigma^2}\right)$$

where σ is the Root Mean Square Height.

Of course, the surface is all the rougher as σ is greater.
Concerning the horizontal variation, the autocorrelation function of the stochastic variable h(x,y) or $h(\vec{r})$:

$$C(\vec{\rho}) = < h(\vec{r}).h(\vec{r}-\vec{\rho}) > \text{ with } C(\vec{0}) = \sigma^2$$

With the Gaussian distribution hypothesis, the correlation function is given by:

$$C(\rho) = C(0)\exp\left(\frac{\rho^2}{\tau^2}\right)$$

where "τ" is called the Correlation length.

He Torrance model admits of course some limitations and restriction of availability domain. Too small Correlation Length limits to short wavelength (visible/LWIR), for instance MWIR ⇔ τ = 2 µm. Too important Root Mean Square Height limits to long wavelength, for instance MWIR ⇔ σ = 2 µm. Those limits can be understood by looking more precisely at the model expression.

BRDF makes the link between radiance diffused in an output direction $(\theta_{out},\varphi_{out})$ given the irradiance in an input direction $(\theta_{in},\varphi_{in})$:

$$f_r(\lambda,\theta_{in},\varphi_{in},\theta_{out},\varphi_{out}) = \frac{dL_{out}(\lambda,\theta_{out},\varphi_{out})}{L_{in}(\lambda,\theta_{in},\varphi_{in})\cos\theta_{in}d\omega_{in}}$$

where $d\omega_{in}$ is the solid angle of incident wave.

Within the He Torrance model, BRDF is made of 3 terms respectively qualified by:

- specular (sp)
- directional diffuse (dd)
- uniform diffuse (ud)

$$f_r = f_{r,sp} + f_{r,dd} + f_{r,ud}$$

Specular term depends on:

- Fresnel coefficients (refraction index, permittivity …)
- "Shadow masking function" based on "in/out" angles and surface state parameters τ and σ
- "Apparent roughness" that is a complementary fading of the specular "Dirac" based on a special evaluation of δ taking into account the masking effects for different incident angles. The "apparent roughness" is all the bigger as the surface roughness is higher, wavelength smaller and angles more grazing i.e closer to the tangent plane.

Directional diffuse term depends on:

- Fresnel coefficients (refraction index, permittivity …)
- "In/out" angles
- Polarization
- Wavelength
- Correlation Length τ
- The "Slope Distribution Function"
- The bisector vector of the "in/out" plane
- The "Apparent roughness"
- The "Effective Slope" i.e. the ratio of quadratic mean height divided by Correlation Length taking into account masking effects

Uniform diffuse term depends on:

- A user defined constant value that physically corresponds to the multi scattering inside and outside the non metallic material.
- This value can be approximated by $\frac{\rho}{\pi}$ where ρ represents the directional-hemispherical reflectance due to the multiple scattering.

6 SOME DETAILS ON WAVELET APPROACH FOR COMPRESSING AND INVERTING BRDF

The memory cost in term of storing the BRDF tables (spatial, angular and wavelength sampling) can be prohibitive in some accurate modeling situations. For this reason, compression are needed to solve this problem. Besides the compression efficiency, the way of compression must also allow an efficient and practical importance sampling.
Moreover, one interesting feature of compression function is the multi resolution capability. The same BRDF can automatically fit the required level of detail. A good example is far distance observation, or observation according grazing angles (Figure 9).
Last year, several prototypes were made by OKTAL-SE and partners [7] specialized in compression and computer graphics. The choice of wavelets compression has been made, after various trials on canonical tests that are very promising. This year the implementation is ongoing.

A generic approach has been selected i.e. a compression scheme whose data type is not known by advance. This compression could also apply to hyper-spectral image storing, texture or atmospheric data. Standard operation of addiction, multiplication by a scalar and normalisation must be available for this generic type of data.

Wavelet transformation encodes a set of samples f_i , $i \in [1, N]$ in two parts:

- Scaling coefficient for low frequencies and average value,
- Wavelet coefficient for high frequencies details.

The sampling process is recursively repeated and creates a dyadic decomposition, i.e. 2^N values leading to N levels or resolutions.
The signal rebuilding is done sequentially from the low frequencies adding details of high frequencies up to the final level, which only requires addition and multiplication by a scalar.

Compression basically consists in suppressing wavelets inferior to a given threshold. The norm of a given coefficient is directly linked to its importance. Controlling the RMS error consist to annul or not some coefficients. The important point is to access efficiently to the “memory tree” that store the wavelet representation.

The figure below illustrates a canonical BRDF compression using wavelets:

Figure 12: Illustration of a canonical BRDF compression using wavelets as function of the compression level.

Some classical canonical tests [7] have been assessed in the spectral domain that shows the upper limits of compression. The figure shows a rendering spectral comparison between a pure analytical formulation of BRDF and its expression using wavelets.

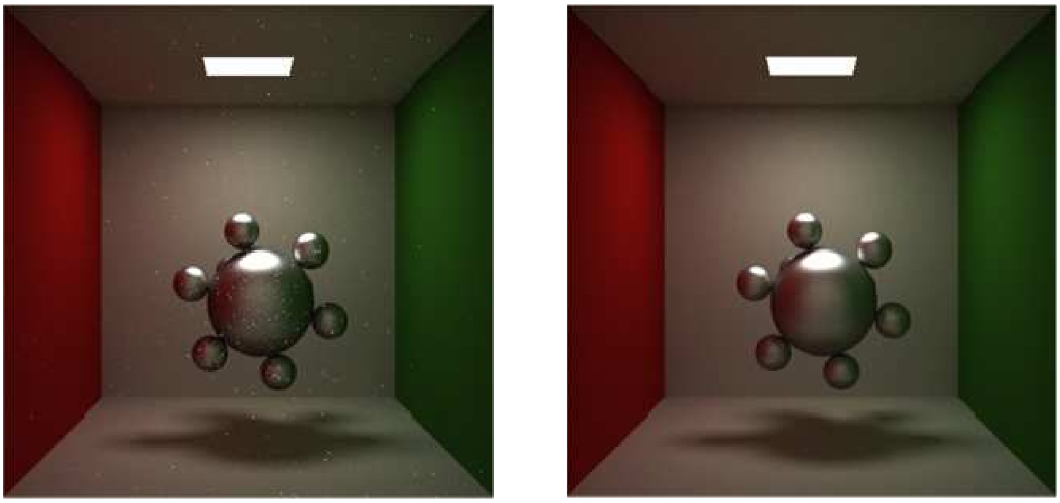
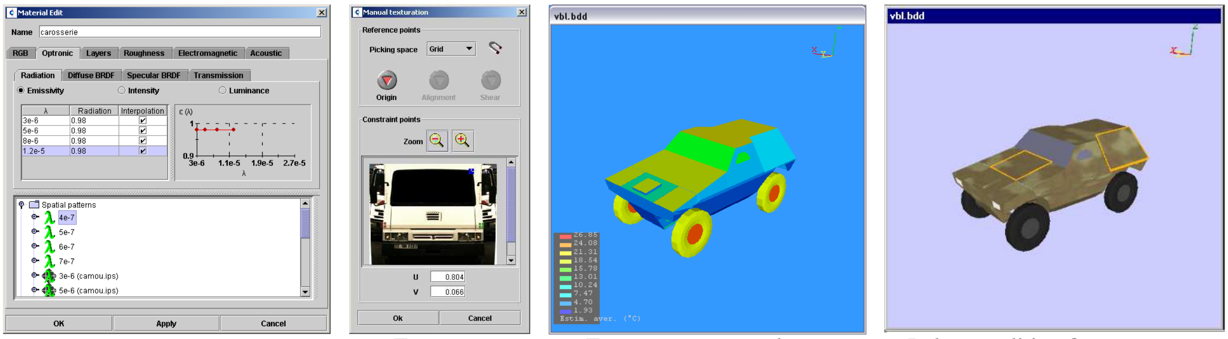


Figure 13: Rendering spectral comparison between a pure analytical formulation of BRDF (left) and its expression using wavelets compression (right).

7 SOME DETAILS ON CORRELATED ENHANCEMENTS OF SE-WORKBENCH TOOLS GUI

The SE-PHYSICAL-MODELER (Synthetic Environment Physical Modeler) product enables the 3D synthetic environment developer to easily characterize the elements of the scene in terms of their physical properties. It gets state-of-the-art display capabilities, including interactive 3D visualization window based on Coin^{TM}. The visualization windows are updated when modifying mapping or material. All the material used can be shown with a palette editing, with spectral and thermal characteristics graphic display.

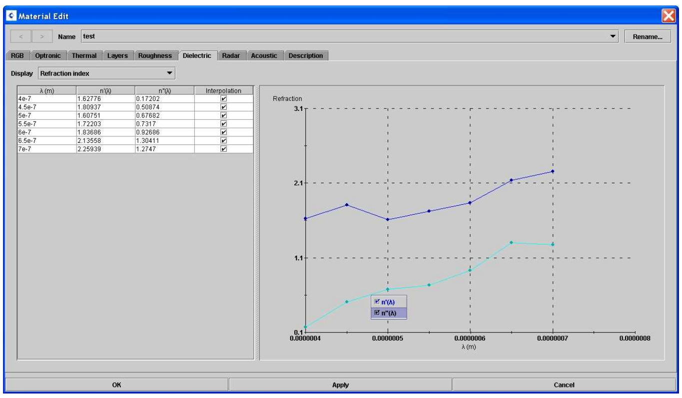


Infrared material physical properties edition | Texture mapping | Temperature control | Polygon edition for structure, geometry; material, modification

Figure 14: Example of User Interfaces of the SE-PHYSICAL-MODELER software.

In the frame of the next capabilities of defining material either using Fresnel model, He Torrance model or wavelet models, new SE-PHYSICAL-MODELER GUI are under development. The following image shows snapshots of the next version of the software.

Figure 15: Snapshot view of the refraction index real and imaginary values as a function of wavelength.



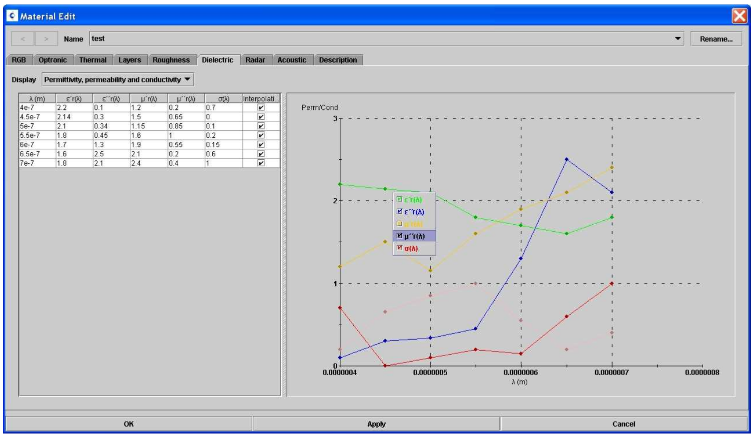


Figure 16: The snapshot shows permittivity real and imaginary values, permeability real and imaginary values and conductivity values as a function of wavelength.

8 CONCLUSION

SE-RAY-IR has been stable for years and applied in several applications in the Defence domain. In the frame of infrared spectrum, French DGA/CELAR and BWB/WTD81 (associated to FGAN-FOM) have strongly supported this product.

In 2007, 2008 and 2009, DGA/CELAR and other DGA technical centres, in the frame of CHORALE the French acronym for SE-WORKBENCH-IR, have founded OKTAL-SE to significantly improve the physical realism of SE-RAY-IR rendering and accepted to share these evolutions with SE-WORKBENCH users. One important part of these evolution concerns physical material characterization enhancements, which has been rapidly presented in this paper.

Lots of models have been implemented, that will be assessed and really used in 2009 by OKTAL-SE in the frame of applications for aircraft IR signature prediction with French DGA, but also by SE-WORKBENCH-IR users themselves.
These evolutions are very important for SE-WORKBENCH-IR future. They are also correlative to evolution of demand for real time capabilities.
First of all, non real time SE-RAY-IR quality is fundamental in order to assess the validity of SE-FAST-IR, the SE-WORKBENCH-IR clone of SE-RAY-IR, based of Open GL graphic board shaders, since SE-FAST-IR is validated by comparison to SE-RAY-IR.

Secondly, thanks to the exponential progress of 3D graphic board HW & SW, many of SE-RAY-IR enhancement can be now implemented on Graphical Process Unit. According to this, wavelet compression is very promising for real time implementation.

Besides, a lot of work had been done formally in the frame of EM/RF domain, especially around physical optics. This mass of work has been partially reused which leads the way to fill the gap between optics and electromagnetism. The main objective for that now is the active domain simulation (laser), which is on the road.

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