Unattended Acoustic Sensor Simulation of TG25 Trials using CHORALE Workshop

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ABSTRACT

The simulation workshop CHORALE of the French DGA is used by government services and industrial companies for weapon system validation and qualification trials in the infrared domain, and detection of moving vehicles in the acoustic domain. Recently, acoustic simulation tests were performed on the 3D geometrical database of the DGA/DCE/ETBS proving ground. Results have been compared to the acoustic measurements of the NATO-TG25 trials. This article describes the trials, the modeling of the 3D geometrical database and the comparison between acoustic simulation results and measurements. The 3D scene is described by a set of polygons. Each polygon is characterized by its acoustic resistivity or its complex impedance. Sound sources are associated with moving vehicles and are characterized by their spectra and directivities. A microphone sensor is defined by its position, its frequency band and its directivity. For each trial, atmospheric profiles (air temperature, pressure and humidity according to altitude), trajectories and sound spectrum of moving objects were measured. These data were used to prepare the scenario for the acoustic simulation.

1. INTRODUCTION

Used in battlefield observation, the area-control systems allow an area to be supervised, the acquisition and the transmission of any aerial or ground vehicle motion, such as main battle tank, light vehicles. These systems are often equipped with a treatment module for data fusion. Then the results trigger reaction to destroy a detected, recognized and identified threat.

The evaluation of such systems requires having a complex environment allowing the generation of realistic physical signals in the various spectral bands. CHORALE (simulated Optronic Acoustic Radar battlefield) is used by the DGA/DCE (Directorate for Test and Evaluation of the French Ministry of Defense) to perform multi-sensors simulations. The CHORALE workshop is now operational for the evaluation of optronic systems (visible and infrared spectra). The development of the electromagnetic model is in progress thanks to a close partnership with the Electromagnetic Department of the French ONERA Research Center. The acoustic model is now fully operational in the CHORALE workshop. It fulfills the following requirements:

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- compatibility with realistic 3D scenes,
- compatibility of the 3D scene with the optronic and electromagnetic sensor,
- performances on the computation time.

Unitary tests were performed to validate each functionality of the acoustic model. Recently, a global validation test was performed.

2. THE CHORALE WORKSHOP

2.1. General concept

The CHORALE workshop enables the user to create synthetic descriptions of multi-spectral environments as realistic as possible. In CHORALE, priority is given to the physical accuracy of the database used and the physical materials characterization. The usage of ray tracing and 3D graphic board techniques for the scene analysis enables the generation of high quality images of complex scenes. The images produced with the help of CHORALE can be used in two different ways depending on the needs. First of all, static images can be generated in order to be used in non real time data processing applications. These images can find applications in the sensor calibration area, for complex systems analysis, for mission preparation/rehearsal, for image recognition algorithms tuning. Real time images can also be generated. These images can be used for training purposes, calibration problems, system tuning or recognition training. Furthermore, Monte-Carlo based systems and hardware in the loop systems can be designed with the help of these real time images. With the help of the CHORALE tools suite, it is possible to produce multi sensor "images" from visible 3D synthetic environments (cf. Figure 1).

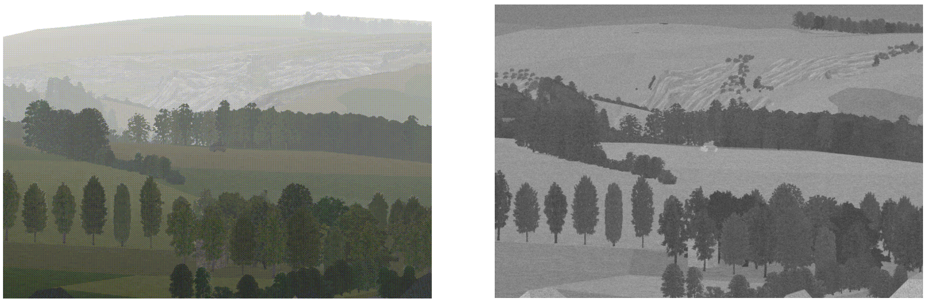


Figure 1: Examples of visible and infrared simulations

The first objective of the CHORALE tools suite is to provide the user with an easy to use, integrated and efficient simulation workshop of synthetic environment. The second objective is to provide a coherent and accurate way of simulating the sensor perception of Synthetic Environments in visible, infrared, electromagnetic and acoustic spectrum.

In addition, CHORALE is also delivered as a library with a comprehensive API, enabling the user to build transverse applications.

3. THE ACOUSTIC SIMULATION SOFTWARE IN CHORALE

3.1. Geometry model

CHORALE is based on the SDM++ format, which is an ASCII format for the representation of 3D databases, and the definition of physical data. SDM++ is compliant with standard geometrical files format such as SEDRIS, VRML or Open FLT. For the needs of acoustic simulation, materials are enhanced with the spectral specific acoustic impedance Z_S (in $kg.s^{-1}.m^{-2}$), or the acoustic resistivity σ (in $kg.s^{-1}.m^{-2}$), or a mean foliage thickness (for the vegetation).

3.2. Acoustic sensor

An acoustic sensor is characterized by its directivity, its bandwidth, its position and orientation. According to these features, the acoustic software calculate the incoming acoustic pressure p(f, t) as a function of the frequency f and the date t.

3.3. Sound sources

Sound sources are associated to moving (or not) objects (for instance a vehicle on a road, a helicopter, …) and are positioned with regard to the coordinate system of the objects. A sound source is characterized by its spectrum and its directivity.

3.4. Simulation software

The acoustic simulation software is based on an efficient and powerful ray tracing kernel called SE-RAY-AC. For each acoustic sensor in the 3D scene, SE-RAY-AC calculates the incoming acoustic pressure. "Acoustic" beams are cast from each sound source, in all directions, through an "acoustic system" (cf. Figure 2) composed of a set of pixels. The beams are propagated into the 3D scene, interact with polygons, are reflected or diffracted, and, for some of them, are received by a sensor.

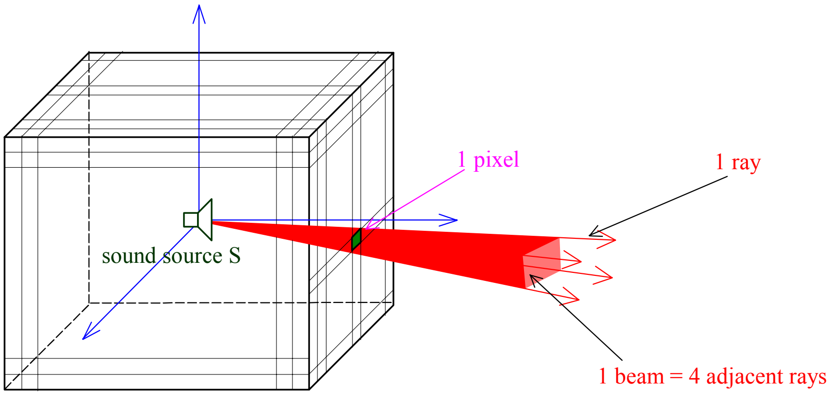


Figure 2: "Acoustic system" associated with a sound source

3.5. Antialiasing

One of the main difficulties of the acoustic simulation is to find the intersection of the beams with the 3D scene. Indeed, due to refraction effects, beams are bent. So, to calculate the intersection of a beam with the 3D scene, the acoustic software splits each ray of the beam into small linear segments, and uses this set of segments to compute the intersection. Using this method, the acoustic software is able to calculate the intersection of the beams thrown through the "acoustic system" with the 3D scene, and create a spatial sampling of the 3D scene. On the other hand, one of the major inconveniences of this method is that small elements or objects may be missed, or inversely, large elements are uselessly sampled. This default is called "aliasing" and a way to take into account aliasing is to implement antialiasing methods. Antialiasing allows the acoustic rays to be focalized on the complex parts of the 3D scene. The antialiasing mechanism is adaptative: it allows a pixel splitting proportional to the 3D scene complexity.

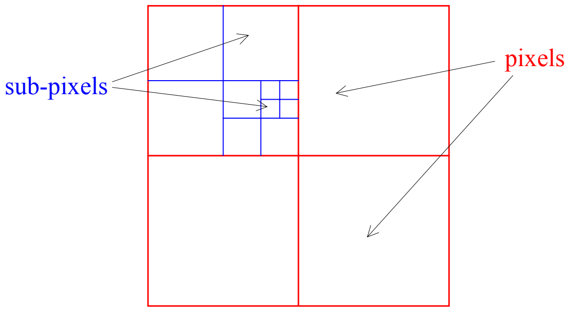


Figure 3: Antialising mechanism

3.6. Main features

The acoustic software takes into account:

- the atmospheric transmission,
- the geometrical divergence,
- the refraction of acoustic waves due to vertical gradients of air temperature,
- the reflection on materials characterized by their acoustic impedance or acoustic resistivity,
- the diffraction on edges (limitation to the 2D diffraction),
- the natural and non natural diffuse sources (wind noise, rain noise, …),
- the transmission through the vegetation (forest, trees, …),
- the speed and orientation of wind,
- the Doppler shift of moving objects.

3.7. Atmospheric transmission

Along a horizontal path of range d, the atmospheric transmission τ is given by: $\tau = e^{-\alpha d}$

α depends on frequency f and atmospheric parameters (air humidity h, static air pressure p, air temperature T) and is calculated according to the norm ISO 9613-2. The atmospheric parameters are stored in atmospheric data files (.atm).

Atmospheric files are used for multi sensor simulation and contain spectral data (sun irradiance, sky radiance, atmospheric transmission) and ephemeris data.

3.8. Geometrical divergence

The acoustic simulation software takes into account the geometrical divergence. In case of refraction, ray tubes are bent, and the pressure at the receiver is proportional to $\sqrt{\frac{S_{ref}}{S}}$.

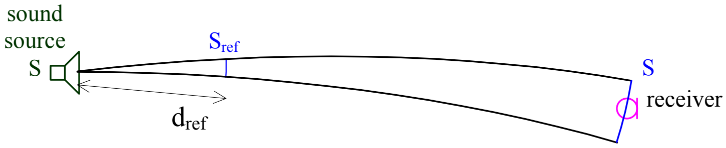


Figure 4: Geometrical divergence

3.9. Refraction of acoustic waves

Atmosphere is modeled by horizontal layers. Each layer is characterized by a constant gradient of sound celerity. The data (air pressure, air temperature, wind speed and wind direction) used for the description of the atmospheric layers are stored in atmospheric propagation files (.atm file). From these data, air temperature variation as a function of the altitude is used to calculate sound celerity at the top and bottom of each layer. For a layer between altitude z_i and altitude z_{i+1} ($z_i < z_{i+1}$), sound celerity at the bottom of the layer is c_i, and sound celerity at the top of the layer is c_{i+1}.

c_i is proportional to $\sqrt{T_{air}(z_i)}$

c_{i+1} is proportional to $\sqrt{T_{air}(z_{i+1})}$

The gradient of sound celerity for layer i is:

$$g_i = \frac{c_{i+1} - c_i}{z_{i+1} - z_i}.$$

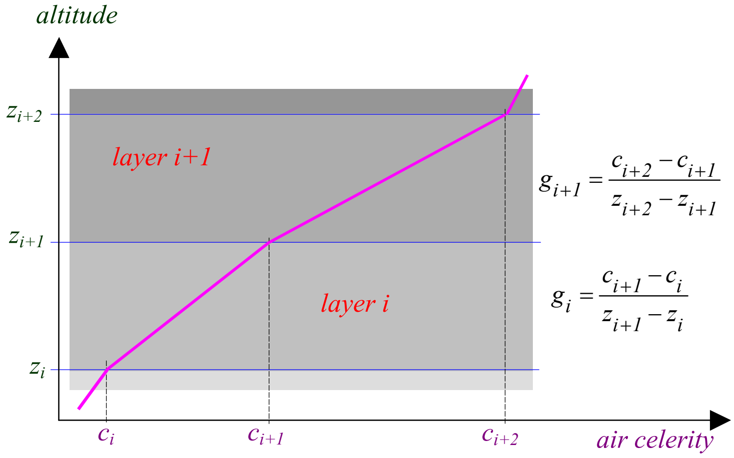


Figure 5: Atmospheric layer

In order to take into account the intersection of an acoustic ray with the 3D scene geometry, the ray is divided into small segments so that the arrow (the distance between the segment and the ray) is small enough. Nevertheless, the true distance d along the bend acoustic ray is calculated according to the radius of curvature. This distance is used for the computation of the phase φ.

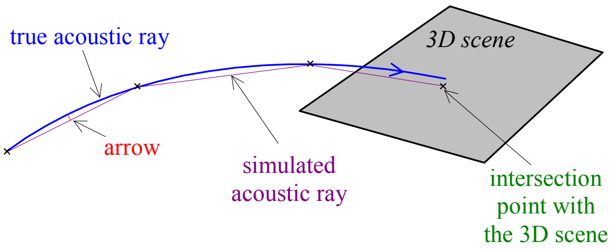


Figure 6: Subdivision in segments of an acoustic ray

3.10. Reflection on materials

Primary ray tubes are emitted by the sound source. If the ray tube intersects the geometry of the 3D scene, then a reflected ray tube is built according to the local normal vector $\vec{n}$ in the reflection point M.

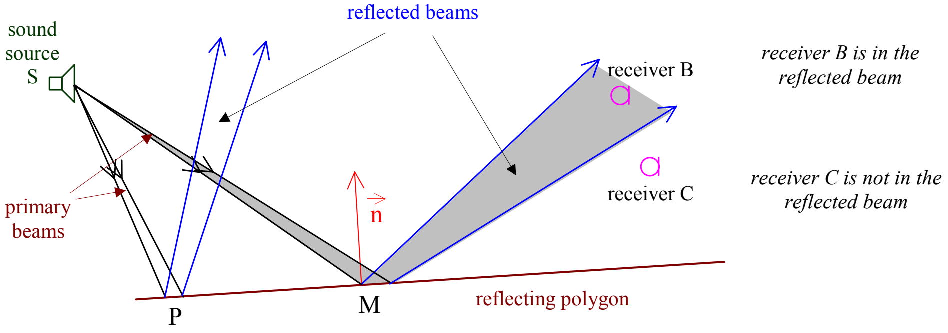


Figure 7: Reflection of acoustic beams

This mechanism is implemented recursively and one ray tube can generate a tree of reflected ray tubes. At each "stage" of the reflection, SE-RAY-AC checks if each receiver belongs to the reflected ray tube. If a reflected ray tube contains the receiver, then acoustic pressure due to the reflection is processed. The acoustic parameters used to characterize a reflection are:

- the acoustic impedance Z_S,
- or the acoustic flow resistivity σ.

3.11. Diffraction

If an obstacle is present between a sound source and a receiver, then the direct path is masked. The acoustic wave is diffracted by the obstacle that behaves as a secondary sound source. The acoustic pressure at the sensor location is calculated according to the Fresnel number $N = 2 \cdot \frac{d_1 + d_2 - D}{\lambda}$.

d_1 and d_2 are the path lengths along the diffracted path, D is the length of the direct path, λ is the wave length.

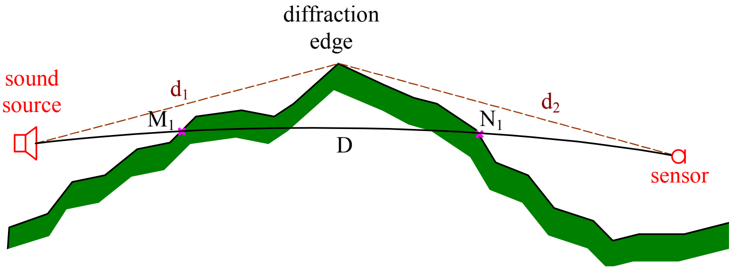
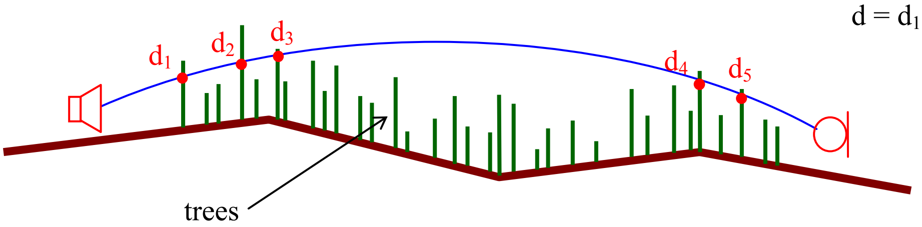


Figure 8: Edge diffraction

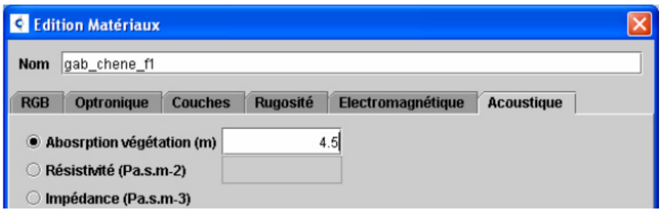
3.12. Vegetation transparency

The attenuation of the sound wave due to vegetation is a function of the frequency f and the thickness d of foliage. The 3D model of an isolated tree is a billboard polygon or a set of 2 crossed polygons. When a ray intersects one of these polygons, the ray tracer associates a thickness d_i to this polygon. The thickness of the foliage along the way of the ray is the sum of the thickness of all the intersected polygons.



$$d = d_1 + d_2 + d_3 + d_4 + d_5$$

Figure 9: Thickness of the vegetation



Nom gab_chene_f1

● Abosrption végétation (m) 4.5
○ Résistivité (Pa.s.m-2)
○ Impédance (Pa.s.m-3)

Figure 10: GUI for the edition of the vegetation thickness

Attenuation due to the vegetation (in dB) :

$$A_{tree}(f) = \frac{f^{1/3} \cdot d}{100} \qquad \text{with} \quad d = \sum d_i$$

If a forest is modeled with a "shoe box" (cf. Figure 11), 3D hypertexture can be used to replace the geometry of the "shoe box" by a plantation of randomly planted trees (cf. Figure 12).

Figure 11: Visualization of a "shoe box" forest with a real time viewer

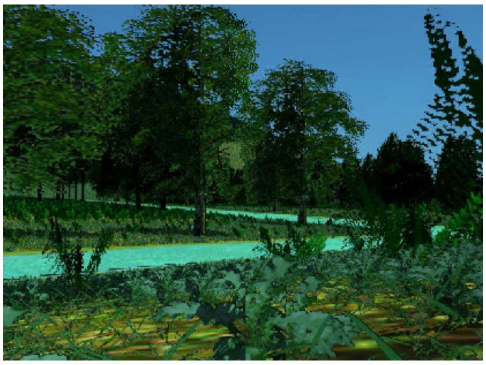


Figure 12: Visualization of the "shoe box" forest with SE-RAY (visible spectrum)

3.13. Sensor and sound source directivity

A directivity can be associated to a an acoustic sensor or a sound source. The directivity can be omnidirectional, or dipolar, or with a cardioide shape or tabbed.

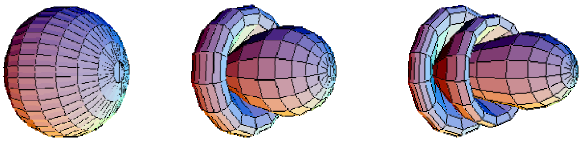


Figure 13: Representation of different kinds of directivity

4. THE TG25 EXPERIMENTS ON THE ETBS PROVING GROUNDS

4.1. Description

The NATO/RTO/SET/TG25 group, chaired by the US Army Research Laboratory (ARL), is involved in demonstrating advanced concepts of acoustic and seismic technology for military applications. Within the framework of the mandate of this working group, the Technical Establishment of Bourges (DGA/DCE/ETBS) organized a joint field trial during the autumn 2002. A dozen industrials and governmental agencies representing six nations (United States, France, Germany, Netherlands, Norway and Great Britain) settled on the area. The participants deployed their sensors on five zones around the command-and-control post covering a dynamic scenario of about 2 km2 with a varied environment (field, mounds, curves). The acoustic sensors operated by ISL ((French-German Research institute of Saint-Louis) team were located near the intersection of two roads (cf. Figure 14). The main topic of the field tests was the acoustic and seismic detection of vehicles, even though other detection techniques such as magnetic, infrared, optical ones, etc., were also tested by some teams. The acoustic data were analyzed, first of all, to allow the acoustic sources used (tracked or wheeled vehicles...) to be characterized, secondly to study the propagation characteristics of these different sources according to the local environmental situation. The area was flat, with cultivated fields and grasslands, some isolated trees and some butts.

4.2. Trajectory

During the tests, the vehicles moved with a constant speed around a closed loop. The moving vehicle was equipped with a real time GPS system allowing the user to have at his disposal of the instantaneous speed and the distance between the acoustic sensor and the moving vehicle.

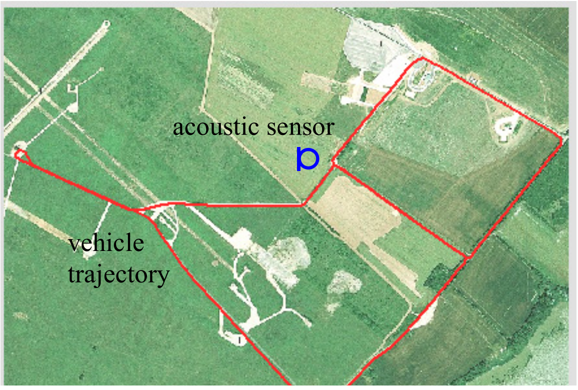


Figure 14: Plot of the GPS data superimposed on an aerial view of the site

4.3. Acoustic properties

The acoustic properties of the ground near the acoustic sensor were measured using the "Level Difference Method". This method enables the user to measure the difference of the incoming acoustic level between 2 microphones, then to calculate the acoustic resistivity (cf. Figure 15).

Figure 15: Device for the measuremt of the road's acoustic resistivity

4.4. Meteorological data

The values of mean meteorological data (air pressure, air temperature, humidity, wind velocity and wind direction) according to the height were measured.

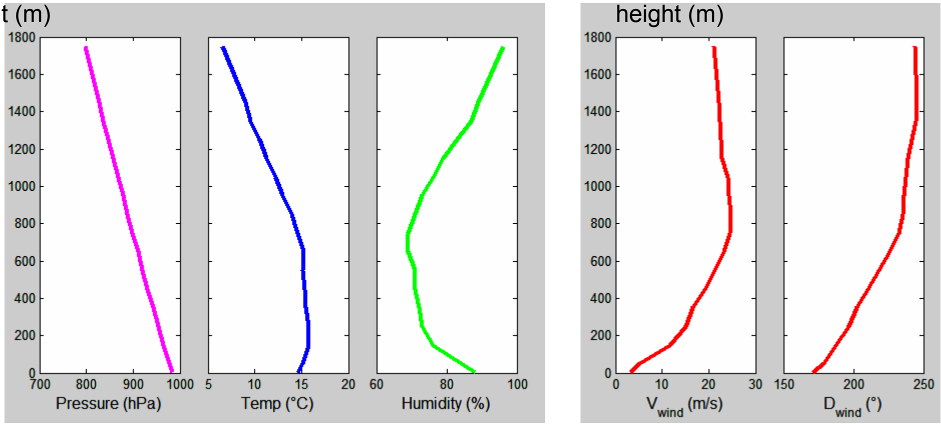


Figure 16: Profiles of meteorological data according to the height (in m)

4.5. Acoustic signal

Many microphones were put by ISL on the area in order to listen and record the sound of the moving vehicle during each TG25 trial (cf. one example in Figure 17). Moreover, some measures of the background noise were taken (cf. one example of background noise spectrum in Figure 18).

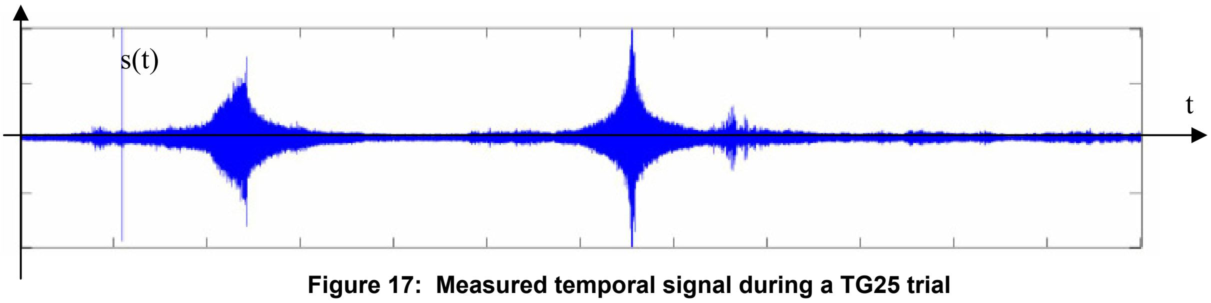


Figure 17: Measured temporal signal during a TG25 trial

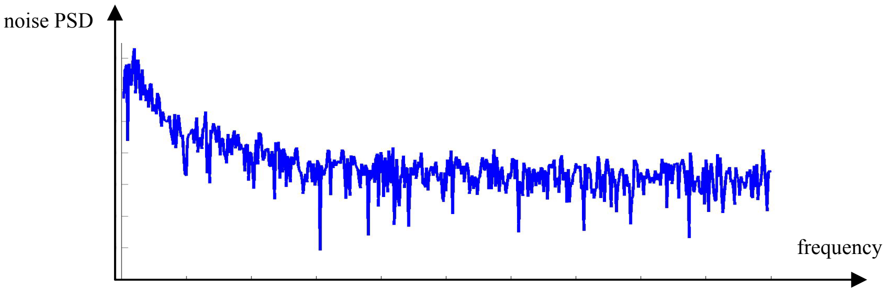


Figure 18: PSD of the measured ambiant noise

5. THE ACOUSTIC SIMULATION ON ONE TG25 TEST

5.1. The modeling step

The area was modeled using the terrain modeler SE-AGETIM. The source data used are altimetry and planimetry data. Altimetry data stem from DTED files. Planimetry data stem from the scanning of the georeferenced orthographic picture (cf. Figure 14). Specific objects such as butts were modeled using an object modeler. The result of the modeling step is a 3D database with the fields, the roads, the trees, … (cf. Figure 19).

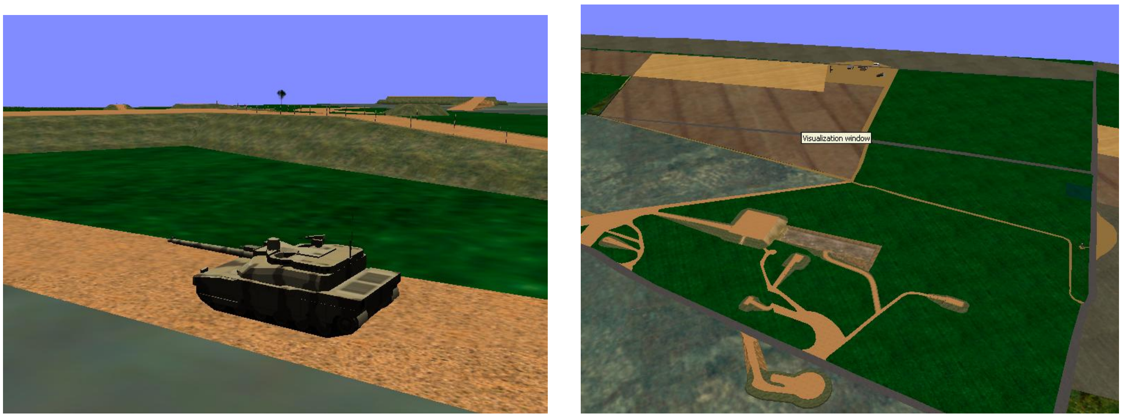
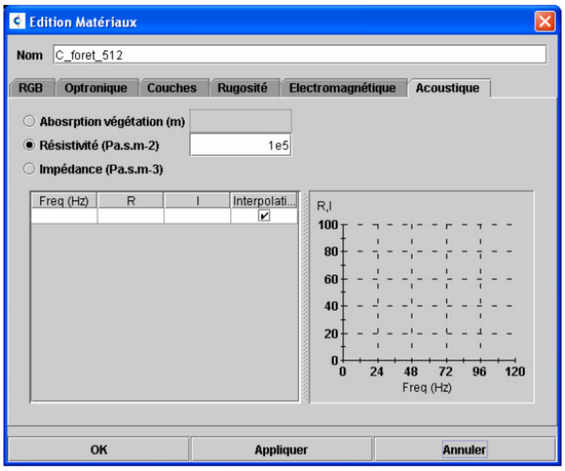


Figure 19: Views of the 3D scene

The materials associated to each polygon of the 3D scene were enhanced with acoustic parameters using the SE-PHYSICAL-MODELER tool (cf. Figure 20) and the atmospheric profiles were edited using the atmospheric tool SE-ATMOSPHERE of CHORALE (cf. Figure 21).

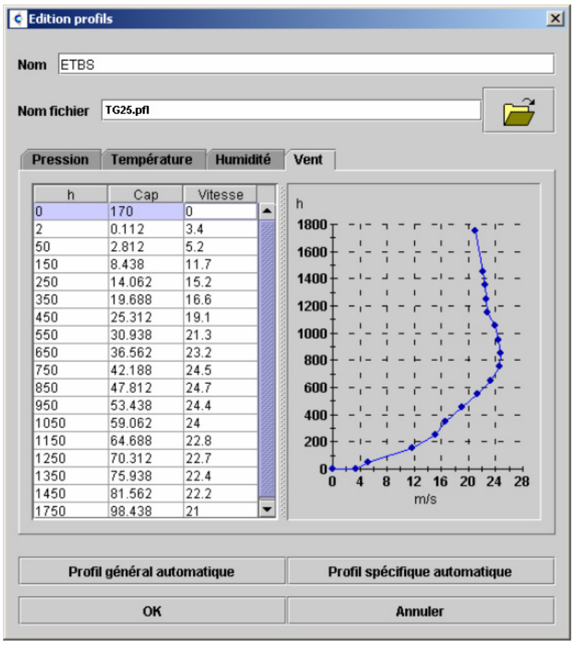


Nom: C_foret_512

○ Abosrption végétation (m)
● Résistivité (Pa.s.m-2): 1e5
○ Impédance (Pa.s.m-3)

Freq (Hz)	R	I	Interpolati...
			☑

Figure 20: SE-PHYSICAL-MODELER GUI for the edition of the acoustic resistivity of the materials



Nom: ETBS

Nom fichier: TG25.pfl

h	Cap	Vitesse
0	170	0
2	0.112	3.4
50	2.812	5.2
150	8.438	11.7
250	14.062	15.2
350	19.688	16.6
450	25.312	19.1
550	30.938	21.3
650	36.562	23.2
750	42.188	24.5
850	47.812	24.7
950	53.438	24.4
1050	59.062	24
1150	64.688	22.8
1250	70.312	22.7
1350	75.938	22.4
1450	81.562	22.2
1750	98.438	21

Figure 21: SE-ATMOSPHERE GUI for the edition of the atmospheric profile

5.2. Parameterisation of the sound source

A sound source is associated to the moving vehicle. This sound source is characterized by an acoustic spectrum deduced from the measured sound of the vehicle in the nearby field (cf. Figure 22). As we are mainly interested in the low frequencies of the acoustic spectrum, we made the assumption that this source is omnidirectional. A 1 second sample was extracted from the acoustic signal for the date t = 220 s (date corresponding to lowest distance between the vehicle and the acoustic sensor). The spectrum of the sound source was finally calculated by a Fast Fourier Transform of the filtered sample.

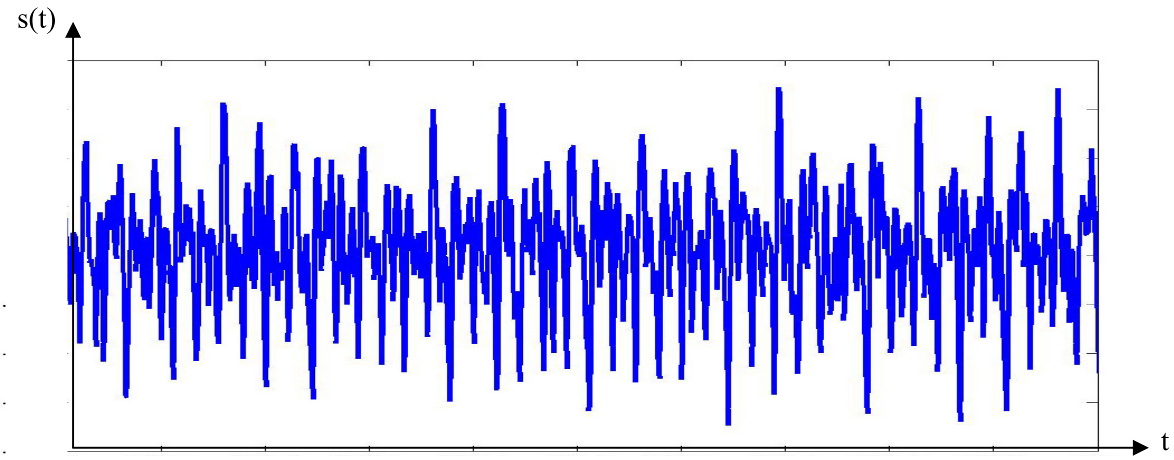


Figure 22: Extract of the acoustic signal (time t = 220 s / duration = 1 s)

5.3. Preparation of the simulation scenario

We prepared a simulation scenario using the scenario editor SE-RAY-AC. It refers to :

- the 3D model of the terrain,
- the 3D model of the vehicle, its associated trajectory, the sound source,
- the sensors and their characteristics,
- the atmospheric profile.

For the acoustic sensor, we defined an omnidirectional directivity.

At last, the ambient source (cf. Figure 18) was associated to the scenario.

5.4. Computation of the acoustic "images"

2 calculations were performed. The first one corresponds to the moving vehicle's position a long way from the sensor.
The functionalities validated in this case are: the absorption of air, the refraction due to the air temperature gradient and the wind effect, the geometrical divergence.
The comparison between the measured acoustic signal and the calculated acoustic signal shows that they are in accordance (cf. Figure 23).

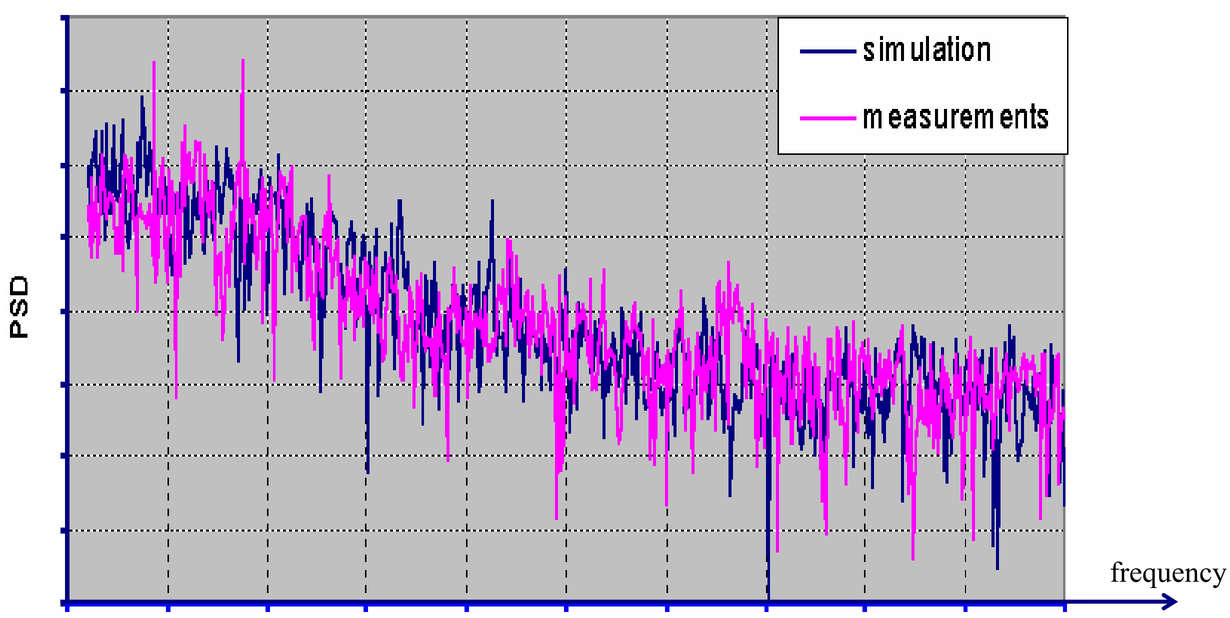


Figure 23: Comparison between measured and calculated acoustic signal (date t1)

The second computation corresponds to a position of the vehicle located behind an obstacle (a butt). The functionalities validated in this case are: the absorption of air, the refraction due to the air temperature gradient and the wind effect, the geometrical divergence and the diffraction. In this case too, there is a good correlation between the measured and the calculated acoustic signal (cf. Figure 24).

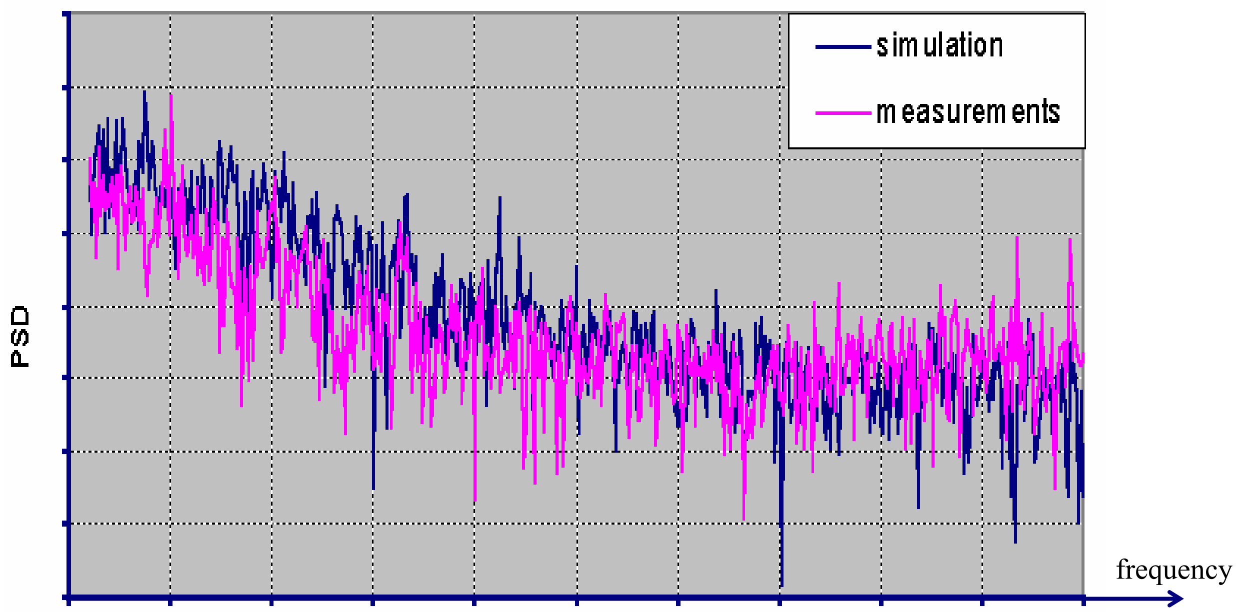


Figure 24: Comparison between measured and calculated acoustic signal (date t2)

6. FUTURE EVOLUTIONS OF CHORALE ACOUSTIQUE

The future evolutions of the CHORALE workshop acoustic software are:

- implementation of multiple scattering for the far field acoustic pressure computation,
- use of the physical theory of diffraction for the acoustic pressure computation due to diffraction,
- urban simulation,
- indoor simulation,
- impulse noise (gun shots, …),
- time computation optimization,
- tools for the exploitation of the acoustic simulation

Moreover, additional comparisons between others TG25 experiments and simulations are planned. A measurement campaign is foreseen on the DGA/DEC/ETAS (Technical Establishment of Angers) proving ground to validate the transmission model in the vegetation.

CONCLUSION

The acoustic functionalities are now fully operational in the multi sensor simulation CHORALE workshop. It is dedicated to physical realistic simulations on very accurate and complex 3D scenes. The general philosophy of the acoustic software is:

- capability of simulating several acoustic, infrared and electromagnetic sensor technologies with the same Synthetic Environment,
- availability of an API to built transverse applications,
- compatibility with the infrared and electromagnetic 3D scenes (same geometry, new physical extensions added to materials) allowing the user to perform data fusion (for example between an infrared sensor and an acoustic sensor).

This simulation approach is on all accounts promising. The full 3D computation enables the user to forecast highly complex test cases with immeasurably accurate achievements compared to reality.

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