Analysis of Infrared (IR) Signature of a Ship Operating in MIR and FIR Bands

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Abstract: In this paper a methodology for calculating the infrared signature of complex objects is presented. The transient thermal analysis allows us to evaluate the temperature distribution on the investigated object, pointing out which parts tend to be warmer. These temperature values are handled in the post processing phase in order to evaluate the zero range radiance distribution and the radiance of the target filtered by the Earth's atmosphere, according to the observer view direction. The comparison of the object radiance with the background one allows us to evaluate the IR signature contrast.

Keywords: Thermal analysis, infrared signature, maritime background, apparent sun motion, radiance contrast.

1. Introduction

The increased interest during the last decade in the infrared (IR) signature in civil and military applications results in the need of accurate and effective analysis.

In this paper the study of infrared signature of a ship, operating in the MIR (3-5 μ) and FIR (8-12 μ) bands, analyzed by using COMSOL Multiphysics, is presented.

Infrared prediction techniques have been extensively used for several military purpose such as target acquisition, surveillance and night vision.

A typical approach to predict the IR signature, in terms of radiance and contrast with background, consists firstly in evaluating the thermal properties of the investigated object and then evaluating the characteristic equations involving the infrared emission and propagation problem [1]-[2].

In order to obtain accurate results and to model the problem as realistic as possible, the following phenomena, including the heat generation and transfer problem, have been taken into account:

- shadowing;
- solar irradiance by considering the apparent sun motion during the day/night cycle;
- convection with external air;
- conduction between the inner volume and the external one;
- heat generation by the propulsion system.

Moreover, in order to address the infrared radiation emission and propagation problem, the following effects on the radiant flux from the target have been considered:

- the absorption by several of the atmospheric gases;
- the scattering away from the line of sight by small particles suspended in the atmosphere.

In this work COMSOL Multiphysics has been used to perform the transient thermal analysis by considering the apparent sun motion during the whole day. Then, in post processing phase, the functions that calculate the interested radiometric terms, such as zero range radiance, are developed directly in the MATLAB model code.

The transmission through the Earth's atmosphere and the sea radiance have been accounted for by using a free Fortran code named Lowtran 7. In particular, the contrast of the radiance with the maritime background has been evaluated by considering the summation of four contributions: the path radiance, the reflected sky and solar radiance and the thermal blackbody emission.

The paper is organized as following: in the next section the investigated geometry is presented, successfully the formulation of the methodology and the calculation of the radiance contrast are discussed and finally some preliminary numerical results are shown.

2. Geometry and background

The investigated geometry, represented in Figure 1, consists in a ship operating in a typical maritime background.

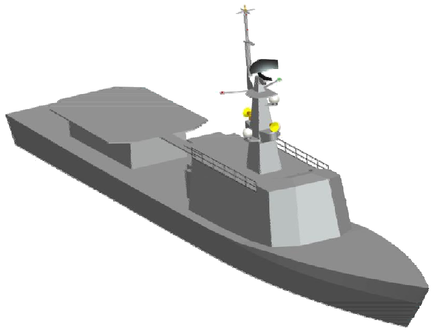


Figure 1: the investigated geometry consists in ship operating in a maritime background

The main heat source here considered is the propulsion system, installed toward the stern of the internal hull, therefore the model of Figure 1 can be simplified as illustrated below.
The engine, involved in heat generation, has been modeled as a steel made ellipsoid placed internally the ship as shown in Figure 2.

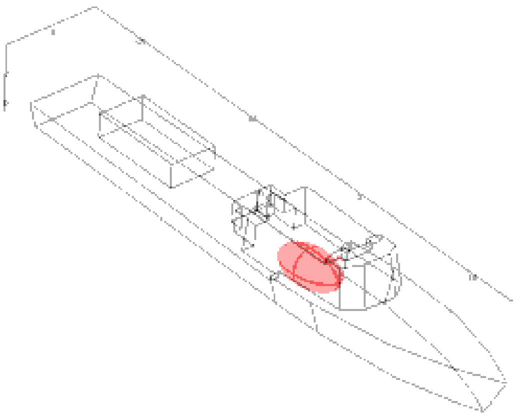


Figure 2: the simplified model of the ship and engine position

As indicated in Figure 2, the ship has been simplified by deleting the warm parts such as the tower with radar and the antenna devices. The dimensions are 60 m of length, 10 m of the width and 7 m of high. The hull of the ship has been modeled as an empty structure with walls thickness of 10 cm. Steel material has been used to realize both the ship and the engine, the two boxes placed on the deck have been modeled as solid structures.
The ship has been supposed to operate in a maritime background, tropical atmosphere has been considered as background model and the aerosol model has been set to navy maritime. The meteorological range has been fixed at 20 Km, the temperature of the sea and the sky has been set at 25°C and 30°C, respectively. No rain and clouds have been considered as sky conditions and an eastward wind of 5m/s has been taken into account into the model.
In the next section the formulation of the methodology is discussed.

3. Methodology Formulation

In order to evaluate the infrared properties of the object shown in Figure 2, a Lambertian grey surface has been considered. In this hypothesis, the reflected flux per unit solid angle is proportional to the cosine of the angle between the direction of interest and the normal to the surface, moreover the emissivity, denoted with ε, depends only on the object properties (greybody).
The fundamental approach is to evaluate the zero range radiant intensity J_{zr}, defined as radiant flux per unit solid angle, as the integral on the object boundaries (A) of the zero range radiance N_{zr}, weighted by the scalar product between the view direction and the normal to the surface:

$$J_{zr} = \int_A N\hat{n} \cdot \vec{d}(\theta,\varphi) dA \qquad (1)$$

where θ and φ denote the observer direction.
The term zero range means that no effects due to the atmosphere, in terms of radiance and transmittance of background, are considered (in the next section the contrast with environment has been taken into account).
The radiance N_{zr}, defined as radiant flux per unit solid angle per unit area, has been computed as the integral on the wavelength λ by using the following equation:

$$N_{zr} = \int \frac{\varepsilon W_\lambda^{bb}(\lambda)}{\pi} d\lambda \qquad (2)$$

where the emissivity ε is defined as the ratio of radiant emittance of a source to that one of a blackbody at the same temperature and W_λ^{bb} represents the spectral radiant emittance of the blackbody. This last term depends on the temperature distribution T on the object surface and it is evaluated as:

$$W_{\lambda}^{bb} = \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T} - 1} \qquad (3)$$

where C_1 and C_2 are coefficients defined as first and second radiation constant and their values are $3.741 \cdot 10^{-16}$ Wm^2 and $1.439 \cdot 10^{-2}$ mK, respectively [1].

COMSOL Multiphysics heat transfer module has been used to evaluate the temperature distribution on the geometry shown in Figure 2.
In particular, the 3D model of the investigated structure has been imported from CAD in COMSOL Multiphysics. The classical heat flux equations have been imposed on the boundaries. Particular attention has been dedicated to model the sun irradiance: the inward heat flux has been defined by using a function that simulates the apparent sun motion with respect to the earth.
In order to model the ship operating at the fully operational temperature, the transient solution has been performed starting from the steady state one, accounted as initial condition.
Once the simulation has been performed, in the post processing phase, the zero-range radiance distribution has been calculated according eq. (2).
In the next section the background effects have been discussed.

4. Sea contrast

The detection of a target is made possible depending on the contrast with the temperature of the background. In order to calculate the radiation contrast of the ship with the sea, Lowtran 7 code has been used [3].
In particular, SeaRad, a modification of Lowtran, allows us to predict the radiance of the ocean surface (*Nsea)* depending on the range and the elevation according the following equation:

$$N_{sea} = N_{path} + (N_{sea}^{bb} + N_{sky} + N_{sun})\tau_{path} \qquad (4)$$

In equation (4) the four contributions to the radiance are:

- the optical path radiance (N_{path}) between the footprint and the observer;
- the reflected sky radiance (N_{sky}) due to the reflection of a portion of sky on the sea surface toward the observer;
- the reflected sun radiance (N_{sun}) due to the reflection of the sun on the sea surface toward the observer (sun glint);
- the thermal blackbody emission (N^{bb}_{sea}) of each sea facet that emits a spectral radiance given by Plank's equation for a black body whose temperature is equal to the sea one.

The τ_{path} is the atmosphere transmission.
In order to correctly evaluate the emission and propagation (N_{path} and τ_{path}) of the infrared radiation from the target and the sea through the Earth's atmosphere, MODTRAN2 model, implemented in SeaRad code, has been used by taking into account the following effects:

- the absorption by several of the atmospheric gases;
- the scattering away from the line of sight by small particles suspended in the atmosphere.

In order to analyze the target embedded in the background, the zero range radiance (2) has to be handled by considering the atmosphere radiance and transmittance trough the Earth's atmosphere as:

$$N_{target} = N_{zr}\tau_{path} + N_{path} \qquad (5)$$

Once the sea radiance has been evaluated, the contrast with the target, for several ranges and observation directions is calculated by subtracting the eq. (4) to the eq. (5) as:

$$\Delta N = N_{target} - N_{sea} = [N_{zr} - (N_{sea} + N_{sky} + N_{sun})]\tau_{path} \qquad (6)$$

where N_{target} represents the radiance of the target weighted by the Earth's atmosphere properties.

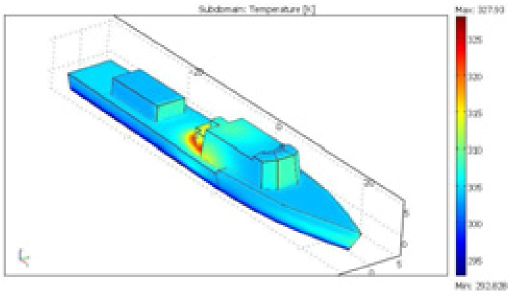
5. Preliminary Results

In this section the results relative to the thermal and infrared analysis of a ship operating in MIR and FIR band are presented.
Let us consider the simplified model of the ship shown in Figure 2.
According to the typical supplied power, let us suppose that the propulsion engine system,

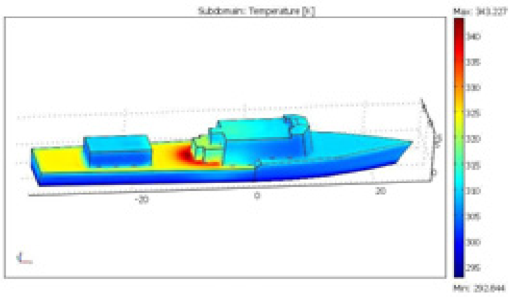
placed as indicated in Figure 2, generates a power of 700 W/m^3.

The apparent sun motion has been taken into account by considering that the ship is oriented towards east direction. The solar flux mean value has been estimated 800 W/m^2, each facet of the ship receive a solar flux depending on the scalar product of the normal to the facet and the sun direction.

In Figure 3 the temperature distribution on the ship is shown corresponding to several day moments: at 6 a.m. (a), 12 a.m. (zenith) (b) and 6 p.m. (c).



(a)



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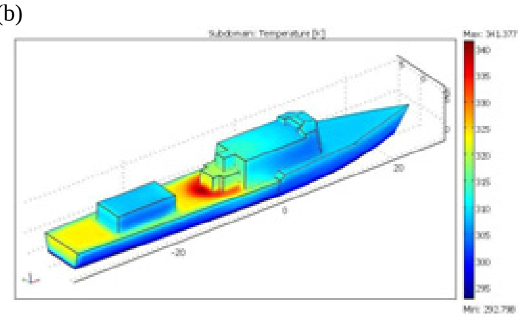
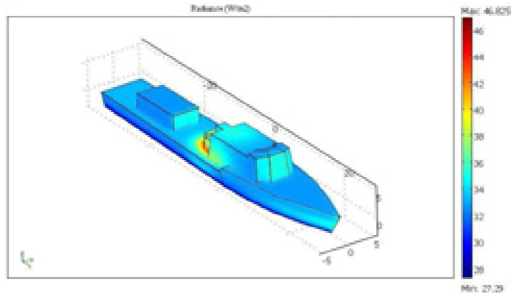


(c)

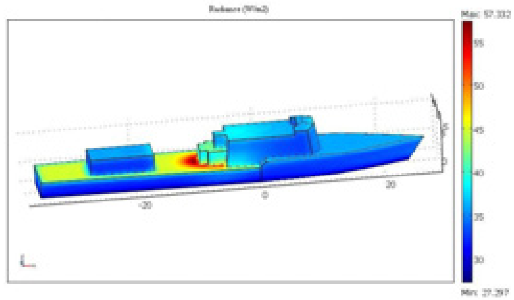
Figure 3: temperature distribution on the ship for several day moments: 6 a.m. (a), 12 a.m. (zenith) (b) and 6 p.m. (c).

Since the hull has been modeled as an empty structure, the deck reaches a very high temperature while the two solid boxes maintains low temperature.

In Figure 4 and Figure 5 the zero range radiance, evaluated in FIR and MIR bands respectively, is shown corresponding to the times previously mentioned: 6 a.m. (a), 12 a.m. (zenith) (b) and 6 p.m. (c).



(a)



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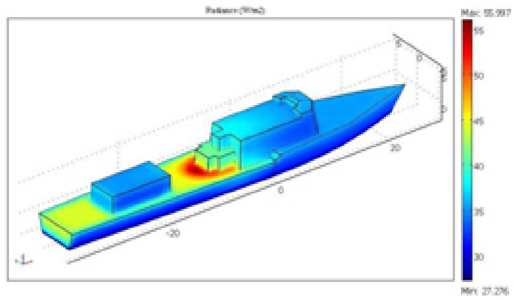
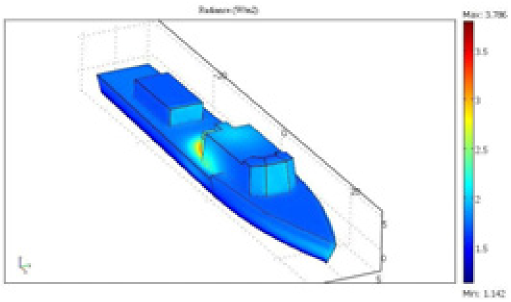
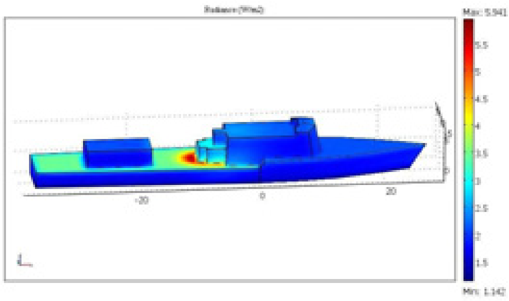


(c)

Figure 4: zero range radiance distribution on the ship for several day moments in FIR band: 6 a.m. (a), 12 a.m. (zenith) (b) and 6 p.m. (c).



(a)



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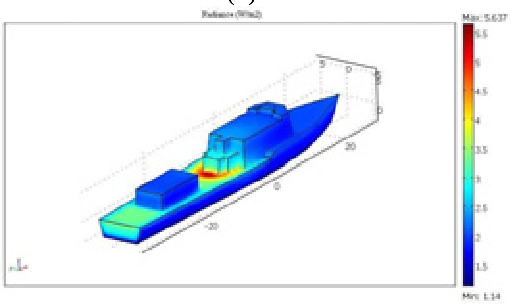


(c)

Figure 5: zero range radiance distribution on the ship for several day moments in MIR band: 6 a.m. (a), 12 a.m. (zenith) (b) and 6 p.m. (c).

By observing the previously figures, it is important to note that the sun introduces an additionally heat source that warms different areas of the ship during the day.

By fixing the observation direction at an elevation point of 10° and the range at 10 Km, it is possible to calculate the transmittance of Earth's atmosphere, shown in Figure 6,as function of the wavenumber [cm^{-1}].

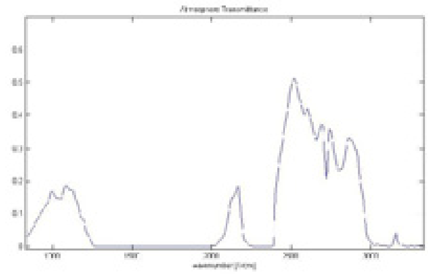
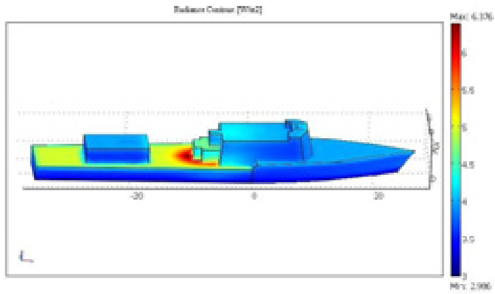
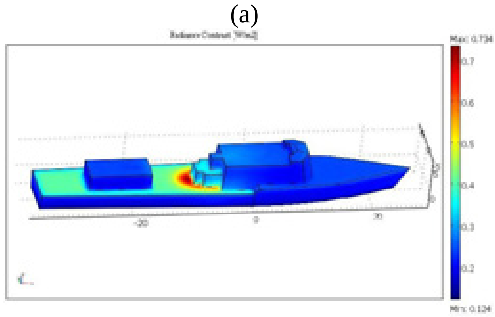


Figure 6: transmittance of Earth's atmosphere.

The radiance contrast of the ship with the sea has been shown in Figure 7 FIR(a) and MIR(b), both calculated at 12 a.m. when the sun is in zenith position.



(a)



(b)

Figure 7: radiance contrast evaluated in FIR (a) and MIR (b) bands with the sun in zenith position.

The previously figures shows that the contrast with sea is very low both in FIR and MIR bands, in the former case it achieves 6.7 W/m^2, in the latter one the maximum contrast value is 0.2 W/m^2.

6 Conclusions

Transient analysis of heat transfer module of COMSOL Multiphysics is very suitable for analyzing and modeling complex problems as real ones. Moreover the MATLAB interfacing

availability allows us a dedicated approach to the problem and a high level of result parameterization. The properly post processing operations leaded us to the infrared signature evaluation of the investigated object.
In particular, the zero range radiance of the object has been evaluated starting from the temperature distribution on the target surface. Successively, by considering the Earth' atmosphere properties, the target radiance has been evaluated and finally the contrast with sea has been calculated by using Fortran code Lowtran7.
It must be highlighted that the analysis discussed in this paper is finalized only to point out the effectiveness of the developed methodology. Therefore the results presented in this paper are intended only to support the description of the methodology. This context justifies the simplifications performed in the ship model used for the analysis together with materials characterizations in terms of equivalent mass and thermal properties. Also the mesh is not perfectly calibrated for the aim.
The methodology keeps the validity with reference to all made assumptions and/or simplifications and could be applied with success wherever the parametric level of the studied physical phenomenon is very high.
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7 References

[1] 1. R. D. Hudson, Infrared System Engineering, John Wiley & Sons, 1969.
[2] F. Kreith, Principi di trasmissione del calore, Liguori Editore, 1974.
[3] C. R. Zeisse, "SeaRad, A Sea Radiance Prediction Code", *Technical Report 1702*, November 1995.