

# Aircraft infrared signature, taken into account body, engine and plume contributions

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## 1. INTRODUCTION

The IR signature of an aircraft is the result of several major contributions, namely:

- Hot engine parts of the tail pipe and/or the air intakes
- Combustion hot gases (and in some cases hot carbon particles) in the plume
- Skin of the airframe, due to the thermal emission resulting from aerodynamic heating and internal heat sources and the reflected ambient radiation from the sun, the sky and the ground.

The aim of this paper is to explain how the combination of CFD++, CFD computational code, RadTherm-IR, 3D thermal computational code and SE-Workbench-EO from OKTAL-SE is an adequate solution for computing the IR signature of a jet aircraft taking all this major into account.

An F16 fighter jet cruising at  $Ma=0.8$  has been simulated in CFD++ including a multi species gas with the plume included in the CFD simulation. The engine intake is simulated as a mass outlet and the engine exhaust was treated as a mass inlet with a typical mixture of species that represents the state of the gases after the combustion in the jet engine. The correct temperature of the gases are imposed at this boundary and the plume is then just what will be advected downstream including turbulence dispersion and mixing. For this to work properly, the free stream air must also be divided into its standard components so the mixing at the shear layer will produce a correct mix of species including what is in the free stream air. The simulation was done using CFD++ Real Gas solver and the mesh was built using 3-matic from Materialise for the surface mesh and MIME for the volume mesh. The mesh is a tetrahedral mesh with prism layers on the surface. Wall functions boundary conditions were used at the walls and a free stream boundary condition was used at the outer boundary,  $Ma=0.8$ . The results were exported using the built in CGNS export and this was imported into SE-Workbench-EO.

The solution adopted for computing the radiative transfer through the plume is based on the IRMA module of the NIRATAM software package. The radiation from hot gases is computed using SLG (Single-Line-Group) or MLG (Multi-Line-Group) band model depending on the temperature along the LOS and the Curtis-Godson approximation is used for the mean transmissivity through inhomogeneous gases. The IRMA implementation has been revisited to make faster and more easy to maintain and the new plume radiative transfer module has been extended in terms of the number of species and the spectral resolution.

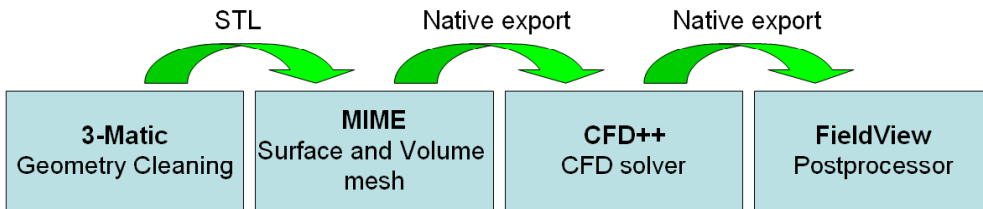
Then the revisited and extended version of IRMA has been integrated in the non real time rendering module of the SE-Workbench-EO, SE-RAY-IR, for computing IR images of jet plumes taking into account the atmosphere between the sensor and the plume but also the presence of clouds on the LOS between the sensor and the plume. Especially for computing properly the atmospheric propagation along a LOS that intersects the plume SE-ATMOSPHERE module is used for pre-computing high spectral resolution atmospheric radiation data.

The paper illustrates the use of SE-RAY-IR for computing the IR signature of the F16, including the plume, either as an isolated target in the sky or with the background behind. The paper also explains how we can render the aircraft with its plume in real time using SE-FAST-IR and a pre-computation of the plume with SE-RAY-IR.

## 2. CFD NUMERICAL MODEL

### 2.1 CFD Process

The following CFD process has been used for the work outlined below:



### 2.2 Mesh

The mesh was an unstructured mesh that consists of about 1.7 million cells mainly tetrahe-dral cells, and about 300.000 prism cells that resolve the boundary layer. There are density boxes in the volume helping the resolution in the plume area, see figure 1 and 2 below.

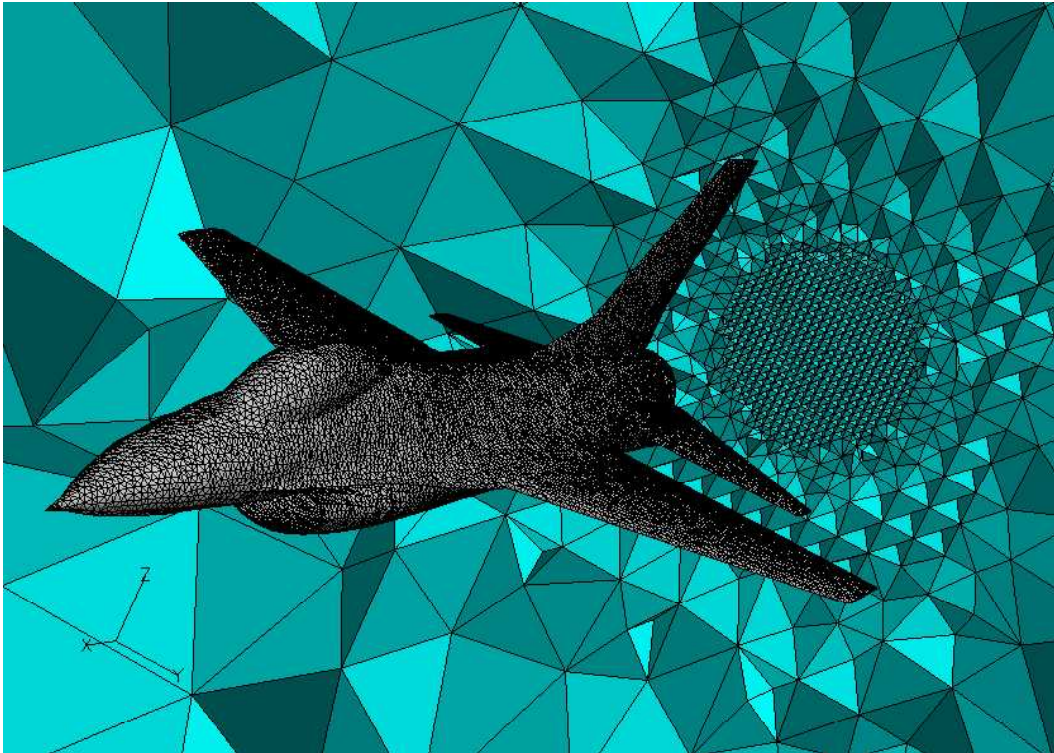


Figure 1. Surface mesh on the plane and a crinkle cut through the domain in the wake region that clearly visualizes the density region.

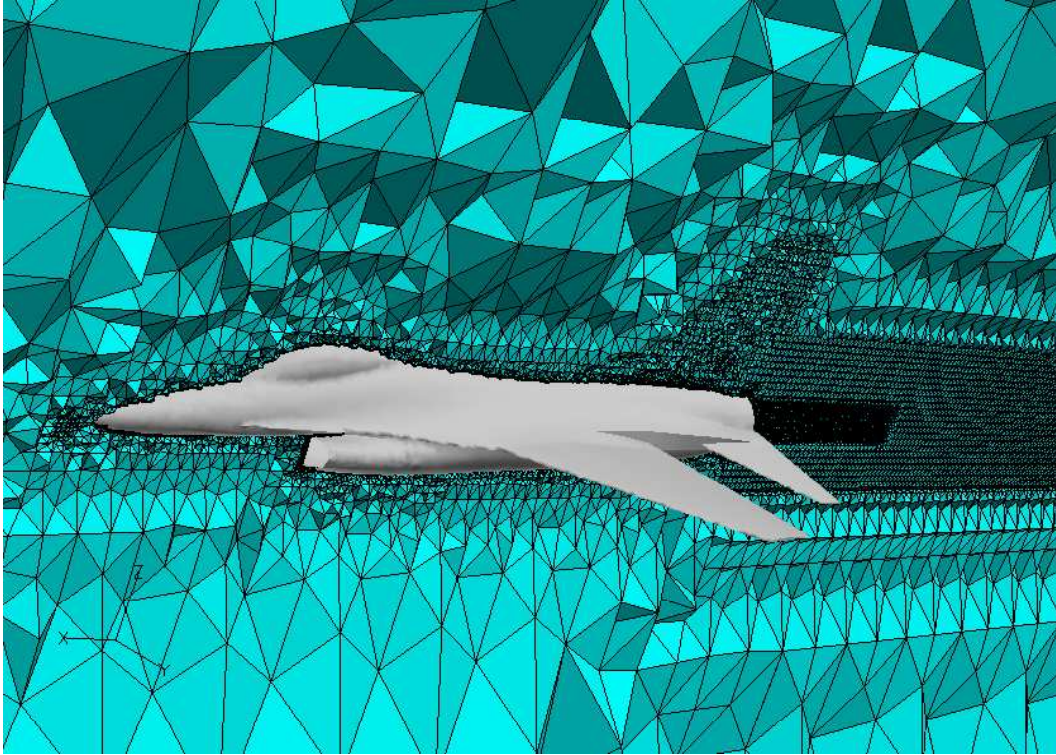


Figure 2. A crinkle cut of the volume mesh around the aircraft.

### 2.3 CFD simulation

The setup of the steady state simulation was relatively straight forward with Velocity Inlet conditions imposed to the free stream boundary if the face is regarded as an inlet face and pressure condition will automatically be imposed if the face is regarded as an outlet face. The velocity vector together with the surface normal of the free stream face is used to define if it is flowing in or out of the domain.

The flight condition is  $Ma=0.8$  and at 2 degrees angle of at-tack and the altitude is 1 km.

At the engine air intake a mass flow outlet is imposed and it is basically an adaptive pressure condition where the pressure automatically is moved to fit a given mass boundary condition. At the exhaust phase a simple mass flow inlet was defined with a hot mass flux defined in the direction normal to the face.

At all boundaries, a gas mix-ture was defined and at the free stream this was basically 70% nitrogen and 30% Oxygen. At the exhaust this mixture also contained some  $CO_2$  and some  $CO$ . The domain is shown in fig-ure 3.

The CFD solver that has been used in the current work is CFD++ from Metacomp Technology Inc. It is a fully coupled Implicit Riemann solver and in the present work, the non reactive preconditioned Real Gas equation set has been used.

As for turbulence, the realizable k-epsilon model has been used, [1] Goldberg et.al 1998.

The case ran in parallel on 2 cores, Intel core 2 Duo 2.5 GHz in about 8 hours.

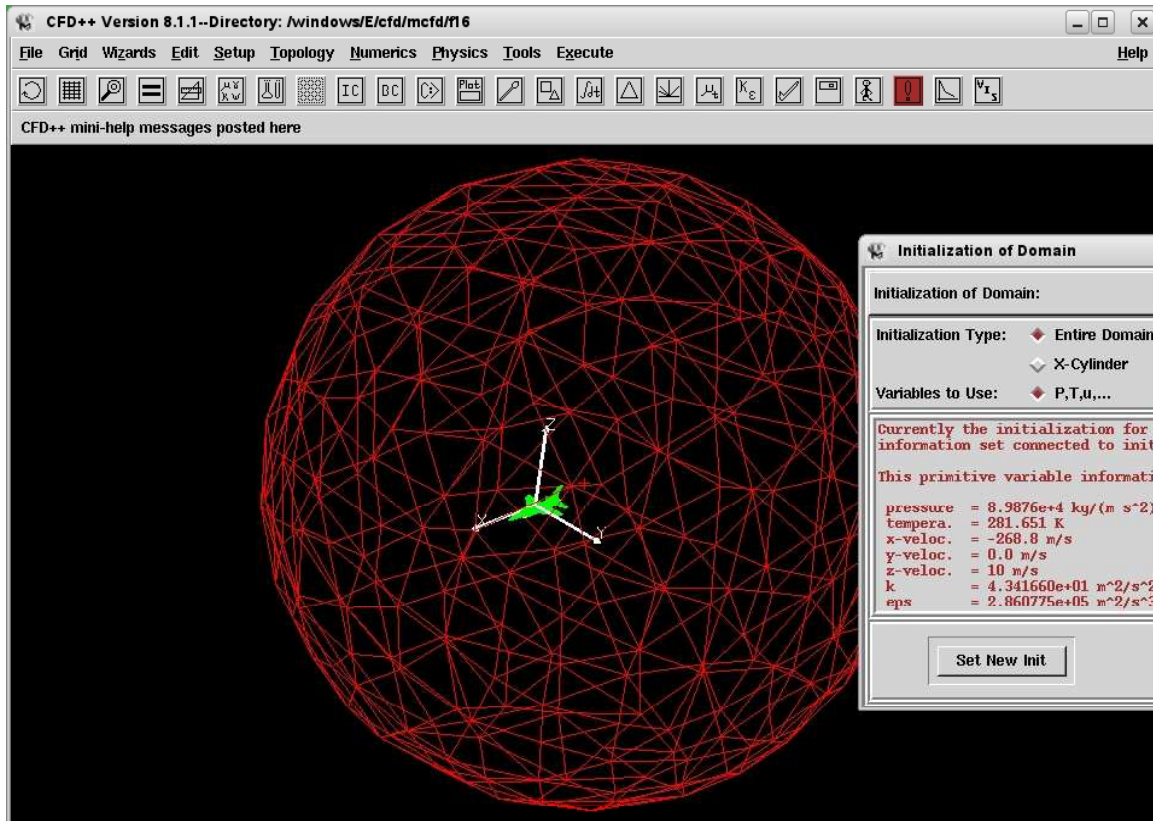


Figure 3. The domain including initial and free stream conditions.

### 3. CFD RESULTS

The results of the CFD simulation is visualized in figure 4-6. The pressure contour is shown in figure 4. Also in Figure 4, a cut plane colored by CO<sub>2</sub> concentration clearly shown the extension of the wake.

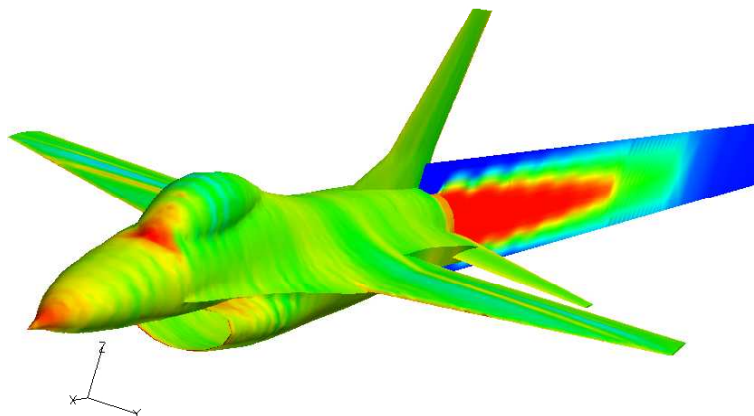


Figure 4. Pressure contours on the plane body and a cut plane colored by CO<sub>2</sub> concentration in the gas mixture.

The result shows quite clearly the relatively poor quality of the geometry. It is shown as localized pressure lines on the pressure contour plot, see figure 4. It is however not aerodynamic performance that is vital for this work and unless aerodynamics has a serious impact on the plume, this fact would not be that significant and in this work at a moderate angle of attack this is not regarded as a problem.

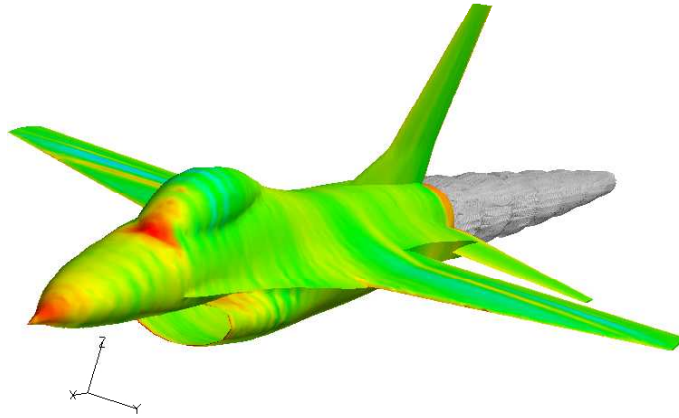


Figure 5. Pressure contours on the plane body and an isosurface of CO<sub>2</sub> concentration in the gas mixture.

In figure 5 an iso-surface of CO<sub>2</sub> concentration is shown. The level is 80% of the concentration that was used at the mass flow inlet boundary. It is clearly shown that the wake with this concentration slowly disappears and this is due to turbulent mixing at the shear layer of the plume.

## 4. SE-WORKBENCH RENDERING PROCESS

Once the fluid computation has been done, data are converted from the CGNS format in order to extract the temperature, pressure and species concentrations needed by the SE-WORKBENCH computations. The airframe and the plume are processed separately.

### 4.1 Skin temperature

The first step is to extract the temperature mesh from the CFD++ output file and to construct the skin thermal definition of the airframe. It consists in constructing a mesh for which the temperature of each vertex is known. This mesh does not need to be the same as the airframe geometry, and is mostly the tessellated mesh used for fluid computations. Then, when computing the radiance for at an intersection point between a ray and the aircraft body, the skin mesh is used to search the nearest vertex temperature or to extrapolate the temperature from the nearest triangles.

### 4.2 Plume conversion

The second step consists in extracting the volume data from the CGNS file. The SE WORKBENCH plume is defined by a set of points for which the temperature, the pressure and the concentration of each handled gas species is defined. The CFD++ output file provides all this data using tetrahedral and prism volume mesh. However, this mesh is not needed for IR rendering computations. Thus only the punctual data are extracted and stored in the SE-WORKBENCH plume file.

### 4.3 Spectral data

Whereas the concentrations of gas species come from CFD++ computations, the spectral data of each species come from a molecular database provided by OKTAL-SE, which contains the values of the absorption coefficient and the line spacing coefficient. This consists in tables function of temperature and wavenumber. The handled species are classified in three categories:

- Active species: that contribute directly to the radiance and attenuation of the plume (H<sub>2</sub>O, CO<sub>2</sub>, CO)
- Inactive species: that only contribute indirectly by modifying the behaviour of the active species if they are present (N<sub>2</sub>, O<sub>2</sub>)
- Particle species: that use a distinct rendering algorithm and could cause scattering (C).

All these species are defined according to a temperature sampling (8 temperatures in the range 100 K to 3000 K) and a thin spectral sampling (921 wavenumbers from 400 cm<sup>-1</sup> to 5000 cm<sup>-1</sup> with a step of 5 cm<sup>-1</sup>).

### 4.4 Preparing the scenario

Once all data have been converted, the original airframe geometry associated with its skin thermal definition and the plume file are loaded in a scenario using SE-SCENARIO software tool. This software enables to define the simulation sensor, to load atmospheric conditions computed with SE-ATMOSPHERE and to edit object trajectories. The software can be used to define the scenario for both studies (SE-RAY) and real time (SE-FAST) simulations.

### 4.5 Non real-time simulation

For non-real time rendering SE-RAY-IR is then used to compute IR images of the scenario. The airframe is rendered using the standard ray tracing provided by the software according to its physical material and the skin temperature definition.

The plume is rendered using an advanced radiative transfer approach based on a high resolution spectral computation using gas concentrations and atmospheric conditions as input. This algorithm is a line-by-line rendering approach based on the Curtis-Godson approximation model. The solution adopted is based on the IRMA module of the NIRATAM software package [2]. The radiation from hot gases is computed using SLG (Single-Line-Group) or MLG (Multi-Line-Group) band model depending on the temperature along the LOS and the Curtis-Godson approximation is used for the mean transmissivity through inhomogeneous gases. The IRMA implementation has been revisited to make it faster and more easy to maintain and the new plume radiative transfer module has been extended in terms of number of species and spectral resolution.

Then the revisited and extended version of IRMA has been integrated in the non real time rendering module of the SE-Workbench-EO, SE-RAY-IR, for computing IR images of jet plumes taking into account the atmosphere between the sensor and the plume but also the presence of clouds on the LOS between the sensor and the plume. Especially for computing properly the atmospheric propagation along a LOS that intersects the plume SE-ATMOSPHERE module is used for pre-computing high spectral resolution atmospheric radiation data.

For a given ray of evaluation travelling through the plume, the plume data are used to determine the temperature profile along the path using a k-nearest neighbour approach. According to this profile, the path is cut in slabs based on a constant temperature definition. Then, for each slab, the pressure and concentrations are also determined using a k-nearest neighbour approach. The path is finally processed to compute its radiance and attenuation. If a ray goes through the plume, the atmosphere computation is done using a narrow band approach in order to ensure the coherency while composing the radiance of the hot plume with the radiance and attenuation of the cold atmosphere. The results are obtained line-by-line, and then are integrated on the visualisation bands of the sensor.

### 4.6 Real-time simulation

The scenario can also be used in a real-time application based on the SE-TOOLKIT and SE FAST-IR. However, the airframe and plume data must be pre compiled, that is prepared for real-time simulation. The airframe is pre compiled using SE-FAST-IR-COMPILER, which consists in preparing the data that will be used in the rendering shaders of graphic cards. The plume is compiled using SE-FAST-IR-PLUME-COMPILER. Whereas the approach of the two compilers is the same one, the data needed for surface and volume are not the same. As for surfaces, the compiled plume

should be viewed for all orientations. While for surfaces the radiance is reconstructed directly from the material properties and textures for all orientations, an accurate plume simulation is costly in terms of time and memory and so it is not possible to compute it in real-time. Our idea is then to use a sort of image-based rendering: the radiances and attenuations of the plume and its surrounding atmosphere are pre-computed using the same accurate algorithm as the one implemented in SE-RAY-IR, for a set of positions and orientations, and stored in textures. These textures are then used in the shaders to reconstruct the radiance and transmission for any orientation using simple interpolations.

This enables to move around the plume in real-time and to obtain results comparable with the SE RAY IR simulation results. Unfortunately, as the plume needs to be pre compiled in the atmosphere in order to take correctly into account the hot/cold gas combination, an error is done when using the plume in conditions very distinct from the compilation one.

## 5. SE-WORKBENCH RENDERING RESULTS

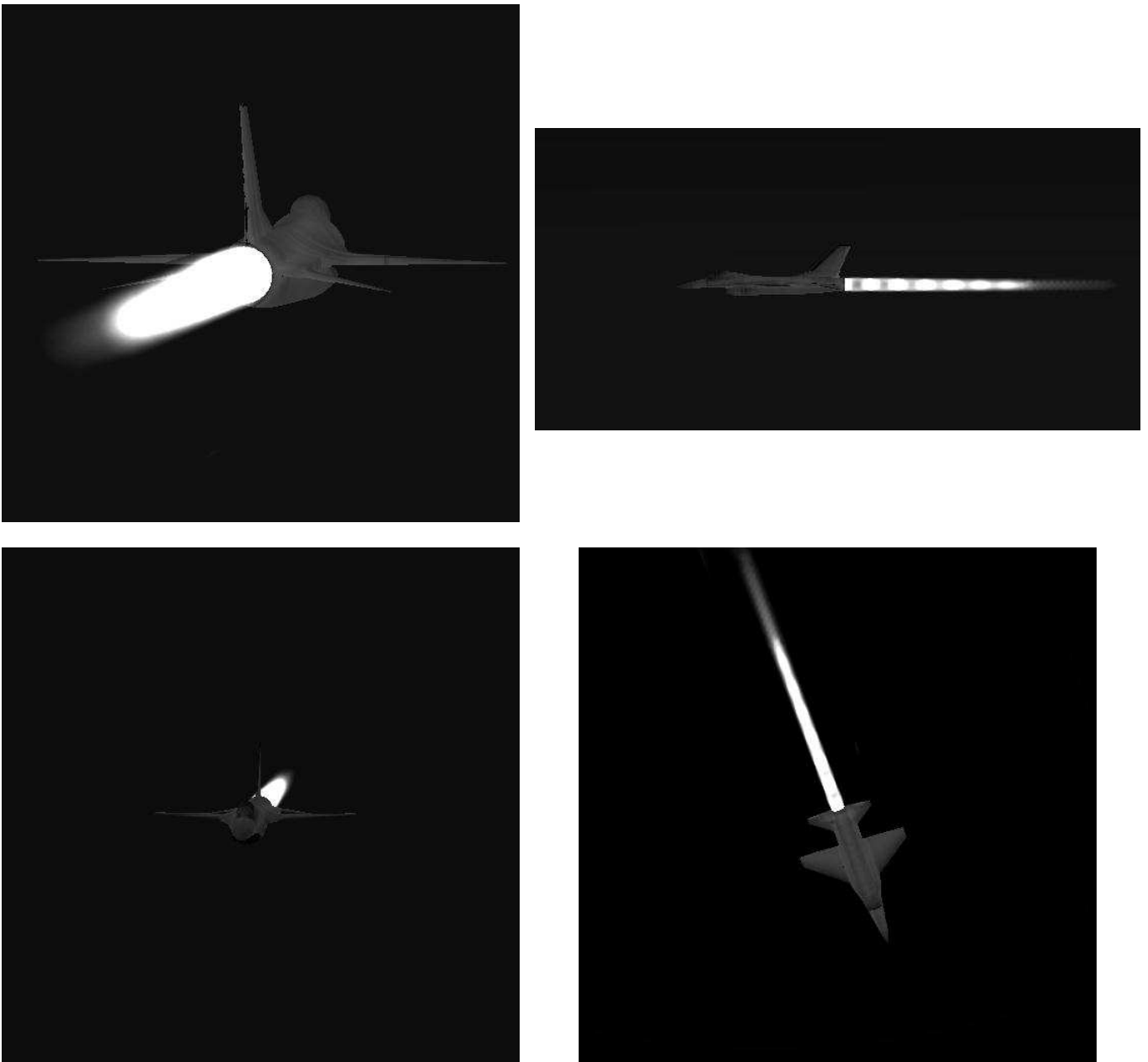


Figure 6. MWIR images computed using SE-RAY-IR (ray tracing)

These IR images of the F16 with its engine plume have been obtained considering the atmospheric propagation effects in the case of fine weather atmospheric conditions. The spectral band considered here is 3 to 5  $\mu\text{m}$ .

In the figure 7 hereafter, the atmospheric conditions are the same but cloud layers have been introduced into the model and have been rendered using the dedicated SE-WORKBENCH library called SE-SPECIAL-EFFECTS.



Figure 7. MWIR image computed using SE-RAY-IR and SE-SPECIAL-EFFECTS

## 6. FUTURE WORKS

This paper demonstrates that the combination of a CFD software code, such as CFD++, and OKTAL-SE SE-WORKBENCH is a relevant solution for producing realistic IR images of a complex 3D synthetic environment including aircrafts and jet engine plumes.

The future works has now to focus on the validation of this software solution through comparisons with other software solutions and/or to measurements.

The challenge for the future is also to be able to produce realistic IR images of a scene including helicopters and/or missiles with their engine plume. In the case of helicopters the deviation effects of the rotor blade flux on the engine plume has to be taken into account since they change the skin temperature a lot. In the case of missiles a realistic simulation of the engine plume is a big challenge since the very hot temperatures in the plume create a complex chemistry between the species and scattering by particles should also be introduced into the model.

## REFERENCES

1. U. Goldberg, O. Peroomian, and S. Chakravarthy, *A Wall-Distance-Free k-e Model With Enhanced Near-wall Treatment*, ASME J. Fluids Eng., volume 120, pages 457-462, Sep-tember 1998
2. K. Beier, *Infrared Signatures from Jet Engines*, in *AGARD Seminar*, p. 193, DLR Institute for Optoelectronics, September 1990