Influence of Various EM Models of an Aircraft to Monostatic RCS

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Abstract—**This paper outlines influence of four EM models of an electrically large aircraft on monostatic RCS results at 2.00 GHz. The differences in calculated RCS results suggest the importance of a choice of an EM model depending on the particular scope. The paper provides better understanding of some of EM scattering effects frequently addressed by engineering, scientific and military working groups interested in RCS. Software tool used for simulations and model manipulations is a full wave 3D EM Method-of-Moments based software with Surface Integral Equations applied to quadrilateral mesh elements.**

Index Terms—**Scattering, aircraft, RCS, simulation.**

I. Introduction

CALCULATION of scattering from electrically large aircrafts is often a subject of interest of scientific, engineering, or military working groups. The purpose of scattering calculation can vary from an academic discussion, to simulation software testing, to anti-aircraft defense tactics preparation. Sometimes a calculation of scattering from electrically large fighter aircrafts is driven by marketing as various teams simulate fighter aircrafts in order to impress existing or future customers. According to information coming from various open sources, pure metallic models of aircrafts are still fashionable in various electromagnetic (EM) software tools (for example, the models of 4th generation of fighter jets are still widely used). They are usually modeled as metallic surfaces. Regarding the shape of an aircraft model, the details are usually classified and the shape usually comes rather from loose visual impression then from precise engineering data. For the sake of modeling some details are usually simplified, e.g., the engine intake is terminated with a metallic plate. The problem of inaccurate modeling arises when such model is chosen as the reference model in a realistic scenario.

The scattering results are usually related with radar operations and obtained after illuminating a target (an aircraft) with a plane wave. This paper will consider monostatic scattering and illumination with EM wave containing electric field with the E_θ component, only [1].

In monostatic radar setup the same antenna is used for both transmitting and receiving the signal. Complex radar targets such as aircrafts generally have (monostatic) cross sections that vary rapidly with frequency and aspect angle. Actually, a radar target is characterized by its radar cross section, which gives the ratio of scattered power to incident power density. The ratio depends on the target shape, the frequency and the polarization of the incident EM wave, and on the incident angle relative to the target. Monostatic radar cross section (RCS) can be defined as RCS where angles of incident and reflected waves are identical. In general, more complex targets require more efficient numerical techniques for software simulations [2].

Here, we will consider four EM models of a single representative sample in the form of the 4th generation fighter aircraft. The EM models encompass scenarios where:

- The aircraft canopy and the radome are modeled as metallic surfaces while the engine intake is terminated with a metallic plate.
- The aircraft canopy and the radome are modeled as metallic surfaces while the engine intake can be considered as one-side open cavity with a metallic plate located in front of the jet engine rotor blades.
- The aircraft canopy is modeled as a metallic surface, the radome is excluded exposing a flat surface of the radar antenna while the engine intake is in the form of the open cavity.
- The aircraft canopy is excluded from the model exposing a pilot's working area which is also an open cavity. The radome is excluded exposing a flat surface of the radar antenna. The engine intake is in the form of the open cavity.

The results of monostatic RCS simulations of the four models will be compared and discussed. The aircraft dimensions and shape are to some degree approximate with the respect to actual aircraft.

The simulations will be facilitated in the frequency domain. In this paper, WIPL-D Software, a full wave, 3D EM frequency-domain Method-of-Moments (MoM) based software will be exploited for importing and modifying available CAD file and simulations applying higher order basis functions on quadrilateral mesh elements with Surface Integral Equations [3]. Since radar frequencies used for long range surveillance are located within L-band between 1 GHz and 2 GHz [4] and airport surveillance primary radar frequencies are about 2.8 GHz [5], the models presented here will be simulated in-between these frequencies trying to grasp EM effects appearing at both bands. Thus, the EM models of the aircraft are simulated at frequency of 2 GHz.

II. Aircraft EM Models

Four CAD models of the aircraft are shown in Figs. 1-4. All models are displayed with a symmetry plane. The symmetry plane represents a software feature where a symmetry of the structure is exploited to reduce an original number of unknowns. The original number of unknowns is approximately halved. Each figure also contains a magnified detail of an aircraft model. For all models it is assumed that aircraft surfaces are perfect electrically conductive metal. The models were imported and subsequently modified to

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have lower surfaces of wings smooth i.e., without pylons intended for carrying various loads.

The first model, which is shown in the Fig. 1 represents the model with the aircraft canopy and the radome modeled with metallic surfaces, while the engine intake is terminated with a metallic plate. This model is probably the most often seen in various software presentations and booklets. Fig. 1 also contains approximate dimension of the model which can be referenced when estimating the dimensions of the other models. In general, the model shown in the Fig. 1 is suitable for simulations with geometrical\physical optic-based EM solvers since the cavity in the form of engine intake is practically excluded from the simulation. From the marketing point of view this model mimics very well the realistic aircraft structure.

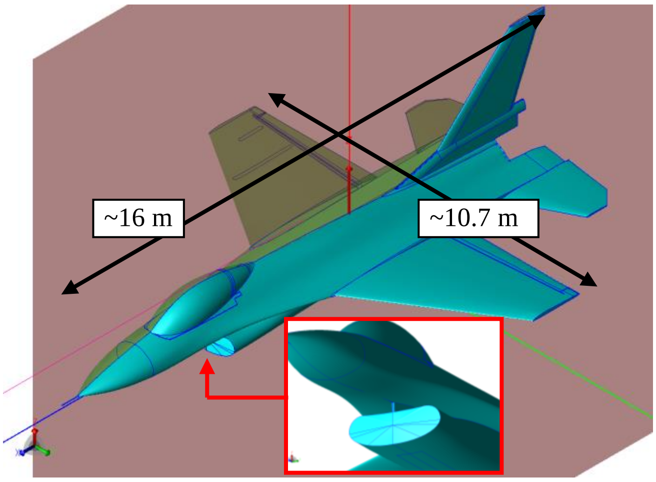

Fig. 1. The aircraft canopy and the radome are modeled as metallic surfaces while the engine intake is terminated with a metallic plate. This is probably the most commonly used EM model of an aircraft.

The second EM model shown in the Fig. 2 represents the model where the aircraft canopy and the radome are modeled as metallic surfaces while the engine intake can be considered as an open cavity with a metallic plate located in front of the jet engine rotor blades. Such model can also be often seen in various software presentations and booklets, despite presence of the cavity.

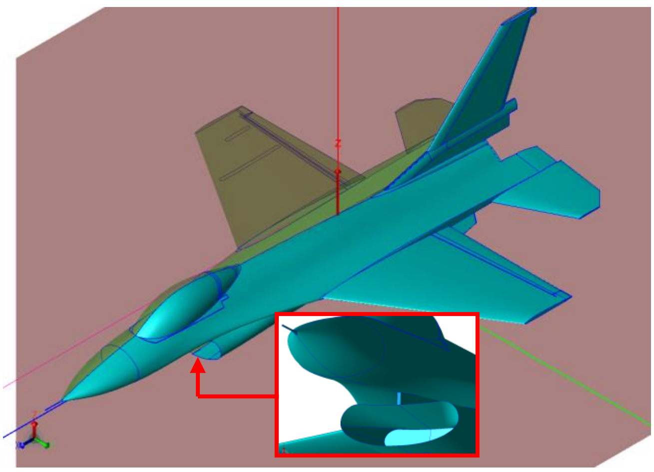

Fig. 2. The model of the aircraft which is also often simulated. The aircraft canopy and the radome are modeled as metallic surfaces while the engine intake can be considered as an open cavity with a metallic plate located in front of the jet engine rotor blades.

The third model is shown in the Fig. 3 and it can be used as a good representation for many types of aircrafts. In order to reduce influence of the pilot working area to RCS which also represents a sort of an open cavity (see also Fig. 4), some aircraft real-life models have canopy painted with the special material which is visually transparent and which increases radar waves reflection [6]. This model has the aircraft canopy modeled as a metallic surface, while the airborne radome covering radar antenna and providing aerodynamic streamlining is excluded from the model exposing radar antenna flat surface. Removing radome is justified as the radomes are generally composed of low-loss dielectrics materials [7]. The assumption applied here is that the radome is transparent for EM waves with frequency of 2 GHz. The engine intake is again in the form of an open cavity.

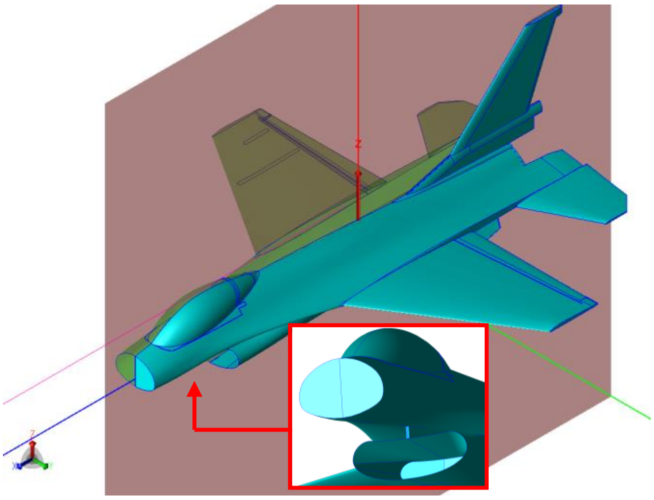

Fig. 3. The model of the aircraft where the aircraft canopy is modeled as a metallic surface, the radome is excluded exposing radar antenna flat surface while the engine intake can be considered as an open cavity with a metallic plate located in front of jet engine rotor blades.

Finally, the fourth EM model is shown in the Fig. 4.

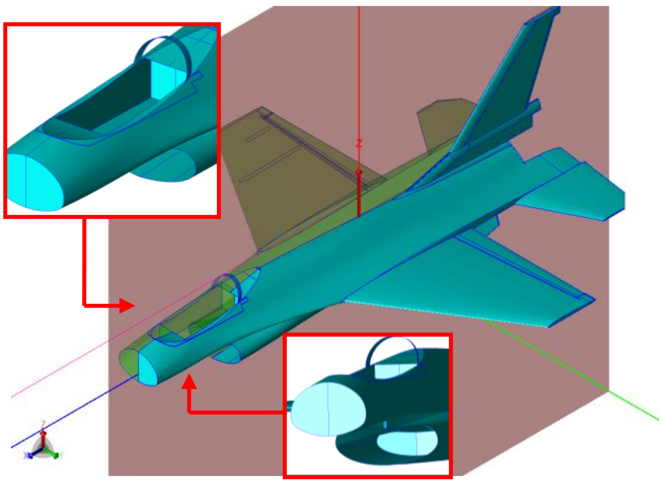

Fig. 4. The model of the aircraft which is probably the most rarely seen. The aircraft canopy is excluded from the model exposing an open cavity which represents a pilot's working space. The radome is excluded exposing radar antenna flat surface. The engine intake is in the form of an open cavity with a metallic plate located in front of jet engine rotor blades.

The model shown in the Fig. 4 encompasses the aircraft canopy excluded from the model exposing cavity representing a pilot's working area. The assumption applied here is that the canopy is transparent for EM waves with frequency of 2 GHz. Also, the radome is excluded exposing radar antenna flat surface. The engine intake is in the form of an open cavity.

In order to define suitable nomenclature of the models, four acronyms will be introduced. The model shown in the Fig. 1 will be named and referred further as MMM since the radome, the canopy, and the termination of the cavity are modeled with metallic surfaces (metal-metal-metal, respectively).

The model shown in the Fig. 2 will be named and referred further as MMA since the radome, and the canopy are modeled with metallic surfaces, while the termination of the cavity is excluded (it is assumed that it is modeled with air surface). In that sense, the name of the model will be MMA (metal-metal-air, respectively).

The model shown in the Fig. 3 will be named and referred further as AMA since the radome is replaced with air, the canopy is modeled with metallic surfaces while the termination of the cavity is excluded (again, it is assumed that it is modeled with air surface). In that sense, the name of the model will be AMA (air-metal-air, respectively).

The model shown in the Fig. 4 will be named and referred further as AAA since the radome, the aircraft canopy, and the termination of the cavity are all excluded from the model (assuming that all of them they are modeled with air surfaces). In that sense, the name of the model will be AAA (air-air-air, respectively).

Meshing details of the four models are presented in the Fig. 5-Fig. 8.

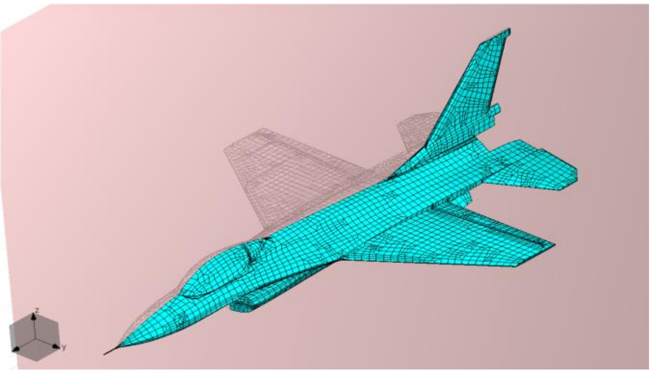

Fig. 5. Meshed metal-metal-metal (MMM) model

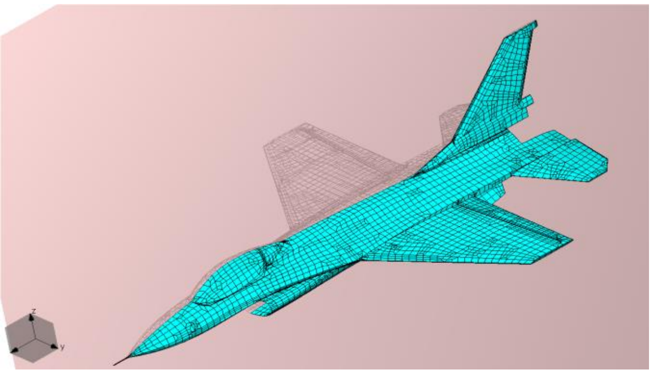

Fig. 6. Meshed metal-metal-air (MMA) model.

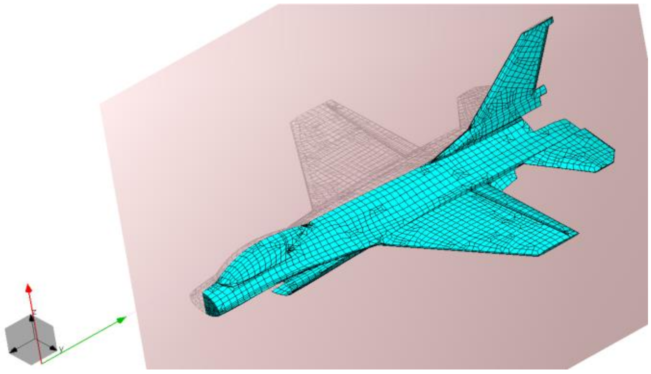

Fig. 7. Meshed air-metal-air (AMA) model.

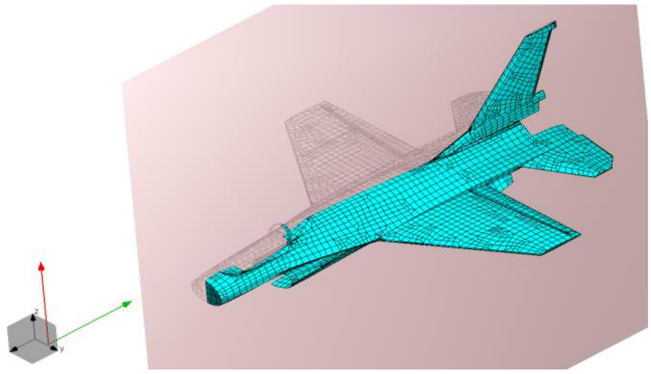

Fig. 8. Meshed air-air-air (AAA) model.

These four figures (Fig. 5-Fig. 8) depict meshed EM models i.e., models after applying mesh procedure and converting CAD files to simulation software native format. In the software native format, the aircrafts are modeled by using bilinear quadrilateral surfaces

III. SIMULATION RESULTS

In order to discuss the influence of various aircraft modelling approaches, the calculated monostatic scattering results for four EM models follow. For the reasons of the careful comparison, it is convenient to present in the same graph the results originating from a pair of two models (three pairs in total, MMM-MMA, MMA-AMA and AMA-AAA). Eventually, MMM and AAA models will be compared.

All the results are obtained after calculating monostatic scattering from the front area of the aircraft. Actually, monostatic scattering is calculated in 901 directions encompassing theta angle span from 45 degrees below to 45 degrees above the aircraft nose. It is adopted that angle $\theta = 0$ degrees points toward aircraft nose (actually, it points toward horizon). The orientation of the aircraft and the theta angle are shown in Fig. 9.

All of the models have been simulated at operating frequency of 2 GHz. The workstation used for the simulations is Intel® Xeon® Gold 5118 CPU @ 2.30GHz 2.30 GHz (2 processors) with 192 GB RAM and 4 GPU cards Nvidia GeForce GTX 1080 Ti used for matrix inversion.

The most time-consuming simulation is MMA requiring less than 90 minutes to complete the simulation. Also, it requires 224,852 unknowns. The model MMM requires 218,601 unknowns while the model AMA requires 192,756 unknowns. Finally, the model AAA requires 193,419 unknowns.

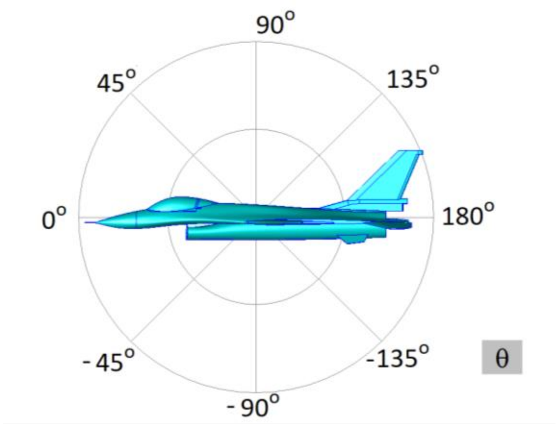

Fig. 9. Theta angle and the orientation of the aircraft.

A. Comparing Results: MMM vs. MMA

The comparison between MMM and MMA results is shown in the Fig. 10. A strong influence of cavity presence can be seen there. Actually, completely different results are obtained for angles between approximately -45 degrees and 5 degrees where, on average, the results differ by approximately 15 dB. This angle span corresponds to the angles of incidence important for ground-based surveillance radars.

The monostatic RCS for angles higher than about 10 degrees is almost the same for both models. It is expected since these directions are not affected by a way of terminating the engine intake, in this case located below the aircraft.

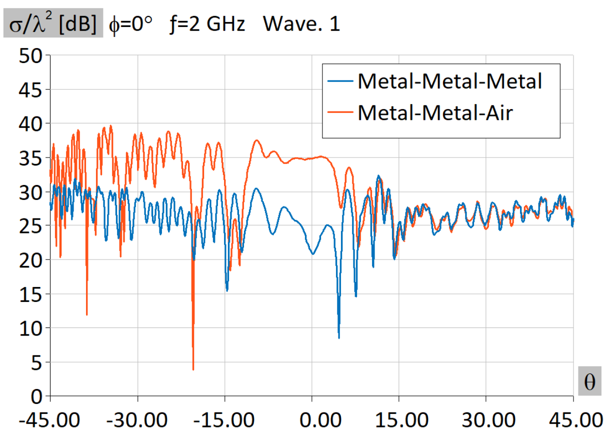

Fig. 10. Monostatic normalized RCS: MMM vs. MMA

B. Comparing Results: MMA vs. AMA

The comparison between MMA and AMA results is shown in Fig. 11. The only difference appears around 0 degrees. This is expected since the main difference between these two EM models appears in the area of the aircraft nose. This difference is significant in environment scenarios in which the aircraft is illuminated from the horizon (e.g., if an aircraft nose is illuminated from another airborne surveillance radar).

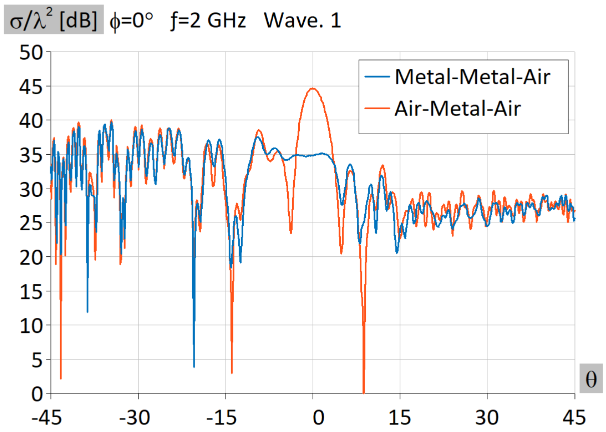

Fig. 11. Monostatic normalized RCS: MMA vs. AMA.

C. Comparing Results: AMA vs. AAA

The comparison between AMA and AAA results is shown in the Fig. 12. The influence of representing pilot's working area as an open cavity is clearly seen in the scattering directions above theta angle of about 15 degrees. The reason for the differences can be explained similarly as in the MMM-MMA case - the presence of the cavity increases monostatic normalized RCS level.

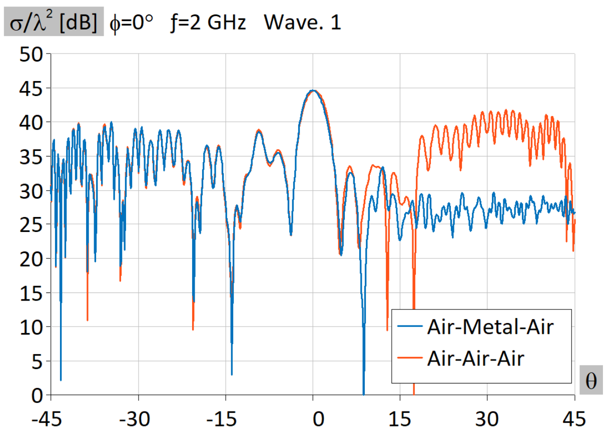

Fig. 12. Monostatic normalized RCS: AMA vs. AAA.

D. Comparing Results: MMM vs. AAA

In order to compare the two extreme cases considered in this paper, (MMM-AAA), calculated monostatic normalized RCS results are presented in the Fig. 13. The differences are considerable in the whole range of theta angles (-45 deg, 45 deg), but the origin for the differences can be easily tracked and explained in each of three mentioned subranges due to the previous three analysis and comparisons.

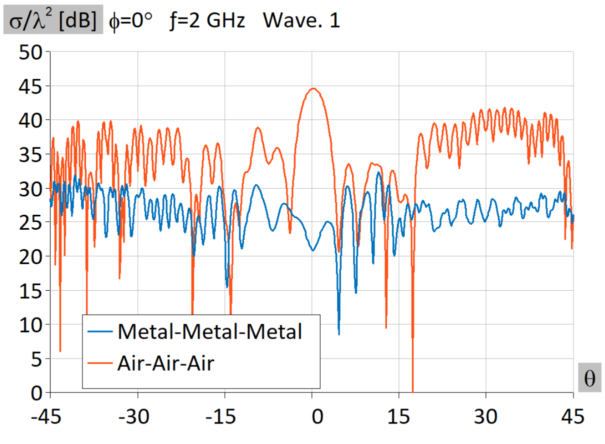

Fig. 13. Monostatic normalized RCS: MMM vs. AAA.

IV. Conclusion

This paper outlines influence of various EM models of an aircraft to monostatic normalized RCS results. The software tool used for the simulations and the model manipulations was a full wave 3D EM Method-of-Moments based software with Surface Integral Equations applied to quadrilateral mesh elements.

The simulated fighter aircraft is modeled using PEC metallic surfaces. The operating frequency is selected to be between frequencies of acquisition radar and frequencies of airport surveillance primary radar. The excitation is a linearly polarized EM plane wave containing only theta component of the electric field.

Four simulated EM models of the aircraft represent four common cases of aircraft models. Starting from a widely accepted model of the aircraft, named MMM here, the models are modified by adding or removing metallic surfaces, while dielectric properties of the surfaces are ignored.

A relevant EM model of the aircraft is related to a particular purpose, from the software marketing to the various military scenarios. From the marketing point of view, the adequate model contains the least modifications and it is easily understandable (MMM). However, for modeling real-life aircraft and obtaining results required for military purposes, the models similar to AMA or AAA should be used. The two models exhibit significant EM effects coming from the details such as jet engine intake, radome and aircraft canopy and are not expected at the first glance.

This aircraft represents to some extent a large and complex radar target. Thus, it can be assumed that in a specific angle span, monostatic RCS levels change if some parts of the aircraft are replaced with another parts. This assumption can be identified easily in the Fig. 11, where a flat plate produces significantly larger reflection compared to a conical shape representing metallic aircraft nose. An effect of this kind is expected, due to the nature of an EM wave scattering from the metallic surfaces of various shape. The similar effect can be noticed if a drop shaped canopy (or flat plate terminating the engine intake) is replaced with the open cavity. Since the aircraft is large and the reflections from these areas are assumed to be almost independent, all the effects presented in Fig. 13 using a single aircraft model can be also obtained by concatenating separately obtained results shown in Figs. 10-12.

The high efficiency of computation can be confirmed through the simulation times as they are all relatively short considering electrical size of the simulated structure and the workstation used.

The further investigation of this structure will include influence of the gun pipe and presence of various door openings to monostatic scattering. Also, further investigation will include application of radar-absorbing materials to selected aircraft surfaces in order to decrease a scattering level.

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