Electrically Large Antenna Placement and RCS Scenarios: Full-Wave EM Simulations

Handling a variety of different simulation scenarios with a single simulation method is rather challenging for many software suites. A single method approach ensures that no error is introduced in modeling the coupling between the parts of the model calculated with different methods. Furthermore, a user does not need to judge where to use a particular method or become an expert in many different fields. One of those which can take up a challenge is WIPL-D, a software based on Method-of-Moments (MoM). When using WIPL-D many different simulation scenarios involving complicated and electrically large models can be addressed using desktop workstations. To illustrate some of the WIPL-D Software capabilities we presented here various antenna placement (Figure 1, Figure 2) and scattering scenarios (Figure 3) interesting for both, defense and consumer industry.

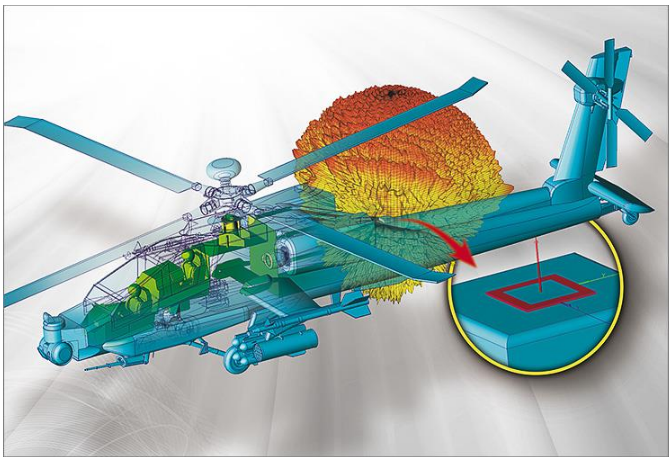

Figure 1. Antenna mounted on a helicopter

WIPL-D Pro CAD, a member of WIPL-D suite enables:

- import of extremely complex geometries from all commonly used CAD formats (for example a model created in some mechanical engineering software tool),
- validation of models,
- easy simplification of details insignificant for EM simulation (typical examples are metallic screws).

This product also includes in-house developed quad mesher which performs subdivision of complex geometries into bi-linear quadrilaterals which are subsequently submitted as input for WIPL-D numerical kernel. The meshing is automated and extremely efficient to allow precise modeling of details, curvatures and small features while the requirements for EM simulation are kept as minimal as possible.

After a quad mesh is created, **WIPL-D Pro** performs EM simulation in very efficient manner. WIPL-D kernel default setting supports mesh elements (quads) of size 2 wavelengths-by-2 wavelengths due to unique higher order basis functions (HOBFs). Current expansion on these mesh elements is in a form of a polynomial of 8^{th} degree covering a length of an edge of two wavelengths. The number of unknown coefficients related to the current expansions (number of unknowns) to be stored in (MoM) matrix is considered as minimal compared to other MoM codes. It can be estimated to be 30 per wavelength squared for a metallic surface, or 60 per wavelength squared for a dielectric surface. In addition, WIPL-D encompasses many advanced reduction features to decrease a number of unknowns even further with the accuracy preserved, which leads to even more efficient EM simulation.

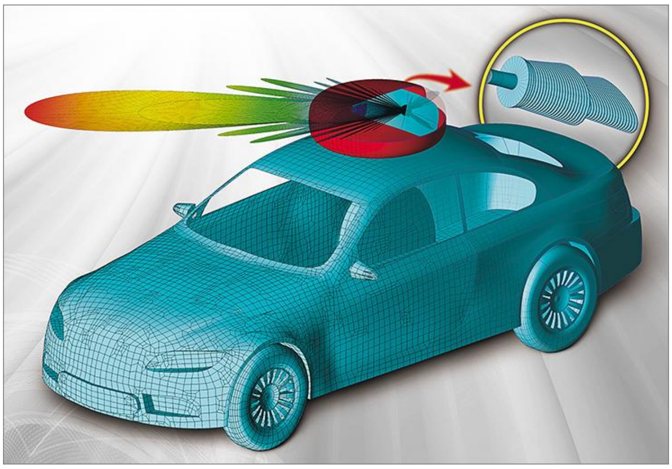

Figure 2. Antenna mounted on a car

Electrically large models either impossible to solve or requiring impractically great amount of computational resources with the original WIPL-D Pro solver, can be solved using the **Domain Decomposition Solver (DDS).** The basic idea behind DDS is that the original model is decomposed into a number of groups. A group is composed of a number of neighboring plates and wires. Each group represents a subproject. In the 0^{th} iteration, subprojects are simulated independently and the coupling between them is not taken into account. Solutions of all subprojects are used as macro-basis functions whose weighting coefficients are determined from the condition that mean-square value of the residuum of the original project is minimized. The residuum of the final solution in the 1^{st} iteration can be used as the excitation in the 2^{nd} iteration, and so on. The entire iterative procedure finishes when the total residuum falls below the predefined threshold.

In case of real-life **antenna placement scenarios**, simulation of antennas mounted on an electrically large platform can be a very challenging problem. In such a scenario, antenna is often electrically small compared to a dominant dimension of the structure sometimes amounting even several hundred wavelengths. Furthermore, the antenna model usually contains details which are several dozen times or even several hundred times smaller than a wavelength. Even with such a contrast in the size of elements, a software has to fulfill the requirements for highly accurate and fast solution.

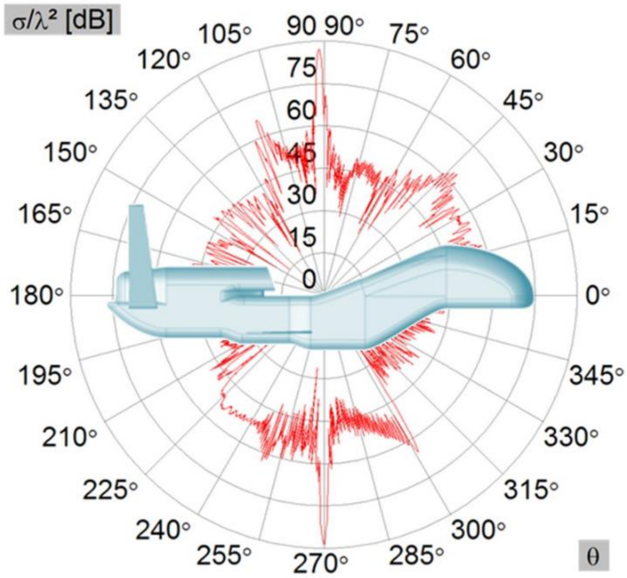

Figure 3. Monostatic RCS of a global hawk model at 5 GHz

The **RCS simulations** also have some specific properties. Due to the electrical size of radar targets, the scattering analysis is often performed using high frequency methods. However, an inherent characteristic of these methods is a limited accuracy. An additional problem occurring when calculating monostatic RCS is a large number of excitations. With WIPL-D this is not a problem as MoM solver uses a direct method to solve a system of linear equations, so finding the solution for a monostatic RCS is just a bit more demanding than for a bistatic case. Usage of full-wave method resolves problem with the accuracy, but it generally has very high requirements regarding the computer memory and simulation time. This is why RCS simulations are among the most complex applications of EM codes. The special attention with RCS simulations is given to the simulations of fighter aircrafts because of their size and complexity. This document will demonstrate how WIPL-D Software can be used for efficient electromagnetic scattering analysis of some fighter aircrafts.

The first scenario discussed in this document is a simulation of an antenna mounted on an aircraft. The EM model will include a dipole antenna fed by coaxial cable with a balun mounted on the fuselage of F-16 military aircraft. It is assumed that the dipole antenna is a part of an IFF (Identification, friend or foe) system. Output results, information about application of current expansion order reduction, number of unknowns, and simulation time will be presented.

The second scenario contains three fighter aircraft scenarios. They are actually scattering simulations from metallic models of F-16 and F-35 aircrafts at various frequencies.

The third scenario contains electromagnetic aspects of an electrically very large antenna placement scenario presenting an anti-collision system (or collision avoidance system) which is a safety system found in cars. In this scenario we consider anti-collision system using radar at 77 GHz and we present the results from simulations of anti-collision radar antenna mounted on a car bumper.

All of the simulated models are treated with WIPL-D Pro CAD, WIPL-D Pro, and DDS software which are products of WIPL-D Company. The benefits of using WIPL-D software, especially if combined with WIPL-D *GPU Solver* and features such as *Smart reduction*, will be also highlighted. The affordable workstation used for simulating the models is outlined in Table 1.

Table 1. Workstation used for the simulations.

Hardware	Description
Processor	Intel® Xeon® CPU E5-2650 v4 @ 2.20 GHz (2 processors)
RAM	256 GB
GPU	Four GPU cards NVIDIA GeForce GTX 1080 Ti
HDDs	6 SATA HDDs

WIPL-D MoM Efficiency, Smart Reduction, and GPU Solver

WIPL-D Pro, a 3D EM Method-of-Moments (MoM) based solver, applies higher order basis functions (HOBFs), thus meshing elements can be very large, with the maximum 2 wavelengths-by-2 wavelengths. It is possible to combine different orders of current approximation along two axis of a quadrilateral mesh element. This yields to the minimization of number of unknowns, even with very elongated mesh elements.

In order to fully exploit capabilities of WIPL-D software, it is desirable to utilize relatively large mesh elements over flat or smooth model surfaces. At the same time, an accurate representation of small or curved details should be obtained by using fine mesh elements on which low-order basis functions (representing a subset of HOBFs) are applied. Finally, on surfaces of the model which are flat or smooth along one axis and curved along the other, elongated mesh elements become the optimal choice.

Very useful feature when addressing an antenna placement problem is *Smart reduction*. It is based on adaptive reduction of current expansion orders over parts of the model which are distant from the antenna (*Antenna placement reduction*) or in the shadow (*Shadow reduction*). By applying the *Smart reduction*, a number of unknowns, directly related to computer memory requirement and simulation time, can be dramatically reduced, but with excellent accuracy preserved.

Usage of the *GPU Solver* enables extremely fast simulation of the models requiring a lot of unknowns. The *GPU Solver* primarily accelerates system matrix solving by utilizing graphical processing units (GPUs). The *GPU Solver* is very suitable and very efficient for simulations of electrically large problems.

1. Coaxial Fed Dipole Mounted on F-16 at 1.9 GHz

1.1. WIPL-D F-16 Models

A model of the F-16 aircraft is imported from a CAD file by using WIPL-D Pro CAD, a member of WIPL-D suite which can be utilized for 3D solid modeling and importing of various CAD formats. The dipole antenna with the feeding is modeled from the scratch using WIPL-D Pro CAD built-in primitives. The antenna with the feeding is placed on the position of the aircraft fuselage shown in Figure 4.

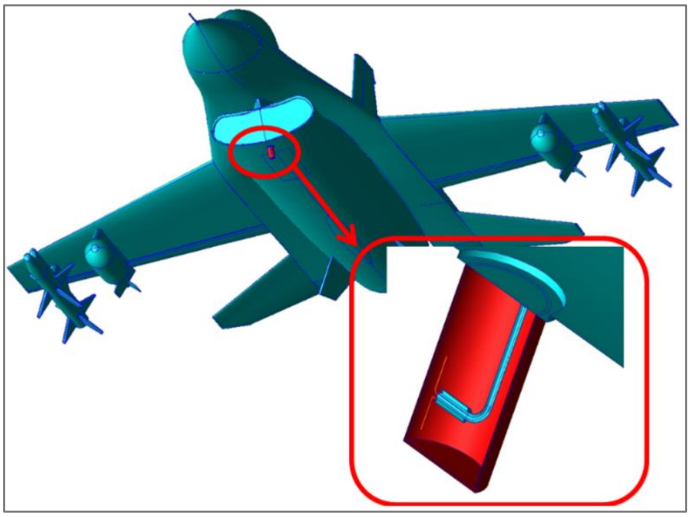

Figure 4. Antenna mounted on aircraft platform – WIPL-D Pro CAD preview

The symmetry of the structure was exploited to half the number of unknowns and thus, to decrease simulation time.

The completed CAD model of the antenna and aircraft platform was meshed by using in-house developed quad mesher. The result of the meshing process is presented in Figure 5. Size of meshing elements on flat and smooth surfaces is set to be slightly lower than 2-by-2 wavelengths. Meshing elements over the small details of the structure are smaller. Cylindrical parts over the antenna are meshed using elongated quadrilateral elements. Such meshing elements enable minimization of number of unknowns over the entire model.

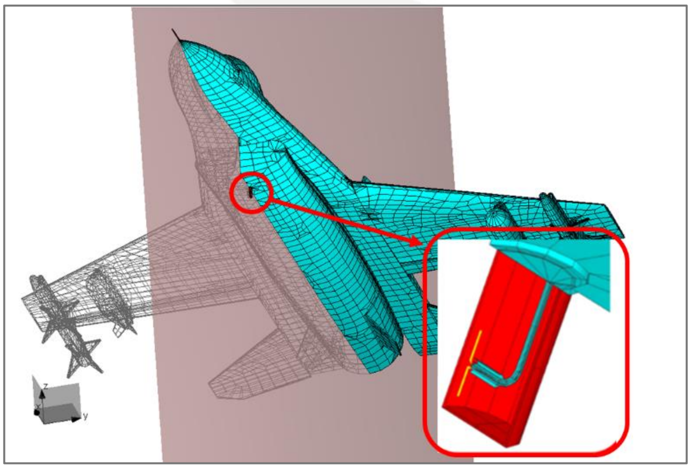

Figure 5. Meshed model of the antenna mounted on aircraft platform - WIPL-D Pro preview

Smart reduction features can be applied in this case. The area in the shade is visualized in Figure 6 by grayed mesh plates.

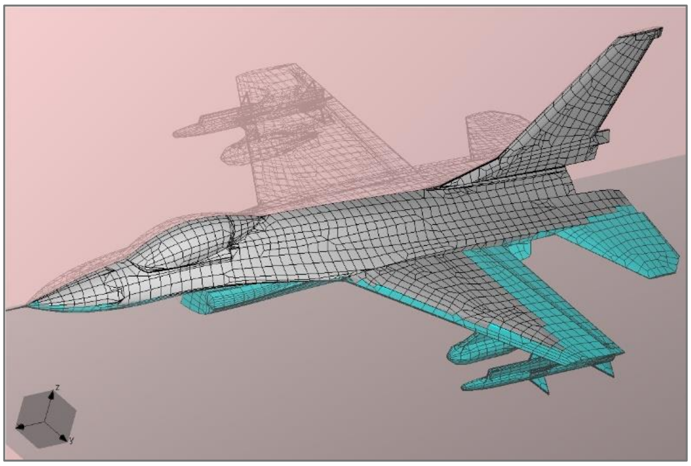

Figure 6. The antenna mounted on the aircraft platform. *Shadow* reduction can be noticed - WIPL-D Pro preview

1.2. Results and Simulations

The models were simulated from 1.7 GHz to 2.1 GHz. Only 5 frequency points are sufficient for given bandwidth as the built-in interpolation algorithm is very powerful especially when calculating the S-parameters. S_{11}-parameters for three simulation settings are displayed in Figure 7. It can be deduced from the figure that the *Antenna placement reduction* and *Shadow reduction* have insignificant influence to the accuracy of calculated S_{11}-parameter. The same conclusion can be drawn if the calculated radiation patterns[1] displayed in Figure 8 are compared. 3D radiation pattern at 1.9 GHz is displayed in Figure 9.

[1] In the coordinate system used in WIPL-D, θ = 0 angle refers to z = 0 (xOy) plane.

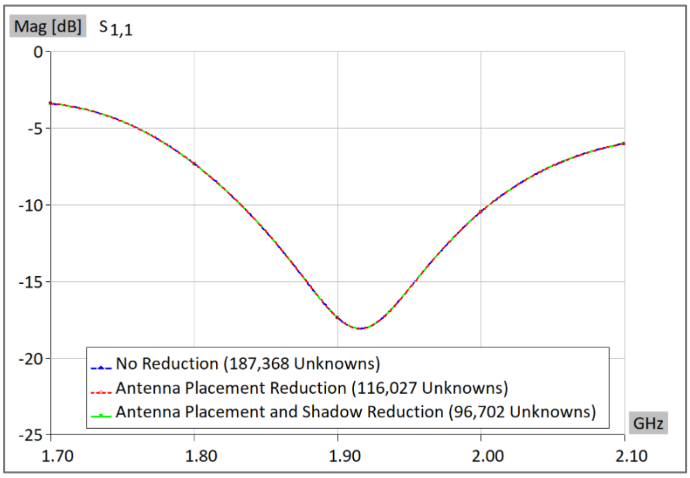

Figure 7. S_{11}**-parameter of the antenna**

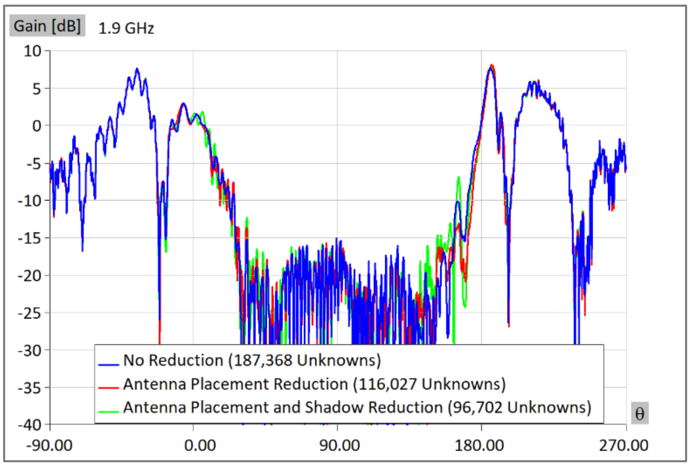

Figure 8. Compared radiation patterns

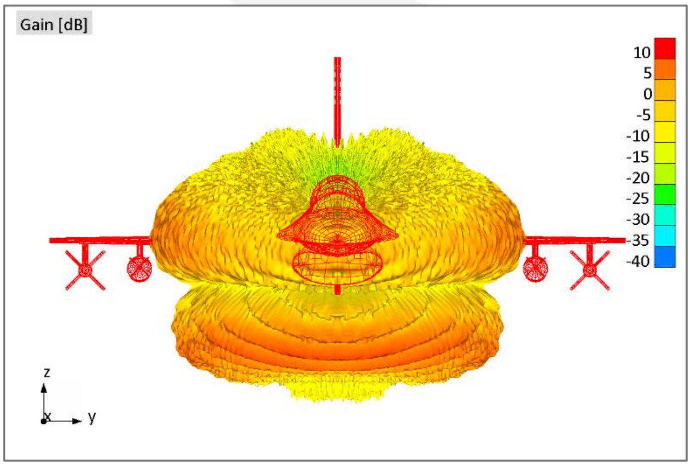

Figure 9. 3D Radiation pattern of the antenna at 1.9 GHz

Number of unknowns and simulation times at one frequency, for simulated models are shown in Table 2.

Table 2. Number of unknowns, simulation time per frequency

Reduction	Number of unknowns	Simulation time per frequency [mins]
No Reduction	187,368	52.5
Antenna Placement	116,027	13.6
Antenna Placement and Shadow	96,702	9.8

2. Monostatic RCS of Fighter Aircrafts

2.1. F-16 Simulation

We will illustrate the efficiency of WIPL-D code by presenting simulation results of monostatic RCS of F-16 fighter (Figure 10).

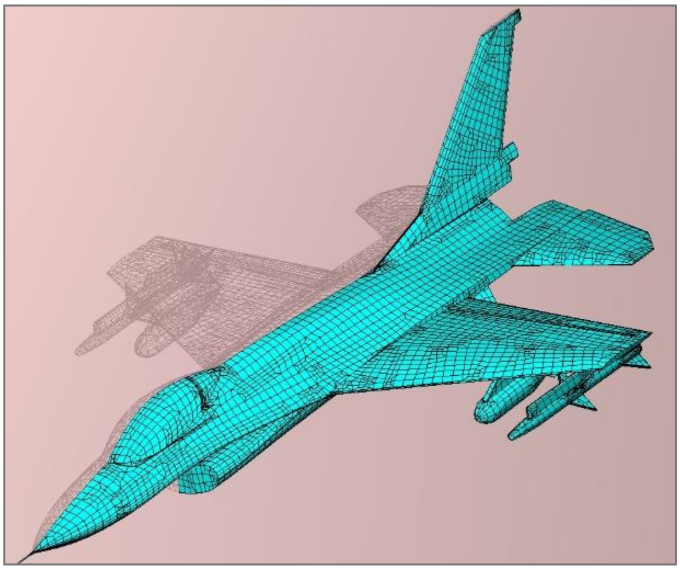

Figure 10. F-16 fighter airplane meshed at 3 GHz

The fighter length is 15.97 m, wing span is 10.73 m. The simulation is performed at several frequencies, up to 3.0 GHz where the airplane is ~160 wavelengths long. Without any reduction of the number of unknowns, the simulation requires 320,822 unknown coefficients.

RCS was performed as monostatic simulation which is generally very demanding. The results are presented in Figure 11. Symmetry of the structure was exploited to half the number of unknowns. Incident wave lies in the symmetry plane and number of directions for the entire span of angles in this plane is 1800. Simulation time reaches 9,863 seconds which is about 2.7 hours.

In order to illustrate how the number of unknown coefficients affects the simulation time, the relevant data for five frequencies have been listed in Table 3.

Table 3. Scalability of the F-16 EM solution

Frequency [GHz]	No. of unknowns	Simulation time [sec]
0.1	7,698	38
0.3	17,484	61
1.0	62,511	342
2.4	220,599	4,733
3.0	320,822	9,863

An RCS monostatic scattering is shown in Figure 11.

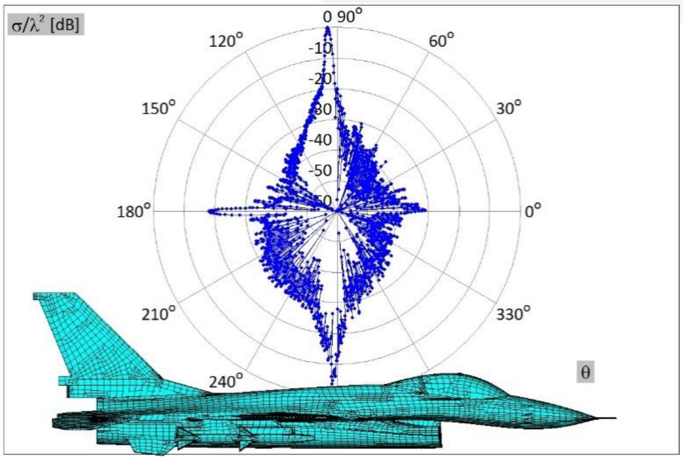

Figure 11. F-16 monostatic RCS

2.2. F-35 Simulation

This challenging model has been used to demonstrate the efficiency of techniques for reduction of number of unknowns without impacting the accuracy. As an illustration, the first simulation represents bistatic RCS of metallic model of the F-35 fighter at 1.5 GHz (Figure 12). The fighter is 15.7 m long with wing span of 12.3 m. That makes its electrical length 78.5 wavelengths. The simulation requires 91,828 unknowns without any reduction applied.

Since the incoming wave is placed below the airplane, we can place the entire upper surfaces of the airplane in the shadow region and reduce number of unknowns on it (Figure 12). In addition, we can reduce reference frequency used for determining level of current expansion (between 1st and 8th order) on quads for 30% (from 1.5 GHz to 1.05 GHz). After this, number of unknowns reduces to 33,852 which means that the reduction reaches 63%. Simulation time without reduction is 444 seconds for 1,800 directions while reduced model's run lasted only 71 seconds which is over 6 times faster. Calculated RCS data are shown in Figure 13. The hardware configuration is again the one listed in Table 1.

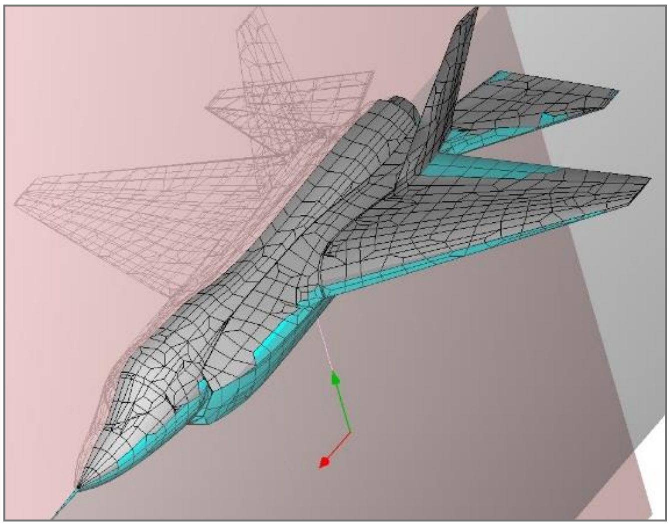

Figure 12. Fighter with the shadow – bistatic RCS at 1.5 GHz

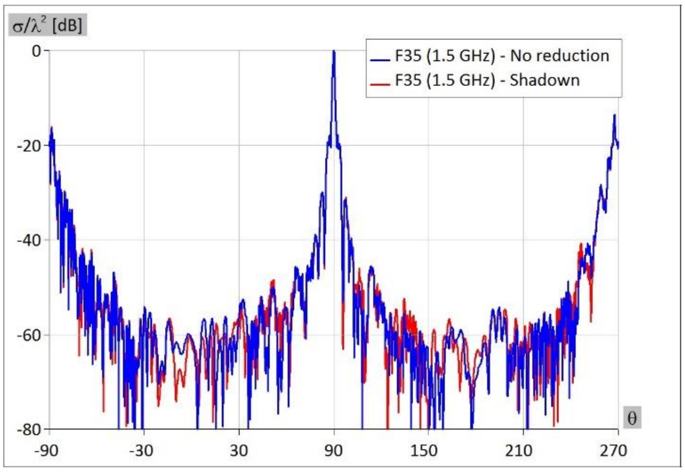

Figure 13. Influence of shadow reduction

Just like for F-16, Table 4 illustrates how the same model of this airplane can be used for simulation at different frequencies and how the frequency, i.e. electrical length influences the simulation time. All simulation times are given for the monostatic RCS simulations at the previously described hardware configuration (Table 1), the same as in the monostatic scattering F-16 case.

Table 4. Scalability of the F-35 EM solution

Frequency [GHz]	No. of unknowns	Simulation time [sec]
0.1	3,482	13
0.3	10,798	27
1.0	46,780	188
3.0	288,492	7,965

However, more challenging simulation is monostatic RCS at 4 GHz (Figure 14). Number of incoming directions is 3,600. Electrical length of the model is 210 wavelengths.

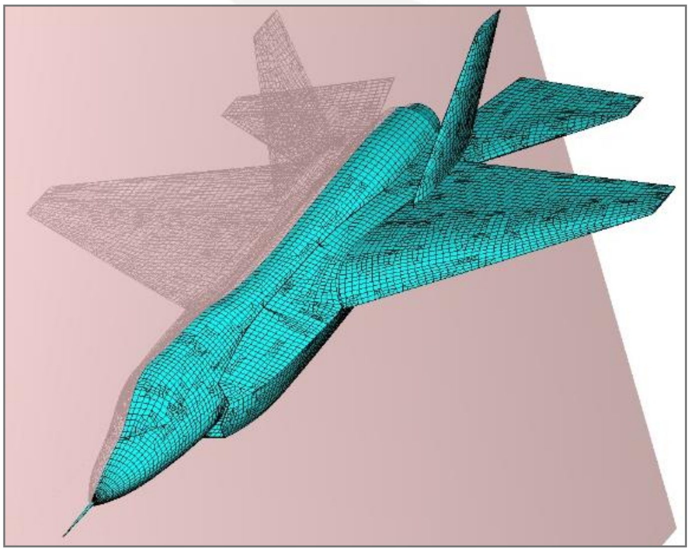

Figure 14. Fighter at 4 GHz

The required number of unknowns (Table 5) is 493,729 and it can be reduced by reducing reference frequency to 3.5 GHz and 3.0 GHz. This yields in 379,381 and 288,492 unknowns, respectively. The results are presented in Figure 15. All simulations are within the reach of the desktop configuration presented in Table 1.

Table 5. A desktop F-35 EM solution

Reference frequency [GHz]	No. of unknowns	Simulation time [hours]
3.0	288,492	2.6
3.5	379,381	4.3
4.0	493,729	8.7

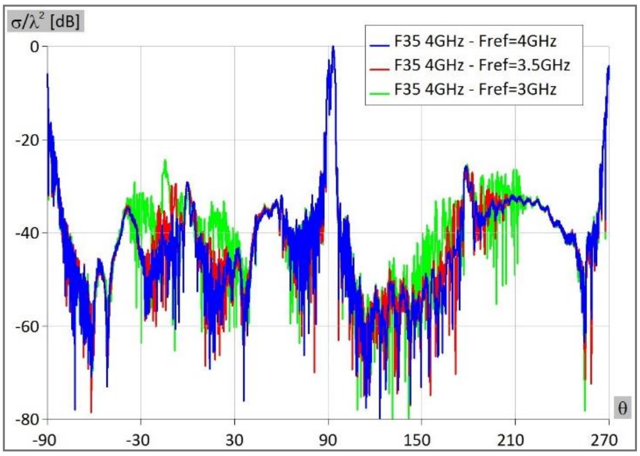

Figure 15. Influence of reduction on metallic model of F-35 at 4 GHz

2.3. F-35 Simulations at 10 GHz with Domain Decomposition Solver

WIPL-D MoM implementation is among the most comprehensive and efficient full wave solution for high frequency EM problems. WIPL-D MoM applies surface integral equations (SIEs) of electromagnetic field in frequency domain by transforming SIEs into a system of linear equations which unknowns are weighting coefficients of adopted basis functions (BFs). MoM solution is expressed as a linear combination of BFs. By proper choice of BFs, the simulation converges toward exact solution when number of BFs increases.

At higher frequencies MoM exhibits a limitation. The main drawback is a poor scalability as the frequency increases. The number of BFs per wavelength squared is fixed, hence total number (N) of BFs (unknowns) raises quickly by increasing frequency. Furthermore, required memory to store MoM system matrix is $O(N^2)$

WIPL-D DDS (Domain Decomposition Solver) constructs macro BFs (MBF) which cover larger surfaces (than typical BFs). The method is iterative and it converges toward MoM solution by employing a correction after each iteration. In each iteration, it determines weighting coefficients for MBFs to minimize difference with respect to MoM matrix. The method advanced implementation includes several unique features. One of them is to only include into the next iteration the MBFs which contribute the certain amount of residuum (default value is 60% and can be changed by user). Also, the user can choose whether the 0^{th} iteration will include all elements or only the elements directly illuminated by a wave (if RCS is result of interest) or close to an antenna (in antenna placement regime).

Particularly, DDS is oriented towards electrically large problems. It needs less memory and significantly less CPU time then rigorous MoM solution. The method is suitable for inexpensive CPU platforms, especially with multicore CPUs. Its accuracy is not as good as with rigorous MoM, but from engineering point of view it can provide sufficient accuracy in CPU time unreachable to MoM. Furthermore, the accuracy is much higher compared to other methods such as PO and SBR.

The efficiency of method will be illustrated at monostatic RCS calculation of F-35 aircraft at 10 GHz. If the frequency is reduced for 12.5% (as it has been explained in the previous section to yield an exact solution), the number of unknowns for the symmetric model is around 2,100,000. If the result of interest is monostatic from bottom directions, the shadow can be applied to reduce number of unknowns to 1,300,000 (Figure 16).

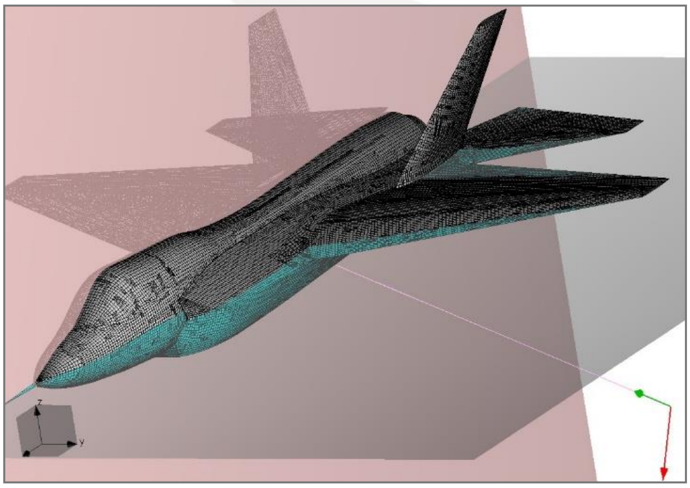

Figure 16. F-35 at 10 GHz with shadow – monostatic RCS

The above-mentioned model is meshed into approximately 38,000 plates. The mesh is so dense that it is hard to recognize mesh elements shown in Figure 16. The DDS solution was applied so that the parts of the structures not illuminated with an incoming wave are not taken into account in 0^{th} iteration. The 1^{st} iteration includes all elements which contribute to residuum with 60% and it is sufficient for the simulation of excellent accuracy. The CPU simulation was done at desktop workstation (Table 1), without using GPU cards.

The 0^{th} iteration lasts 3 hours, while the 1^{st} iteration lasts 4 hours. The characteristic of monostatic RCS simulations with methods such as MLFMM and PO is that they require different residuum for each incoming direction (different current distribution). In this example, RCS was calculated with 25 incoming directions, which made simulation almost two times longer than bistatic RCS. In order to get the result with more directions, interpolation was applied not to RCS result itself, but to current. The monostatic RCS results are shown in Figure 17.

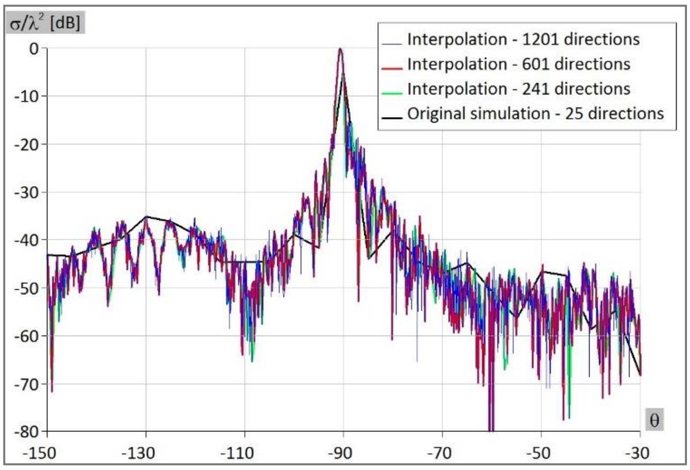

Figure 17. F-35 monostatic RCS at 10 GHz

3. Anti-Collision Radar on Car Bumper

3.1. Anti-Collision Radar Antenna

The anti-collision radar antenna was created from the scratch using WIPL-D software. The antenna is modeled using 4x4 patch array. The antenna model is shown in Figure 18. Due to the symmetry of the antenna, only half of the antenna was modeled. This reduces the complexity of the structure and increases the numerical efficiency of the simulation.

Calculated radiation pattern of the antenna in θ = 0 plane is shown in Figure 22.

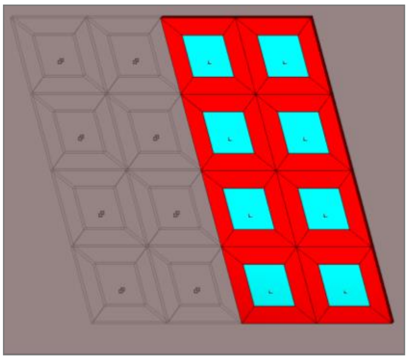

Figure 18. Anti-collision radar antenna – WIPL-D Pro

3.2. Radar Antenna on the Bumper

The model of the bumper was imported to WIPL-D Pro CAD and the patch array has been added to emulate a real-world antenna placement scenario. The CAD model of the bumper together with the antenna is shown in Figure 19. The patch array is magnified and highlighted so its position can be easily visualized. The bumper was modeled using PEC material.

Model of the bumper with the antenna array, after applying the meshing process, is shown in Figure 20.

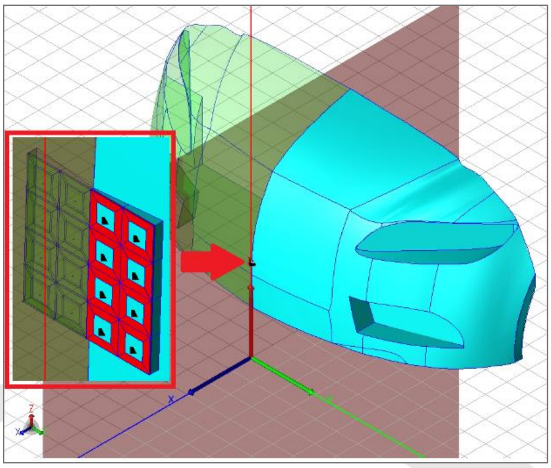

Figure 19. Anti-collision radar antenna mounted on the bumper – WIPL-D Pro CAD

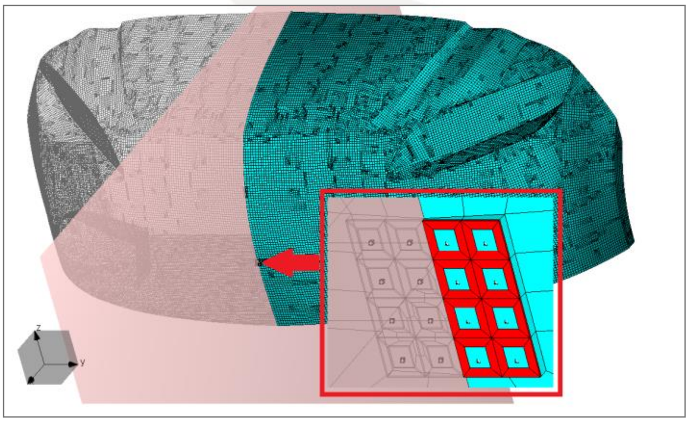

Figure 20. Anti-collision radar antenna mounted on the bumper – WIPL-D Pro

3.3. Simulations, Results and Computer Platform

The model of radar antenna on the bumper was simulated at 77 GHz. Results of five simulations carried out using DDS (Figure 21) are presented. Three simulations are without any reduction, and two simulations are with the reduction applied. The three simulations without reduction represent three DDS iterations. The remaining two simulations represent two DDS iterations with *smart reduction* applied (*Antenna placement reduction* set to 70%). Results obtained in simulations are shown in Figure 22.

Simulations were performed with groups which size was equal to 3,000 unknowns (Figure 21). The simulation time and a number of unknowns per iteration are presented in Table 6.

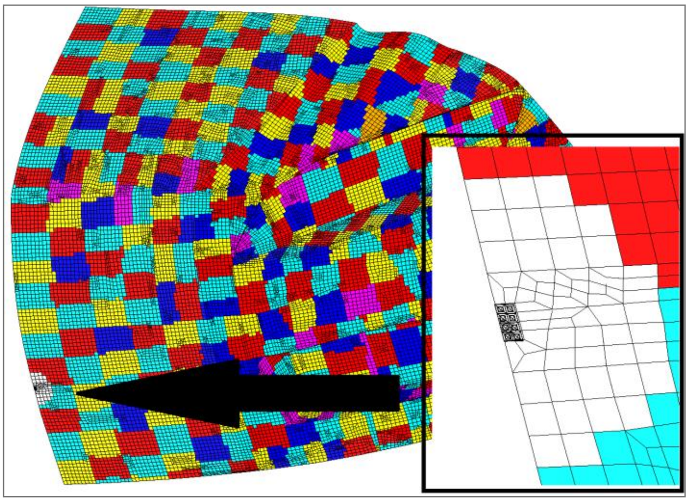

Figure 21. Antenna and the groups – DDS preview

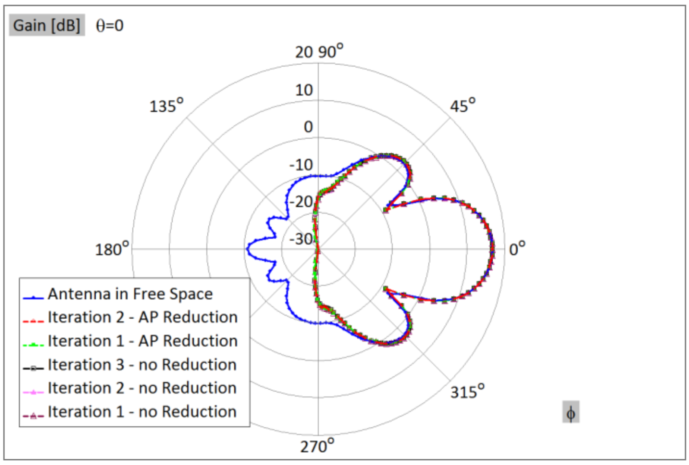

Figure 22. Radiation patterns of the anti-collision radar antenna in free space and anti-collision radar antenna mounted on the bumper

Regardless whether the *Antenna placement reduction* has been applied or not, a value of the residuum was approximately 10^{-4} after the first iteration.

Table 6. Iteration, simulation time and number of unknowns

Model	Iteration	Simulation time [minutes]	Number of unknowns
Without Reduction	1^{st}	41 (0^{th} + 1^{st})	~2.5 Millions
Without Reduction	2^{nd}	12	
Without Reduction	3^{rd}	11	
70% Antenna Placement Reduction	1^{st}	30 (0^{th} + 1^{st})	~1.0 Million
70% Antenna Placement Reduction	2^{nd}	20	

Computer hardware used for simulations is presented in Table 1.

4. Conclusion

This document outlines WIPL-D Software simulations of several real-life scenarios. Several antenna placement, monostatic RCS and bistatic RCS simulation results have been included. In addition to presenting the models and the results, the document presents some WIPL-D features and products and how they can work together to speed up simulations and reduce computational resources. The document also contains short WIPL-D Software theoretical background.

All simulated real-life scenarios presented have been selected from a group of typical challenging examples. In the simulated antenna placement problems, the mounted antennas were electrically small comparing to overall dimensions of the whole structure. The realistic models were, for example, simulated at frequencies used in IFF devices. In addition, details which are several dozen times or even several hundred times smaller than wavelength appeared in the antenna placement scenarios. The RCS simulations showed complexity of RCS models with special focus on fighter aircraft scattering simulations due to their high importance especially in defense industry.

All simulations are performed on the cost-effective workstations with high efficiency, bearing in mind the size and the complexity of the problems. Efficiency grows even further when simulation settings are combined with reductions and/or GPU empowered workstations. The variety of output results were shown. All the results are obtained or metal-only models or the models with dielectric materials included successfully handling the contrast between the small size of the WIPL-D modelling entities and the large size of the whole structure.

Probably, the most important conclusion is that the results obtained are in good agreement with the theoretical predictions. In addition, application of reduction features showed that the results obtained with properly defined reduction matches very well with the results without any reductions applied. This means that engineers and scientists from universities, defense, and consumer industries can obtain accurate results in relatively short time reducing the cost and time-to-market.