Radomes: Efficient 3D EM Simulation

Introduction

Most of the outdoor mounted antennas are covered with radomes [1] to protect the antenna from physical damages and various environment conditions. Ideally, the radome should not affect the antenna performances. However, in real life, the influence of the radomes cannot be avoided, but only reduced to certain extent [2]. The design process of such antennas is typically carried out without taking a radome into account until the final design stages. A volume and surface area of a radome can be even order of magnitude larger than the antenna itself. Thus, the typical outline of radome enclosed antenna simulation includes three phases:

1. Design of the antenna in free space (without the radome),
2. Design of the radome itself aiming towards a minimal influence on the antenna performances (radiation pattern, etc.) and
3. Simulate the antenna with radome to confirm that antenna maintains its characteristics under the radome.

A demonstrational model of the one-layer monolithic spherical radome and the circular horn antenna is shown in Figure 1 [3].
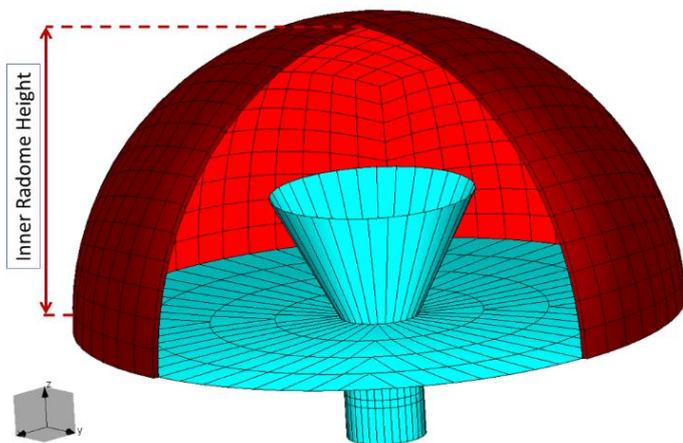

Figure 1. A one-layer monolithic spherical radome over the circular horn antenna

Multilayer radome structures are widely used in practice, whenever a monolithic wall is unacceptable or does not provide adequate performance with respect to bandwidth, weight, or robustness.

A variety of different approaches have been employed to investigate the influence of radomes on antenna radiation pattern. In the case of electrically large radomes the techniques that are most often used are analytical and high frequency techniques [4]. However, in some cases the results obtained by these techniques are not sufficiently accurate. One possibility to obtain very accurate results is to use the method of moments (MoM) applied to surface integral equations (SIEs) [5]. However,

the use of MoM for that purpose has not been widespread in the past since memory and time resources required to perform the simulations were prohibitive. One of the typical examples where the resources required go extreme are multilayered radomes, especially when the influence of these radomes on beam steering should be investigated. However, implementing the recent developments of advanced MoM techniques and using various possibilities for parallelization, such an analysis became available even on a PC computer [6].

In this paper several radome scenarios will be presented and the simulation results are obtained using the commercial full 3D electromagnetic simulation software, WIPL-D [7].

Scenario 1: Antenna array of 12x12 elements covered with flat thin dielectric square-shaped radome [8] (an array element is a microstrip patch antenna @ 4.4 GHz).

Scenario 2: Efficient EM simulation of electrically large multi-layer radomes covering 30-λ Cassegrain reflector antenna. First, a modest 3-layer radome was analyzed (MoM and **D**omain **D**ecomposition **S**olver - DDS) and then a large 7-layer radome (DDS simulation only) [9].

Scenario 3: Steering Array (10x40 elements, 10 steering directions) under 100-λ Ellipsoid Radome via Field Generators (two examples of radome are analyzed, a single-layer radome and a 3-layer radome) [10][11].

Scenario 4: Run Radome feature for analysis of single layer highly transparent spheroid radome (the longest diameter is 112.5 λ) above antenna array (20x40 elements) [12].

WIPL-D Pro is a well-known Method of Moments (MoM) based simulator for full wave EM computations.

WIPL-D state-of-the-art MoM implementation offers some unique advantages for simulation of electrically large structures. Namely, in contrast to commonly used triangles, WIPL-D kernel uses quadrilateral mesh. This significantly reduces the simulation requirements. Another important advantage is the use of Higher Order Basis Functions (HOBFs). They allow usage of very large mesh elements, up to 2 wavelengths. In case of radome simulations, the radome surface is usually smoothly curved or flat. This is perfect example where very large WIPL-D mesh elements contribute to high numerical efficiency as there are 3-10 times fewer unknown coefficients in MoM matrix compared to the low order triangular mesh-based MoM matrix.

Additional advantages of WIPL-D software suite are efficient implementation on multi-CPU/GPU platforms and smart techniques for reduction a number of unknowns.

Last, but not least, WIPL-D team has significant experience in simulation of antennas with radomes and can provide comprehensive expert support.

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1. Flat Radome above Microstrip Patch Array (12x12)

The array consists of 12x12 microstrip patch array (MPA) elements built on 0.5 mm thick FR4 substrate (Er = 4.3, TgD = 0.02). Operating frequency is 4.4 GHz. The patch square, 0.45 wavelengths long and wide. Feeding point is moved from the center along the length of the patch for 0.3 x patch length. Spacing between elements is set to 1.5 wavelengths (calculated in dielectric). Since the array is symmetrical with respect to two symmetry planes, problem size can be reduced, and simulation of only a quarter of the model performed (6x6 elements) with the appropriate symmetry option settings (Fig. 2).
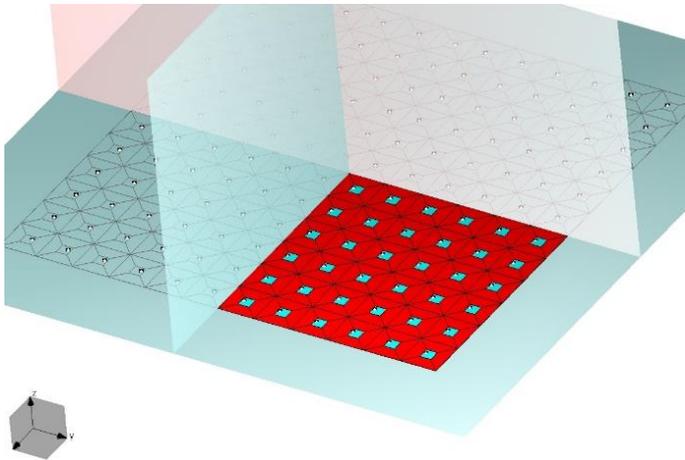

Figure 2. MPA Array Model (total of 12x12 elements)

In the Figure 2 patch is placed over infinite perfect electric conductor (PEC) in order to reduce EM simulation requirements, but it will also be placed above the finite size ground.

The next step was to cover the antenna with dielectric radome (surface of the radome was flat). Finite ground was slightly extended beyond the dielectric surface to 600x600 mm. Radome thickness is 2.3 mm (Er = 3.2, TgD = 0.025). The radome was placed 0.5 wavelengths away from the surface of the array (calculated in array substrate). Radome shape (rectangular parallelopiped) is illustrated in the Figure 3.
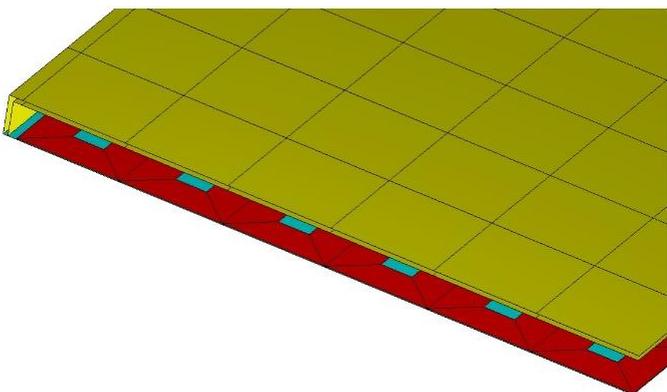

Figure 3. Preview of the quarter model - MPA Array (12x12) Covered with radome

The PC used for simulation is a desktop computer equipped with GPU card: Intel i7 7700 CPU (3.6 GHz), 64 GB RAM, Nvidia GeForce GTX 1080 GPU card.

Comparison of the simulation time for the array over infinite PEC, array over finite size ground and finally array covered with radome are shown in Table 1. The influence of the radome on the radiation pattern of the MPA array is presented in Figure 4.

Table 1. Comparison of the simulation times for different array models

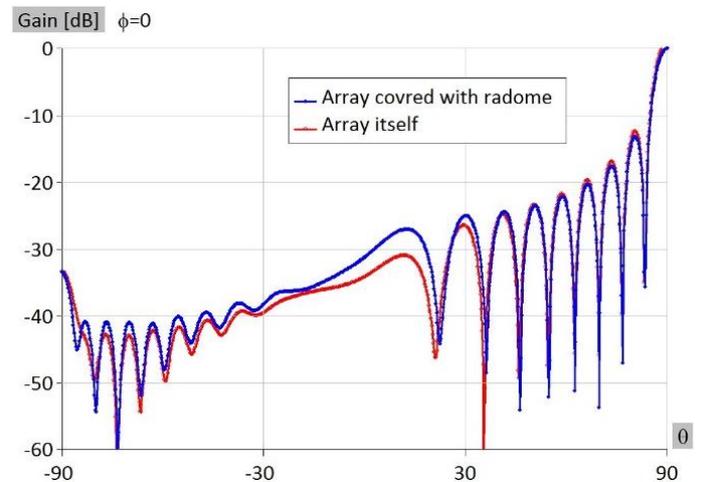| Model	Number of Unknowns	Simulation Time [s]
Array over PEC	10,308	54
Array over finite-ground	17,508	92
Array over finite-ground covered with thin flat radome	24,395	149

Figure 4. Influence of the radome on the radiation pattern of MPA array (12x12), Phi = 0 degrees

2. Efficient EM Simulation of Electrically Large Radomes

In most cases, radome sizes are in the order of hundreds λ, and they are made off several materials arranged in multiple layers. These scenarios are very demanding regarding the computing power as the number of unknowns rises enormously.

Well-designed radome shells affect antenna performances very little. This property is used to significantly reduce the simulation requirements. WIPL-D software suite offers several techniques to reduce number of unknowns on parts of the model (for instance reducing the order of polynomial degrees for the current representation, etc.). Combining these techniques along with extensive experience in radome simulations which WIPL-D support team has gathered through the years, and additionally a

powerful addition of GPU parallel computing, the number of unknowns on large radome surfaces can be greatly reduced preserving the accuracy of the results.

The combined effect of the techniques described will be demonstrated using the Cassegrain reflector antenna below a large multilayer radome. The antenna is operating at **30 GHz** and is shown in the Figure 5.
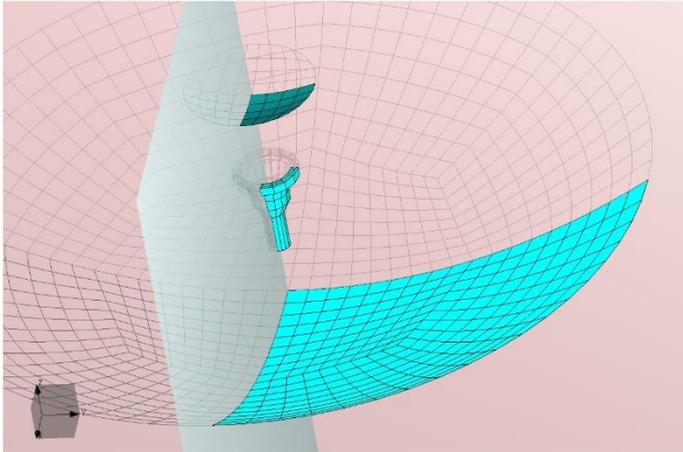

Figure 5. Cassegrain reflector antenna

The antenna's diameter is 300 mm (**30 λ**), and the entire simulation of the structure presented in Figure 5 requires only 4,000 unknowns. On any modern desktop or laptop, the simulation lasts only a couple of seconds.

2.1. Modest 3-layer Radome

In order to demonstrate the techniques to reduce the number of unknowns on radomes, we will first analyze the antenna with the modest-size 3-layer elliptical radome (figure 6). Such a simulation is in the reach of full wave MoM simulation.
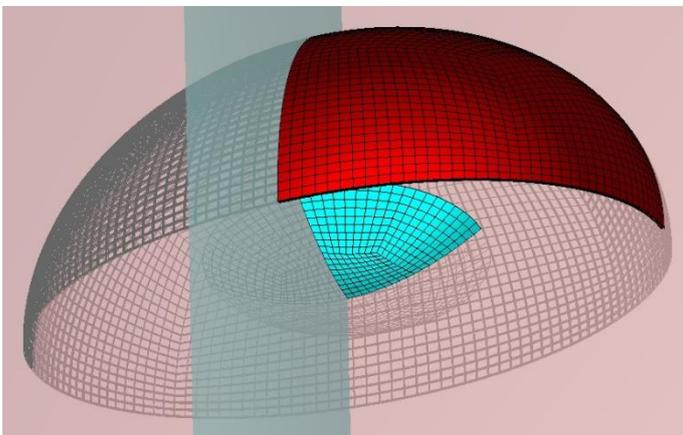

Figure 6. Reflector antenna covered with elliptical radome

Radome height is 300 mm, while the half axes of base eclipse are 200 and 350 mm. The radome has 3 dielectric layers. The thicknesses of layers are 1.4, 1.1 and 1.1 mm, while permittivity of the layers is 2.5, 2.4 and 2.32 respectively. The mesh elements (patches) dimensions are adjusted to be 1.5 wavelength. The

polynomial orders for current distribution representation are between 4 and 6. Such a simulation (the antenna plus 4 dielectric surfaces) requires over 400,000 unknowns. With the affordable hardware resources, this practically approaches the limit for MoM simulations. Actually, on a desktop PC with 3-4 inexpensive GPU cards, simulations with up to 500,000 unknowns require less than 1 day to finish.

However, learning from the previous experience of WIPL-D team, the orders of currents on radome surfaces can be reduced from 4, 5 and 6 to 2 and 3. A very simple way to achieve this is to set **referent frequency** in the project to **12 GHz** keeping in mind that the referent frequency for the feeder should be kept at the original value of 30 GHz. As the Cassegrain antenna from Figure 5 requires a number of unknowns which is two orders of magnitude below the number required by the radome, no reduction is needed there.

Reduction lowers a total number of unknowns to 150,000 unknowns. The agreement between the results obtained in case where no reduction is used and the case where reduction is implemented is excellent (Figure 7).
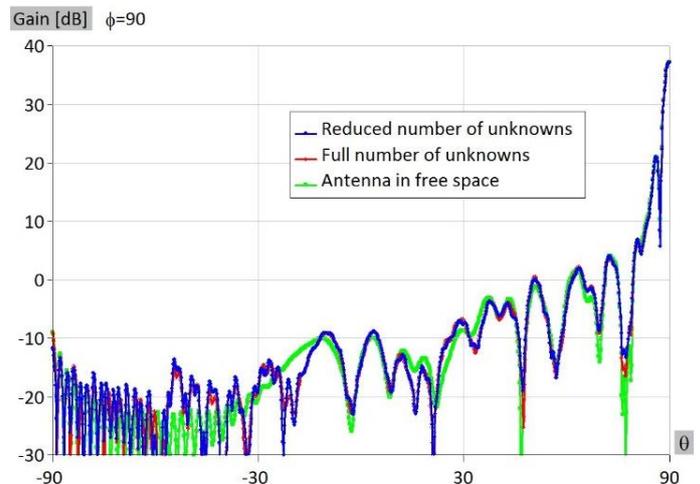

Figure 7. Efficiency of reduction (lower reference frequency), Phi = 90 degrees

The next step in radome simulations is to use WIPL-D product specialized for electrically large structures: [Domain Decomposition Solver (DDS)](#) and perform the same simulations as with full MoM.

The required hardware resources and simulation time are reduced several times, while the accuracy of the obtained results is preserved. This will be rather important later, for simulation of larger radome with even more layers. The DDS tool is an iterative solver, so we present the results for several iterations in order to demonstrate the convergence. As a number of iterations grows, DDS results quickly approach the one obtained by full wave MoM (Figure 8).
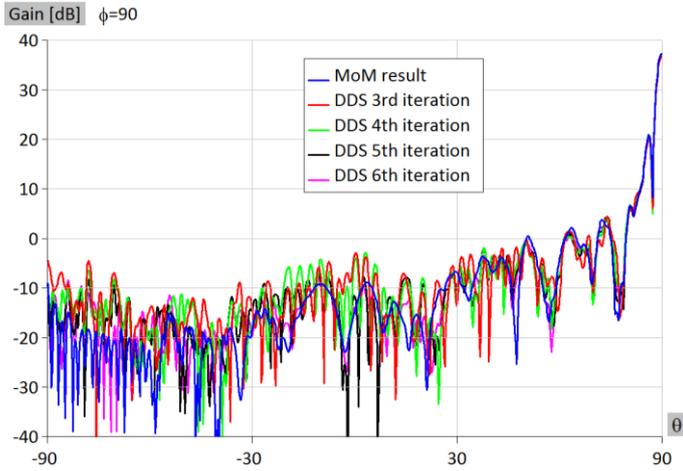
(a) Theta from -90 to 90 degrees
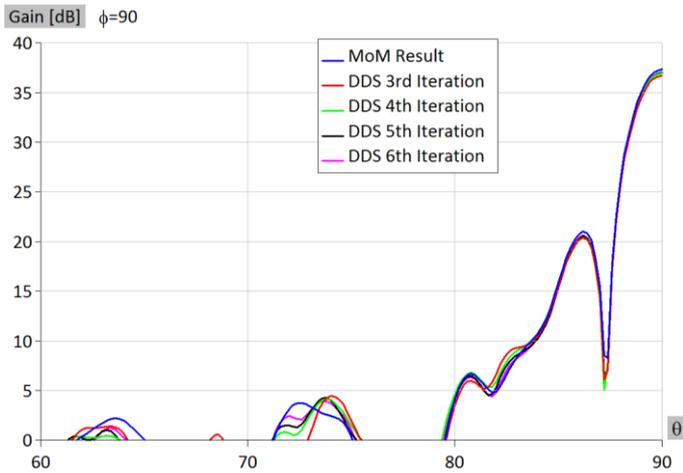
(b) Theta from 60 to 90 degrees

Figure 8. Convergence of DDS results for different ranges of theta angle

The same workstation was used for DDS and MoM simulations: Intel® Xeon® Gold 5118 CPU @ 2.30 GHz (2 processors) with 192 GB RAM and four NVIDIA GeForce GTX 1080 Ti GPU cards.

For the MoM simulations, the matrix fill-in was done on CPU, while the GPU cards are used for matrix inversion.

For the DDS simulations, multi-thread CPU parallelization was utilized. Simulation times for DDS simulation per iteration are shown in Table 2 (model has 300,000 unknowns).

Table 2. Simulation times for DDS (3-layer radome)

Iteration number	t [min]
0	3.1
1	9.0
2	13.4
3	15.7
4	13.11
5	13.29
Total	67.6

Comparison of the simulation time for the radome done by MoM (full and reduced) and DDS simulations are shown in Table 3.

Table 3. Comparison of the simulation times and number of unknowns for MoM and DDS simulations

Model	Number of Unknowns	Simulation Time [min]
MoM simulation (reduced case, lower ref. frequency)	150,00	28
MoM simulation (full model)	422,777	405
DDS simulation (5 iterations in total)	300,000	67.6

The number of unknowns can be significantly reduced for radome simulations. Application of WIPL-D built-in reduction techniques results in simulation times amounting only a fraction of the MoM-consumed time while preserving the accuracy. For the 3-layer radome the reduction is more than threefold.

DDS is efficiently used for radome simulations. Starting from the 4th iteration, DDS result are sufficiently accurate considering the full-wave MoM solution as a reference.

2.2. Large 7-layer Radome

The more challenging task is the simulation of the 7-layer radome of a size greater than previously considered 3-layer case. Total radome thickness is equal to 8 mm, where all 7 layers have the same thickness. The permittivity of radome materials increases starting from 2.0 to 2.08, 2.16, 2.24, 2.32, 2.4 and 2.5 respectively. Radome covering the antenna is shown in Figure 9.
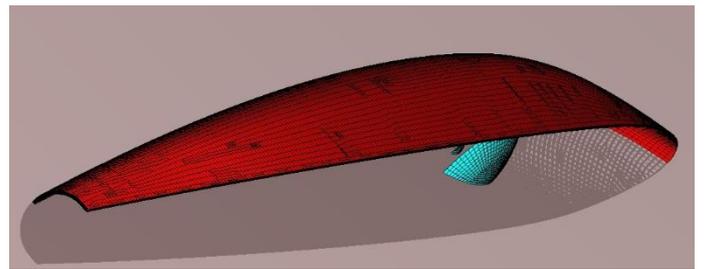

Figure 9. Antenna cover with 7-layer large radome

In this case, only the simulation with DDS is acceptable in terms of reasonable simulation time. DDS model for the **7-layer large radome** scenario requires **2,364,447 unknowns**.

DDS allows such a simulation in reasonable time on moderate CPU-based platform. The tool fully exploits CPU multi-threading capabilities. The final simulation, requiring over 2 million unknowns, is still beyond the reach of full wave MoM, but it can be very efficiently solved using DDS.

Simulation times for the DDS iterations along with the total time are summarized in Table 4.
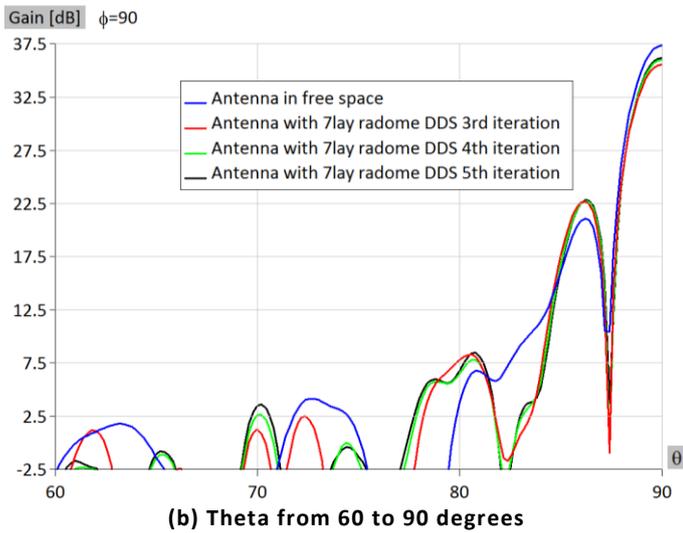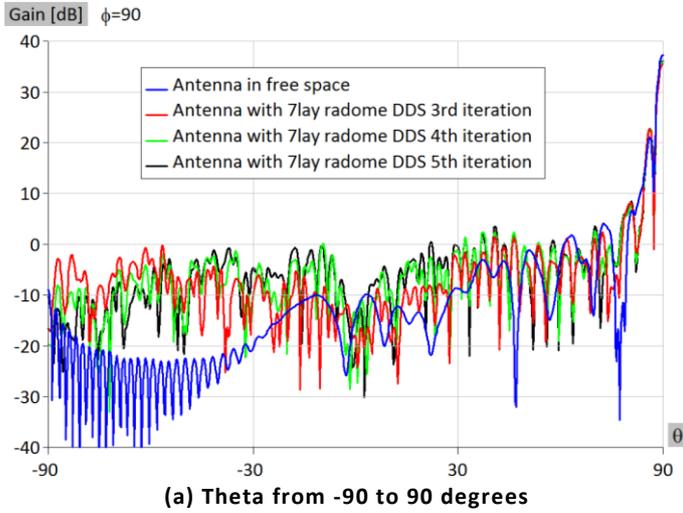
(a) Theta from -90 to 90 degrees

(b) Theta from 60 to 90 degrees

Figure 10. DDS simulation of 7-layer radome for different ranges of theta angle

Table 4. Simulation times for DDS (7-layer radome)

Iteration number	t [min]
0	49.3
1	34.1
2	50.8
3	68.1
4	92.7
5	116.9
Total	411.9

3. Steering Array under 100-λ Ellipsoid Radome via Field Generators

In the first two radome scenarios, it was demonstrated how WIPL-D software can be used for efficient full-wave EM analysis of different radomes and how to reduce the required computing power directly related to a number of unknowns, and speed up the simulations accordingly. In this example, a feature called

"Field generators" will be used to show how to steer the radome illuminator (especially important for antenna arrays) without re-running entire simulations.

Ellipsoid-type radome (the lengths of semi-axes along *x*, *y* and *z*-coordinates are respectively 50λ, 12.5λ and 6.25λ) will be used (Figure 11).
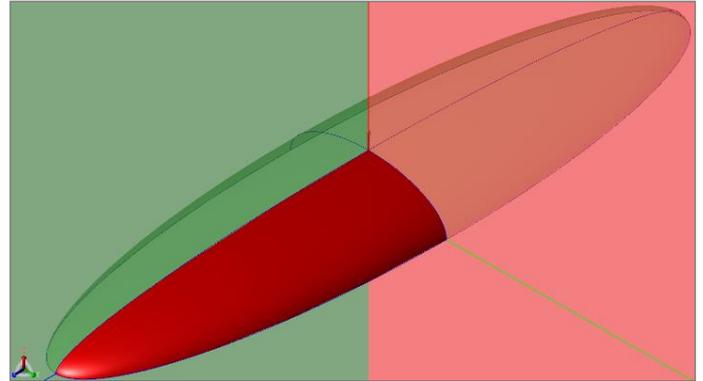

Figure 11. Ellipsoidal radome shell (WIPL-D Pro CAD)

Two examples of the ellipsoid radome illuminated by field generators array will be presented. The first consists of one thin layer (Table 5), while the second consists of 3 thin layers (Table 6).

Table 5. Parameters of the one-layer radome (example #1)

Layer	Thickness [mm]	Dielectric constant
#1	10	1.2

Table 6. Parameters of the 3-layer radome (example #2)

Layer	Thickness [mm]	Dielectric constant
#1	0.5	4
#2	10	1.2
#3	0.5	4

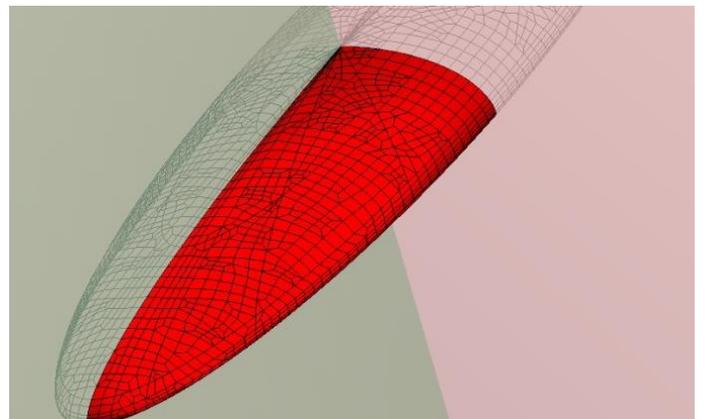The radome model is meshed via WIPL-D Pro CAD tool. The final mesh is quadrilateral (Figure 12).

Figure 12. Meshed ellipsoidal radome shell (WIPL-D Pro)

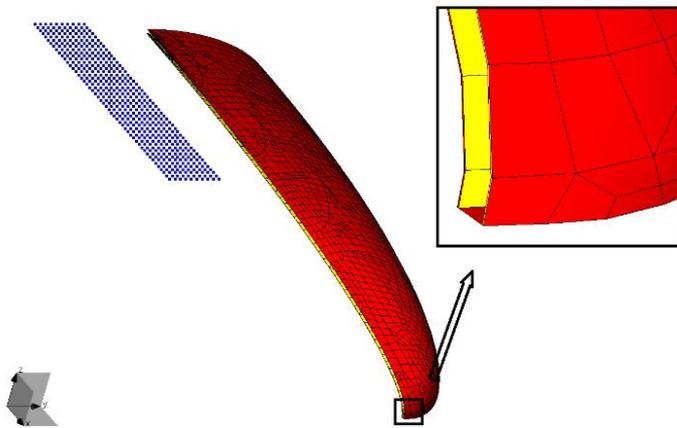Radome is illuminated by a filed generator (FG) antenna array (Fig.13).

Figure 13. 3-layer radome and FG array (quarter model)

Field Generators feature allows user to define the array via Properties Table (shown in Figure 14). In the top area of the table, the radiation pattern of the basic element should be specified. The pattern can be described through analytical expression, imported from another WIPL-D project or another software, or measured. Figure 15 illustrates analytically defined radiation pattern of a single radiation element. In the table fields below, array dimensions and array position should be defined, as number of elements, their mutual distance and its position. Finally, in the bottom area of the table, the steering of the main beam of the array can be controlled through Consider Array as Single Excitation and defining Main Beam Directions fields. Based on array dimensions, Main Beam Direction features calculates phase shifts between array elements in order to obtain desired radiation pattern.

The array is simulated at 10 GHz. Based on the second scenario in this paper, the reduction in number of unknowns on the entire surface on the radome can be achieved by using lower referent frequency. Hence the referent frequency is set to 8 GHz.

The array radiation is steered across the entire surface of the radome. Usage of field generators with multiple steering angles reduces the problem that requires 10 simulations (one for each steering direction) to one simulation with 10 excitations (one for each steering angle). The most demanding phase of MoM simulation is the matrix inversion (done as LU decomposition in WIPL-D). For the array steered into 10 directions, we run only single LU decomposition, which is the most time-consuming phase in EM simulation. After that, for each steering angle, the code only runs numerically inexpensive forward-backward substitution. That way, instead of increasing the total simulation time 10 times for 10 steering directions, the simulation time is at most doubled.

The workstation used for the simulation is: Intel(R) Xeon(R) Gold 5118 CPU @ 2.30 GHz (2 processors), 192 GB of RAM, 5 SSD hard drives in RAID-0 and 4 NVidia GeForce GTX 1080 Ti cards.
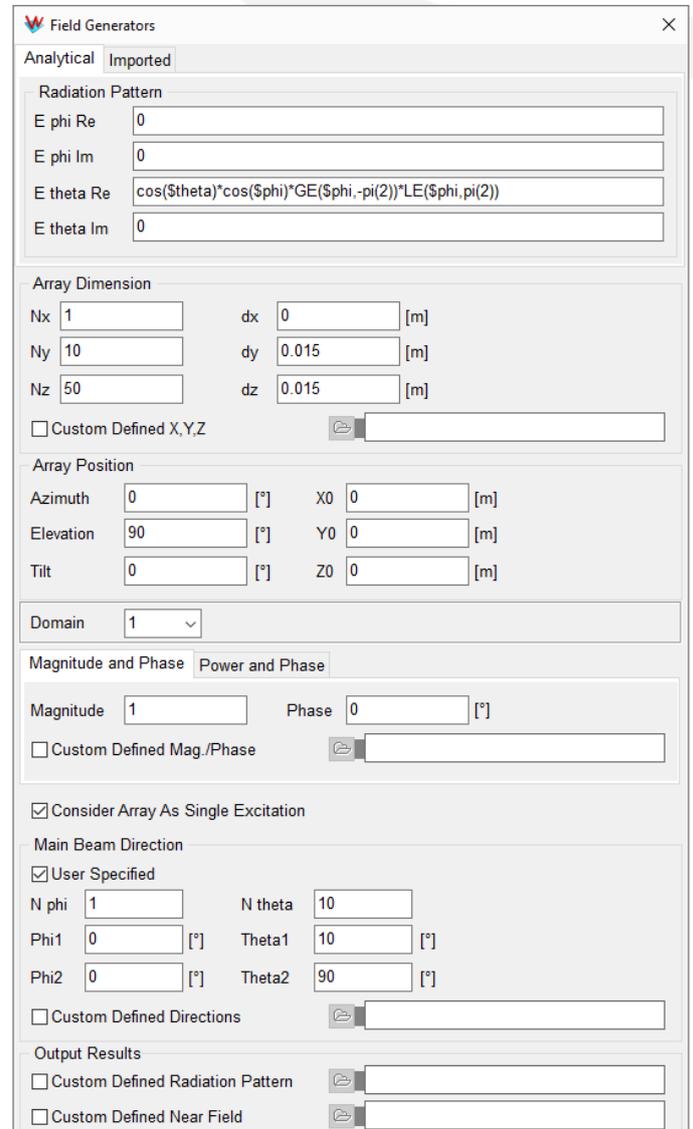

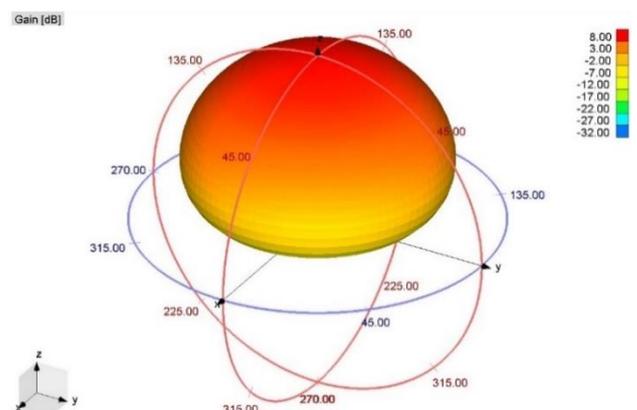**Figure 14. Field Generators Properties**

Figure 15. Radiation pattern of a single radiation element

Simulation times and number of unknowns for both examples (one-layer and 3-layer radome) are shown in Table 7.
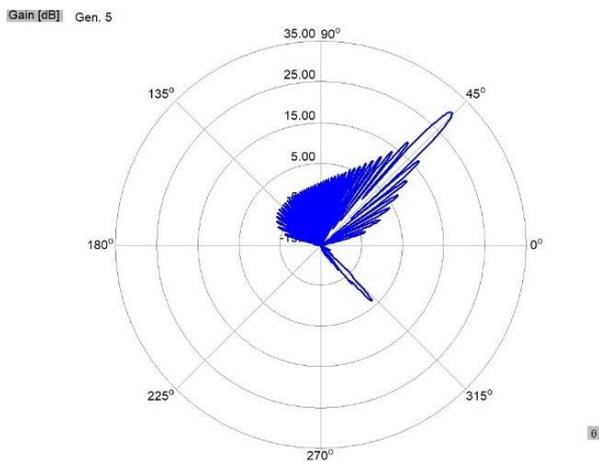
Table 7. Simulation times and number of unknowns for both radome examples

Model	Number of Unknowns	Simulation Time [s]
1-layer radome	81,110	3464
3-layer radome	286,592	23,830

The typical influence of radome is illustrated by showing radiation pattern for filed generator array in free space and when covered with ellipsoid radome (Figure 16).
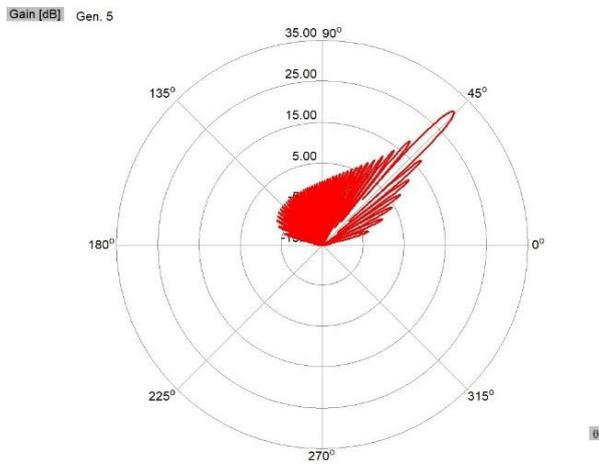
(a) FG array (free space)

(b) FG array with radome

Figure 16. Influence of 3-layer radome to field generators array radiation pattern (beam steering angle theta = 45 degrees)

4. Radome Run for Transparent Radomes

Since radomes are often electrically large regarding the volume and surface area, simulations can in general be so demanding that previously described reduction techniques would not lead to sufficiently reduced number of unknowns. Having in mind these applications, WIPL-D suite was enhanced by a special **Run Radome** feature that reduces the number of unknows for highly transparent radomes.

For most practical cases a radome is highly transparent. The idea behind the method is to use the high transparency of the radome to reduce the antenna-radome structure. The analysis is performed in two steps. In the first step, the antenna in the free space is analyzed, i.e. ignoring the presence of the radome. Based on the results obtained in the first step, and using a special technique, parts of radome having insignificant influence to the accuracy are identified. These parts are excluded in the second step where antenna is analyzed together with the remaining parts of the radome.

The significance of a mesh element to the accuracy of the analysis is determined based on the power illuminating the element. The powers are arranged in a decreasing order and summed until the value of the sum reaches some predefined power factor, i.e., a percent of total power. Mesh elements included in the sum are marked as significant, while the remaining elements are excluded.

In addition, each insignificant element having a common edge with a significant element has also been included in the analysis to avoid the effect of diffraction. The power factor is set by user. The starting value of 90% of the power illuminating the radome is recommended, and then 95%, 99% etc. should be tried.

Radome Run feature will be demonstrated on an example of single-layer radome placed above 2D antenna array (Figure 17).
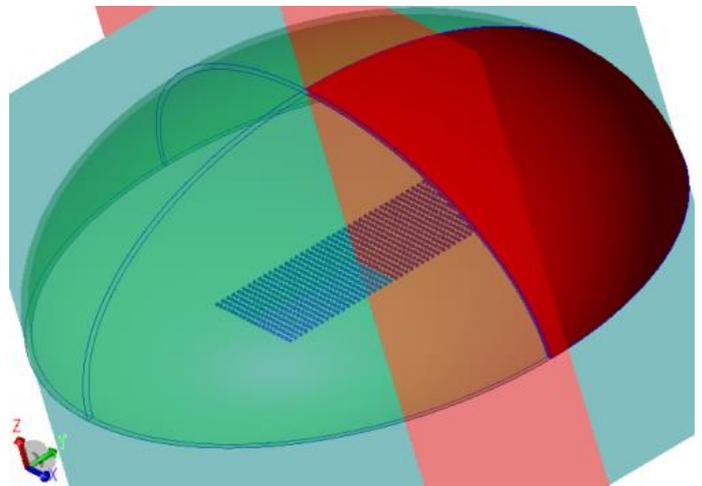

Figure 17. Spheroid radome above antenna array (20x40)

Array specification:

- Frequency of interest is 3 GHz.
- Array elements are far-field sources, θ polarized.
- Antenna radiation pattern is defined as:
  $E\theta = \cos(\varphi)\cos(\theta)$ for $\theta \geq 0°$ and $E\theta = 0$ for $\theta \leq 0°$,
  where θ angle is measured from x0y plane.
- Main lobe has +z-direction.
- Array is uniformly fed.
- Number of elements is 20 along x-axis and 40 along y-axis.
- Distance between elements of the array is equal in both directions and it is 0.05 m.

Radome specification:

- Radome is made of lossless dielectric with relative permittivity of 1.2.
- The shape of the radome is spheroid with the lengths of semi-axes along *x*, *y* and *z* coordinates respectively 5.625m, 5.625m and 3.375m. Therefore, the longest diameter of the spheroid (in *xOy* plane) is 112.5 λ.
- Thickness of the radome layer is equal to 0.05 m.

Mesh elements are shown for two values of power factor (Figure 18). Significant elements are shown in red while insignificant elements are yellow. It is evident that even with power factor equal to 99% a substantial number of radome mesh elements is excluded from the analysis. The analyzed array is highly directive and majority of its irradiated power is concentrated in a very narrow zone.
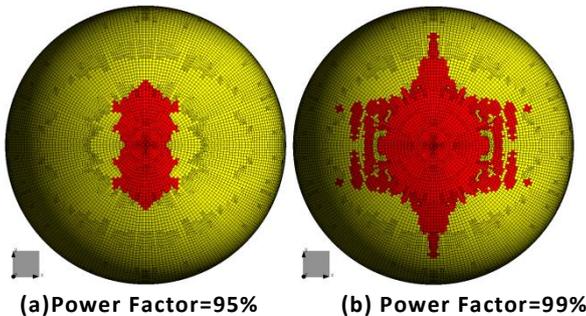

(a)Power Factor=95%   (b) Power Factor=99%

Figure 18. Omitted elements (shown in yellow) for different values of power factor

Simulations are carried out using the following workstation:

Intel® Xeon® CPU E5-2650 v4 @ 2.20 GHz (2 processors) with 256 GB RAM and four GPU cards NVIDIA GeForce GTX 1080 Ti, 6 SATA HDDs configured in RAID-0.

CPU and GPU acceleration are used as well as 2 symmetry planes. The following results confirm that the built-in feature enables huge reduction in number of unknowns/mesh elements. Simulation time has been reduced dramatically.

Table 8. Efficiency of the reduction

Power factor	Number of mesh elements	Number of unknowns	Simulation time [s]
100% (no reduction)	5,946	191,060	6,949
99%	1,428	39,366	707
95%	536	13,780	293

Simulated radiation patterns in φ=90° plane for different values of power factor reveal the accuracy of the method (Figure 19). The model with power factor set to 99% has almost identical radiation pattern. A noticeable difference occurs only on very low radiation pattern levels, i.e., about 60 dB below the main lobe.

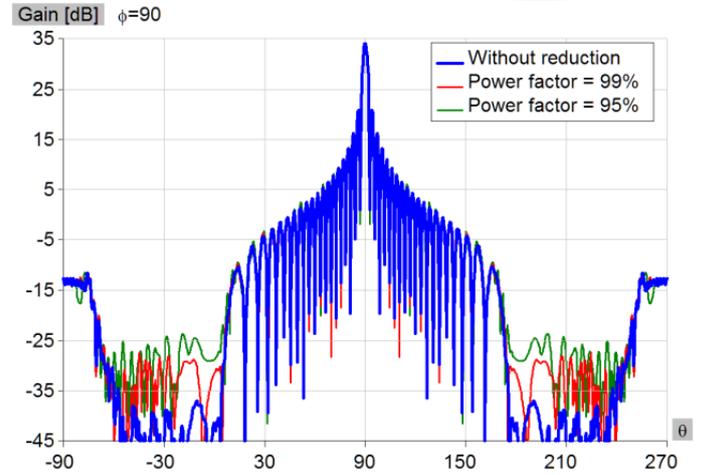Even the results obtained for power factor of 95% are quite acceptable from engineering point of view.

Figure 19. Radiation pattern of the array.

Conclusion

Typical simulation methods for radomes include approximation techniques such as geometrical or physical optics (GO, PO). Due to **very efficient implementation of Method-of-Moments (MoM)**, the simulation in WIPL-D suite is where required performed with much more sophisticated approximations.

Inherent requirements of radome simulations (high transparency, flat surfaces, smooth change of current distribution) allow to simplify the simulation without compromising accuracy. **In-house developed techniques successfully decrease number of unknowns** on radome parts which are less relevant for its EM functionality. The number of unknowns is kept low while **the accuracy remains high**. Straightforward usage and effectiveness of such techniques, including decrease of a referent frequency, implementation of field generators, run radome feature, etc. is described here, in a single comprehensive study.

The ability to simulate very complex models in acceptable time results from the efficient utilization of graphical processing units (GPU) for matrix inversion and multi-thread CPUs. Simulation times are dramatically reduced if a standard workstation with several GPU cards is used instead of single PC workstation with no GPU cards included.

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[9] Application note: "Large Multilayer Radomes"

[10] B. L. Mrdakovic and B. M. Kolundzija, "A method for full wave analysis of electrically large transparent radomes," 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), Fajardo, PR, USA, 2016, pp. 1331-1332, doi: 10.1109/APS.2016.7696373.

[11] Application note: "Steering Array under 100 Lambda Radome via Field Generators"

[12] Application note: "Radome Run Applied to Transparent Radome over Field Generators"