

Cavity RCS using Efield®

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Introduction

This Efield® Cavity RCS documentation describes how the RCS of open ended cavities can be computed using the Efield® frequency-domain solvers.

Efield® has very efficient tools dedicated for RCS analysis of very large open ended cavities such as air intakes and exhausts. RCS of the total target including the cavity can be computed using the Efield® MoM, MLFMM and PO solvers or with a very efficient and flexible domain decomposition method available in Efield®.

The Efield® Domain Decomposition Tool can be considered as a multi-domain and multi-method scheme that reduces significantly the computation time compared to traditional methods. If design changes or parametric investigation are done only the modified domains needs to be re-computed, the other ones are simply re-used. In traditional methods a geometric or electromagnetic modification requires a new computation of the complete geometry.

Domain decomposition method

The full problem includes both the cavity and the exterior structure as shown in Figure 1. The boundary of the full problem is defined by the dashed part S_0 and the solid part S_1 . The RCS (monostatic or bistatic) of the full problem can be computed using Efield® MoM or MLFMM solver. Physical Optics methods (such as Efield® PO) are not well suited for cavity RCS simulations since the accuracy will be very poor due to the multi bounce situation inside the cavity.

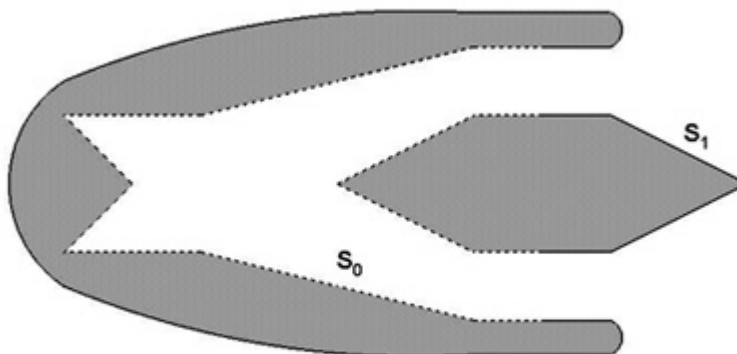


Figure 1: Full problem

Cavity RCS computations can be done in a more flexible way in Efield® that makes use of a decomposition of the problem into an interior and an exterior part. The interior part can also be further sub-divided into smaller problems.

In Figure 2 the full problem is decomposed into an interior cavity problem, defined by domain R_0 with boundary S_0 , Γ_1 and Γ_2 , and into an exterior problem, defined by domain R_1 with boundary S_1 , Γ_1 and Γ_2 . The introduced surfaces Γ_1 and Γ_2 are the interface between the interior and the exterior domains.

In Figure 3 the interior problem shown in Figure 2 has been further decomposed into several smaller sub-problems.

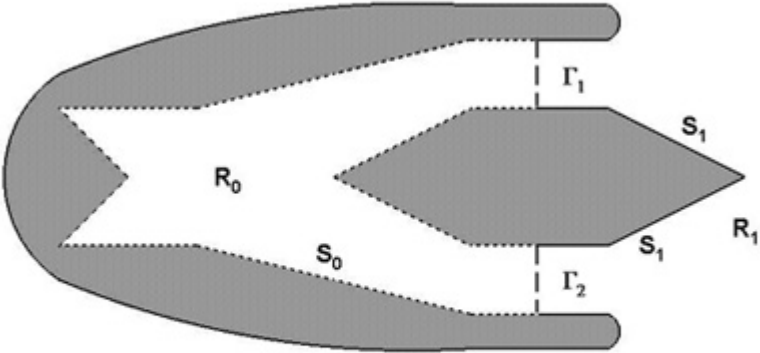


Figure 2: Decomposed problems into an exterior problem and an interior problem

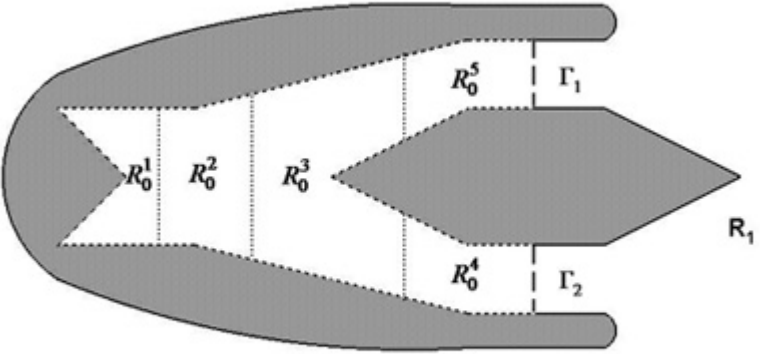


Figure 3: Decomposed problems into an exterior problem and an interior problem consisting of several sub-problems

The Efield® Domain Decomposition Tool for cavity RCS analysis can be considered as a multi-domain and multi-method scheme based on generalized admittance- and scattering-matrices computed for the interior sub-domains and the exterior domain.

The global geometry is split into interior sub-domains and one exterior domain, separated by fictitious surfaces between these domains as shown in Figure 3. At the fictitious surfaces the electric field is expanded into waveguide modes computed by the Efield® Mode Solver.

For each interior sub-domain the generalized admittance- and scattering-matrices are computed with the Efield® MoM solver using the waveguide modes as sources. The Efield® MoM solver is capable of modelling structures involving both perfectly electric conductors and dielectric or magnetic bodies with or without losses. When the generalized admittance- and scattering-matrices have been computed for each interior sub-domain a merging process connects these matrices by cascading the different admittance- and scattering-matrices into one admittance-matrix and one scattering-matrix for the whole interior domain.

For the exterior domain equivalent surface currents are computed for each plane wave excitation and for each waveguide mode used in the expansion of the field at the fictitious surfaces between the interior and exterior domains.

The final exterior equivalent surface current will then be equal to the surface current obtained from the plane wave excitation plus a linear combination of the surface currents obtained from the waveguide mode excitations. The coefficients in this expansion are determined by enforcing the continuity of the electric and magnetic field at the fictitious surfaces between the interior and exterior domains. When the exterior surface currents have been computed the far field and RCS can be computed.

If design changes or parametric investigation are done the generalized admittance- and scattering-matrices needs to be recomputed for the modified domains, the other ones, including the exterior domain, are simply re-used in the merging process. This strategy reduces significantly the computation time compared to traditional methods for which a geometric or electromagnetic modification requires a new computation of the complete geometry.

Using the described decomposition method the following can be computed:

- **Total RCS:** Total RCS of cavity and exterior by solving one large or several small interior cavity problems and an exterior problem.
- **Perfectly matched RCS:** RCS by solving one exterior problem with the cavity perfectly matched. This corresponds to a problem where the cavity is replaced by an infinite waveguide with a cross section as that of the interface surfaces.
- **Cavity RCS:** RCS of cavity with the influence of the exterior taken into account. One large or several small interior cavity problems and one exterior problem have to be solved. In most cases the total RCS will be equal to the sum of the perfectly matched RCS and the Cavity RCS.

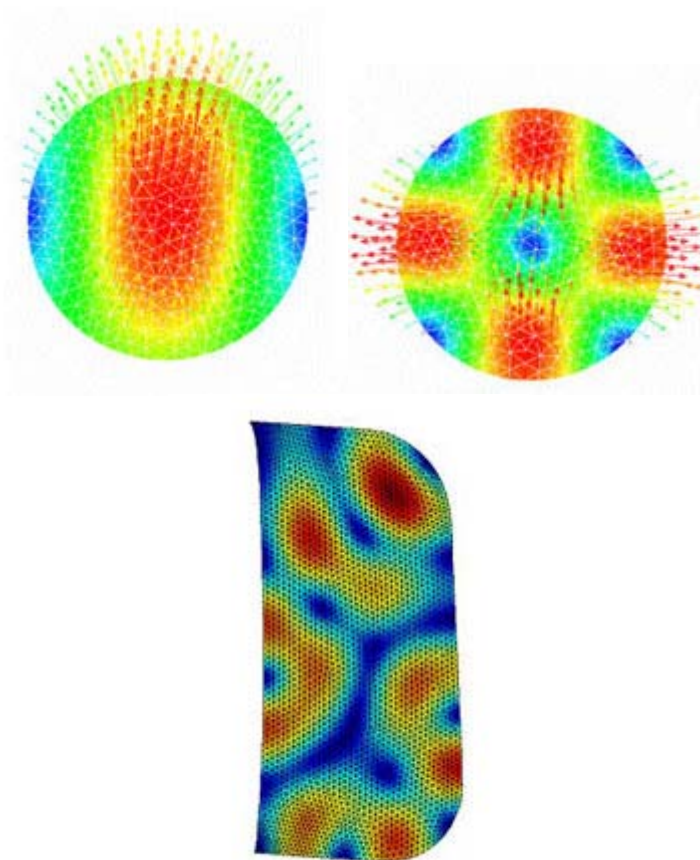
There are a number of reasons why this decomposition method is useful:

- The decomposition makes it possible to compute the cavity RCS contribution which is a part of the total RCS.
- The electrical size of the full problem can be too large to be solved by MoM or MLFMM. Using the decomposition method several smaller problems is solved. Also different methods can be applied on the interior and exterior parts. For example MoM for the interior and MLFMM or PO for the exterior.
- Using MLFMM on the full problem can result in slow convergence due to multiple interactions inside the cavity. In the decomposition method MLFMM is typically only applied to the exterior and this problem will not occur.
- If design changes are made in the cavity (absorbers, engine, shape) only the interior cavity problem needs to be recomputed.

Efield® Waveguide Modesolver

The Efield® Waveguide Modesolver is used to compute waveguide eigenmodes used by the Efield® Domain Decomposition Tool at the interfaces between the domains. The Efield® Waveguide Modesolver can compute different types of modes including:

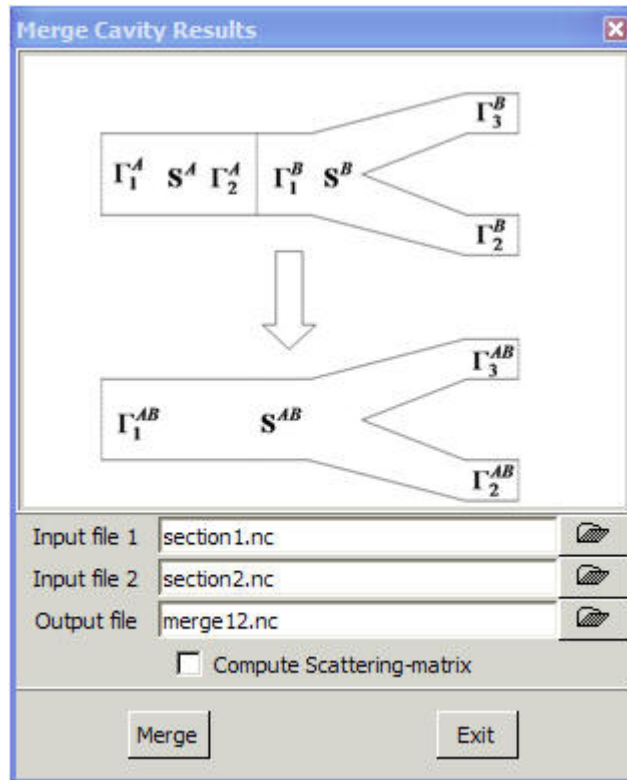
- TE, TM and TEM modes for general shaped homogeneous ports
- Analytical for rectangular, circular and coaxial ports
- Hybrid modes for general shaped inhomogeneous ports



Examples of waveguide modes

Efield® Merging Tool

The Efield® Merging Tool can merge generalized admittance- and scattering-matrices that has been computed for two different interior sub-domains sharing one or more fictitious interface surfaces. The results produced by the tool are new generalized admittance- and scattering-matrices for the combined sub-domains. The tool can be seen in the Figure below.



The Efield® Merging Tool

Example: Channel Cavity

This test case is a cavity enclosed in a circular cylinder [1], see Figure 4 and Figure 5. The entry of the cavity has an elliptic cross section, the end of the cavity has a circular cross section.

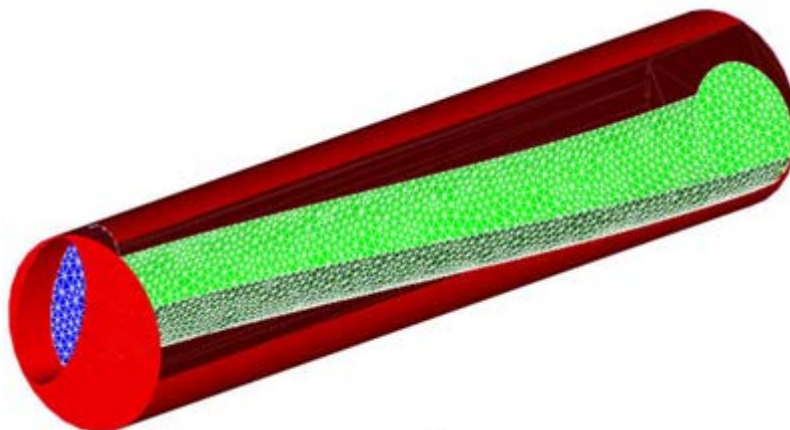


Figure 4: The channel

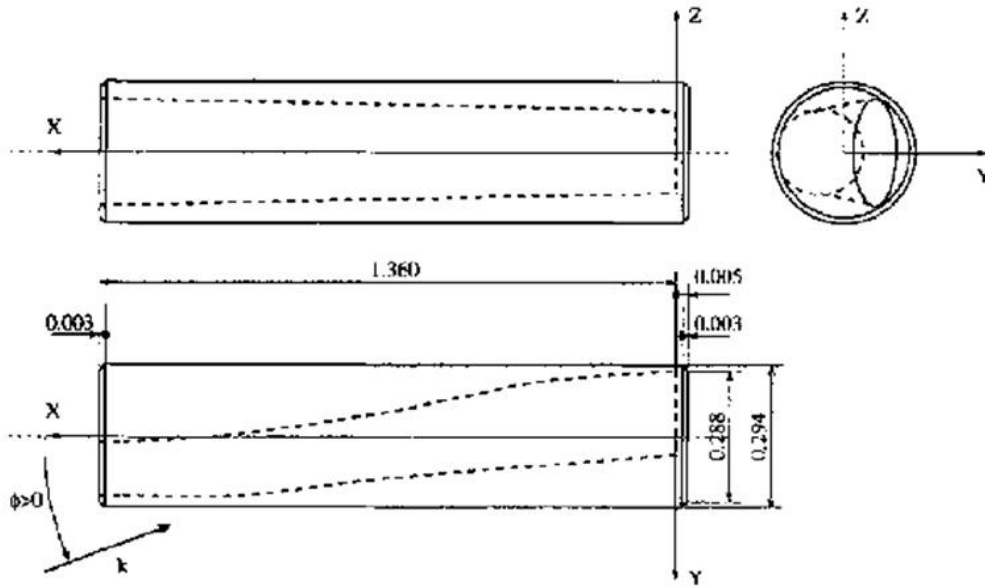


Figure 5: Geometry of the channel

The monostatic RCS is computed from 0 to 360 degrees, indicated by ϕ in Figure 5, at the frequency 2GHz, for the polarisations HH (electric field parallel to Y) and VV (electric field parallel to Z).

The problem is solved for the full problem as well as with the method presented in this report using domain decomposition of the problem into an interior and an exterior problem. The set up of the problem is shown in Figure 6. In case of solving the full problem the computation is done on the whole geometry shown in Figure 6 except that the interface surfaces between the interior and exterior domains are not present in this simulation.

When solving the problem using domain decomposition the interior part is shown in blue, red and green and the exterior part is shown in grey in Figure 6.

The interior problem is solved in two different ways that is compared in terms of accuracy and computational time. In the first case the whole interior problem is solved in one run and in the second case the interior problem is solved by solving three smaller sub-problems that are merged to one result. Sub-problem 1 is called section 1 and is shown in blue, sub-problem 2 is the called section 2 and is shown in red, and sub-problem 3 is called section 3 and is shown in green.

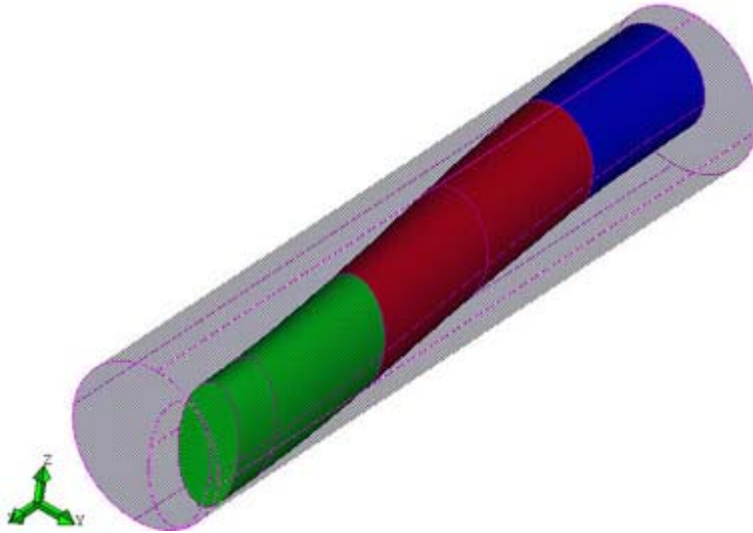


Figure 6: Decomposition of the geometry into an exterior part, shown in grey, and into an interior part shown in green, red and blue. The interior problem is solved in two different ways that is compared in terms of accuracy and computational time.

In the first case the whole interior problem (green, red and blue) is solved in one run and in the second case the interior problem is solved by solving three smaller sub-problems that are merged to one result. Sub-problem 1 is the blue part called the section 1, sub-problem 2 is the red part called the section 2, and sub-problem 3 is the green part called the section 3.

When solving the problem using domain decomposition interface surfaces is introduced between the interior and exterior problem at $x=1.360$ in the cavity aperture, and also between section 1 and 2 and between section 2 and 3.

At 2GHz there are 4 propagating TE-modes and 1 propagating TM-mode at the interface between the interior and exterior domains. In the computation 6 TE- and 2 TM-modes are used to expand the field in the interface. At the interfaces between section 1 and 2 and between section 2 and 3 the field is expanded by 6 TE- and 4 TM-modes.

The number of unknowns for the full problem is 32712, for the whole interior problem 12081 and for the exterior problem 21249. The number of unknowns for section 1 is 3328, section 2, 5992 and section 3, 4340.

The monostatic RCS for VV polarization is shown in Figure 7 and the monostatic RCS for HH polarization is shown in Figure 8. The black curve is the total RCS computed using the full model, the red dotted curve is the total RCS computed using the decomposed model of an interior and an exterior part. As can be seen the agreement are very good. The blue dotted curve represent the monostatic RCS when the cavity is perfectly matched and the green dotted curve represent the monostatic cavity RCS contribution. As can be seen the cavity contribution decays rapidly away from the entrance of the cavity. The dotted green curve is obtained by adding the perfectly matched RCS and the cavity RCS contributions. As can clearly be seen this result is a good approximation of the total RCS.

RCS using the domain decomposition method is shown in Figure 9 to Figure 11. The total RCS is shown for both vertical polarisation, at the top, and horizontal polarisation, at the

bottom in Figure 9. The results in black are obtained by solving the interior part in one simulation and the red result is obtained by solving the interior part using three sections. As can be seen the results are in excellent agreement. The Cavity RCS is shown in Figure 10 and the perfectly matched RCS is shown in Figure 11.

The surface currents for vertical and horizontal polarization for plane wave excitation at $\phi=0$ and $\theta=90$ degrees are shown in Figure 12 and 13.

The time for the different computations is shown in Table 1. As can be seen from this table the time to solve the full problem is much longer than to solve the decomposed problems. The reason for this is that it is faster to solve several smaller problems than one large and the fact that MLFMM on deep cavities can result in slow convergence. The number of iterations for each right hand side is shown in Figure 14. For the full model computation the number of iterations is much larger than for the decomposed exterior problem. After approximately 200 right hand sides the solution is computed by pure interpolation and no iterations are needed.

Model	Part	Number of unknowns	Method	Number of CPUs	Time (seconds)
Full	All	32 712	MLFMM	1	34057
Decomposed	Interior All	12084	MoM	2	803
Decomposed	Interior Section 1	3328	MoM	2	35
Decomposed	Interior Section 2	5992	MoM	2	152
Decomposed	Interior Section 3	4340	MoM	2	68
Decomposed	Exterior	21249	MLFMM	1	2788

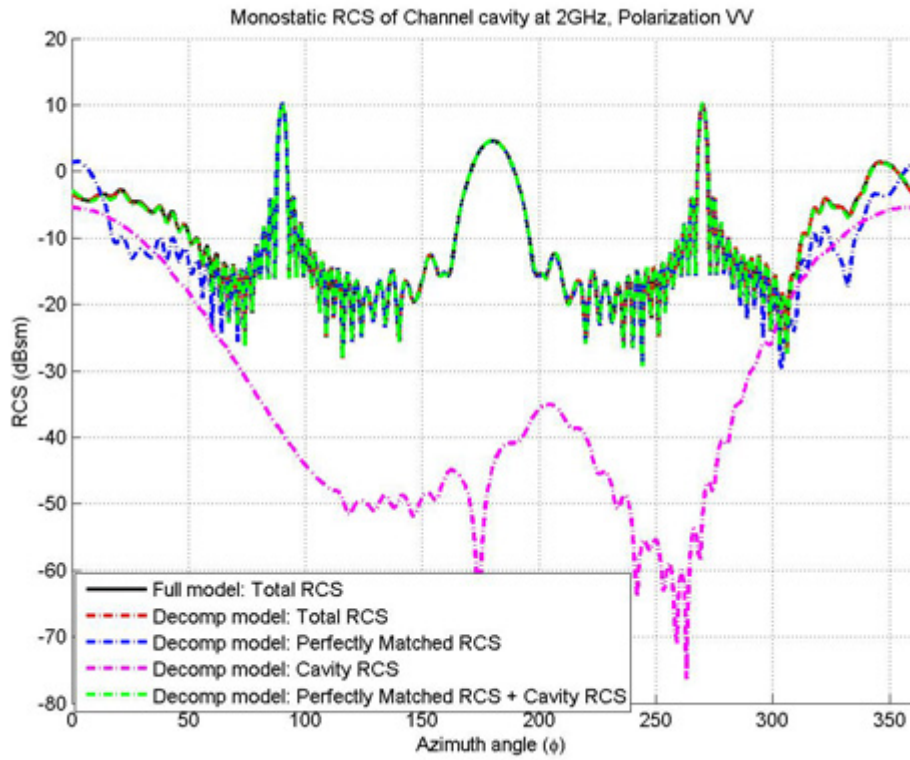


Figure 7: Monostatic RCS of channel at 2GHz. Polarization VV.

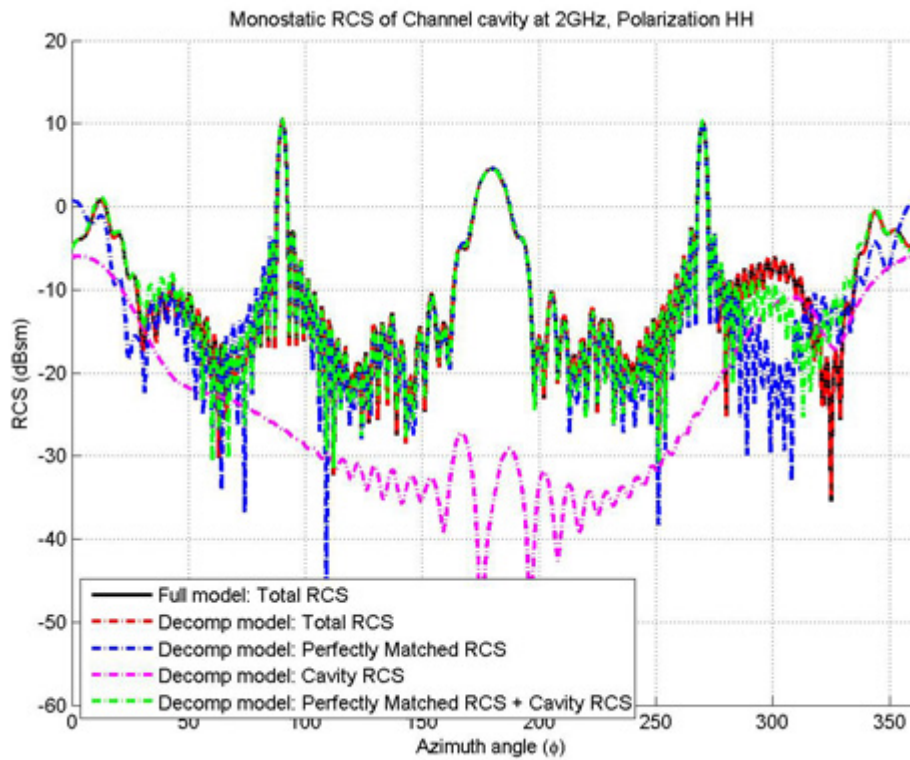


Figure 8: Monostatic RCS of channel at 2GHz. Polarization HH.

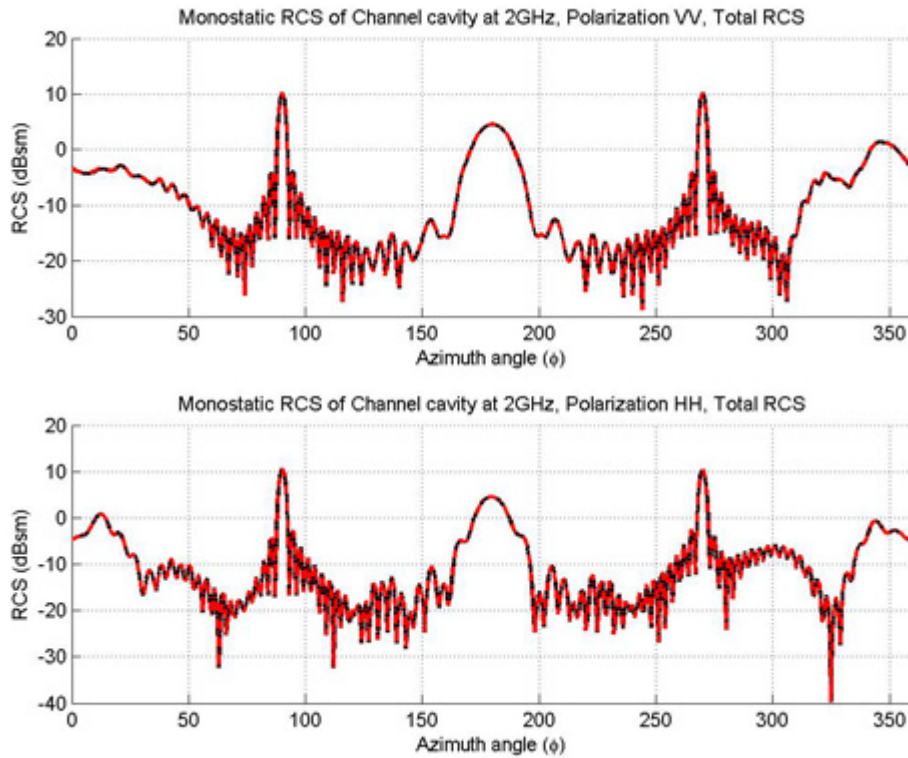


Figure 9: Total RCS using domain decomposition method. Result in black is obtained by solving the interior part in one simulation and the red result is obtained by solving the interior part using three sections. Vertical polarisation is shown at the top and horizontal polarisation is shown at the bottom.

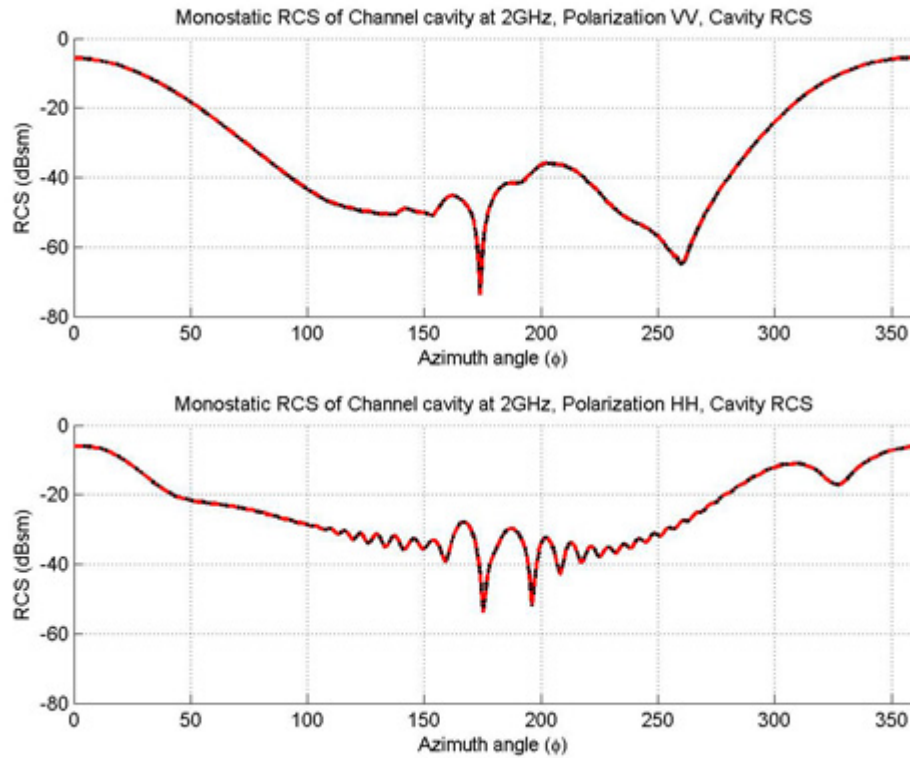


Figure 10: Cavity RCS using domain decomposition method. Result in black is obtained by solving the interior part in one simulation and the red result is obtained by solving the interior part using three sections. Vertical polarisation is shown at the top and horizontal polarisation is shown at the bottom.

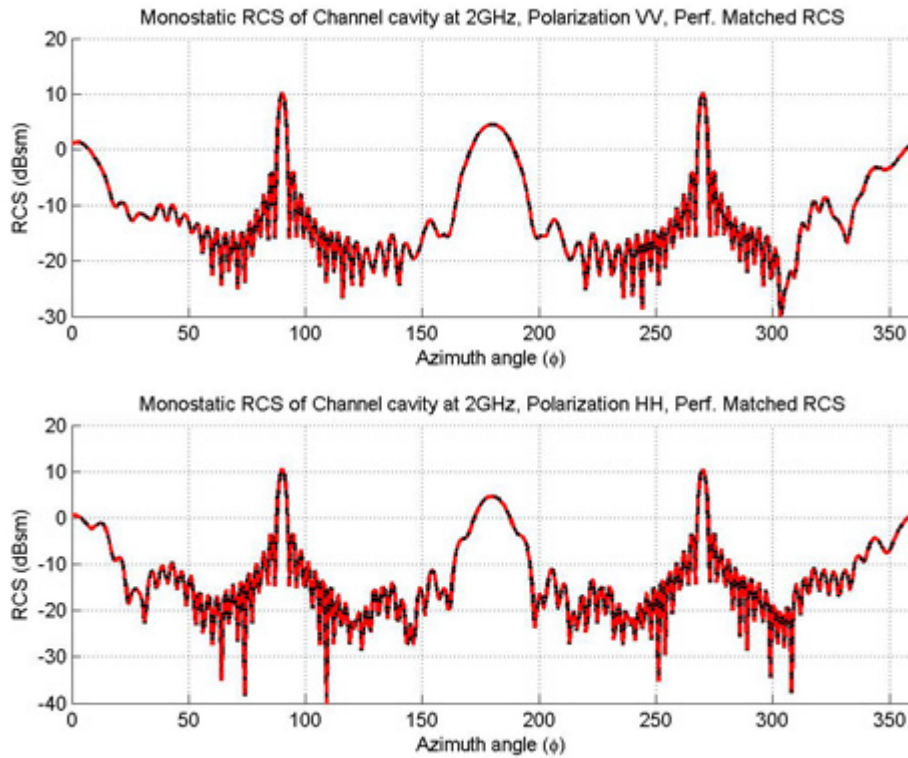


Figure 11: Perfectly matched RCS using domain decomposition method. Result in black is obtained by solving the interior part in one simulation and the red result is obtained by solving the interior part using three sections. Vertical polarisation is shown at the top and horizontal polarisation is shown at the bottom.

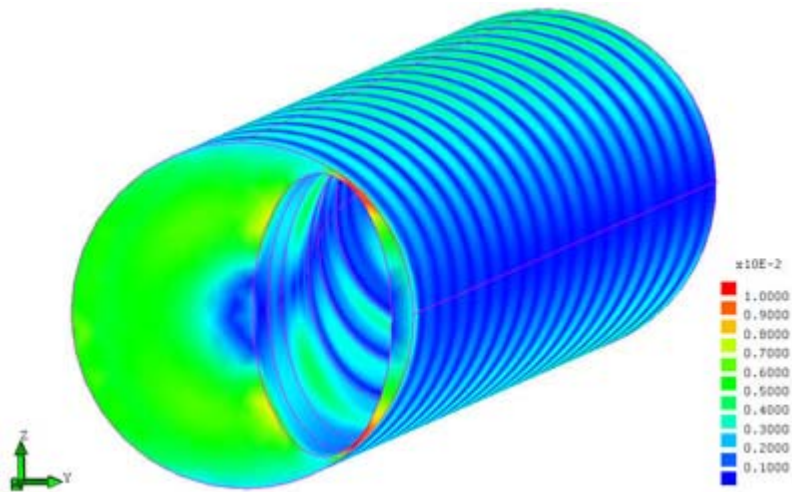


Figure 12: Surface currents of channel at 2GHz with vertical polarization. Plane wave excitation at $\phi=0$, $\theta=90$.

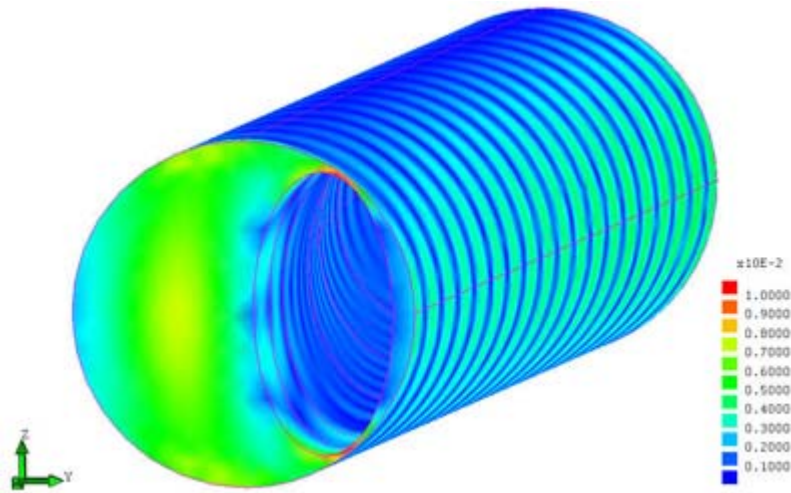


Figure 13: Surface currents of channel at 2GHz with horizontal polarization. Plane wave excitation at $\phi=0$, $\theta=90$.

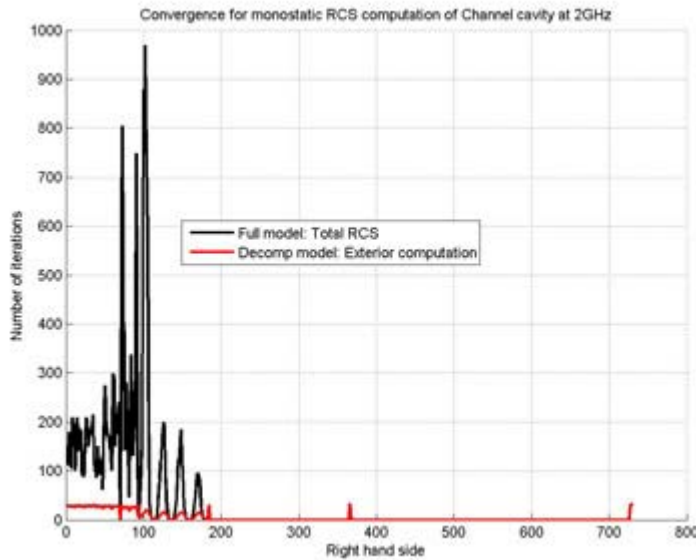


Figure 14: Number of iterations for computation on full model and computation on exterior part of decomposed model.

Example: Double Intake Cavity

This example is a double intake cavity where the cavity is 8 m deep. The entry of the cavity has a rectangular cross section with dimensions 1 m x 0.45 m. The geometry of the problem is shown in Figure 15 with the exterior geometry shown in grey transparent colour and the interior geometry, the cavity part, shown in green, blue, magenta and red colour. The dimensions of the geometry are given in Figures 16 and 17.

The monostatic RCS for θ from 0 to 90 degrees (θ is defined in the spherical coordinate system as defined in Figure 25) is computed at 500 MHz, for the polarisations HH (electric field parallel to X) and VV (electric field parallel to Y). The solution is computed for in total 182 right hand sides.

The flexibility, accuracy and efficiency of using the Efield® domain decomposition method are demonstrated.

The problem is solved using three different settings:

- The problem is solved for the full problem in one single simulation using the Efield® MLFMM solver. In this case the simulation is done on the whole geometry.
- The problem is solved using the domain decomposition method with one interior cavity part (shown as section 1 to 4 in Figure 15) and one exterior part (shown in grey in Figure 15). Two simulations are done, one for the interior problem, and one for the exterior problem. At the interface surface between the interior and exterior domains the electric field is expanded using 9 TE and 3 TM modes. After the two simulations are done the continuity of the fields is enforced at the interface surface between the interior and exterior. This determines the correct surface currents and the far-field and RCS are computed. The interior simulation is done using the Efield® MoM solver and the exterior simulation using the Efield® MLFMM solver.
- The problem is solved using the domain decomposition method with four interior cavity parts (one simulation for each section in Figure 15) and one exterior part (shown in grey in Figure 15). At the interface surface between the interior and exterior domains, and at the interface surfaces between section 2 and section 3 and section 2 and section 4 the electric field is expanded using 9 TE and 3 TM modes. At the interface surfaces between section 1 and section 2 the electric field is expanded using 17 TE and 6 TM modes. After all simulations have been computed the interior results (admittance- and scattering-matrices) are merged to one result for the interior part. When this is done continuity of the fields are enforced at the interface surface between the interior and exterior. This determines the correct surface currents and the far field and RCS can be computed. The interior simulations are done using the Efield® MoM solver and the exterior simulation using the Efield® MLFMM solver.

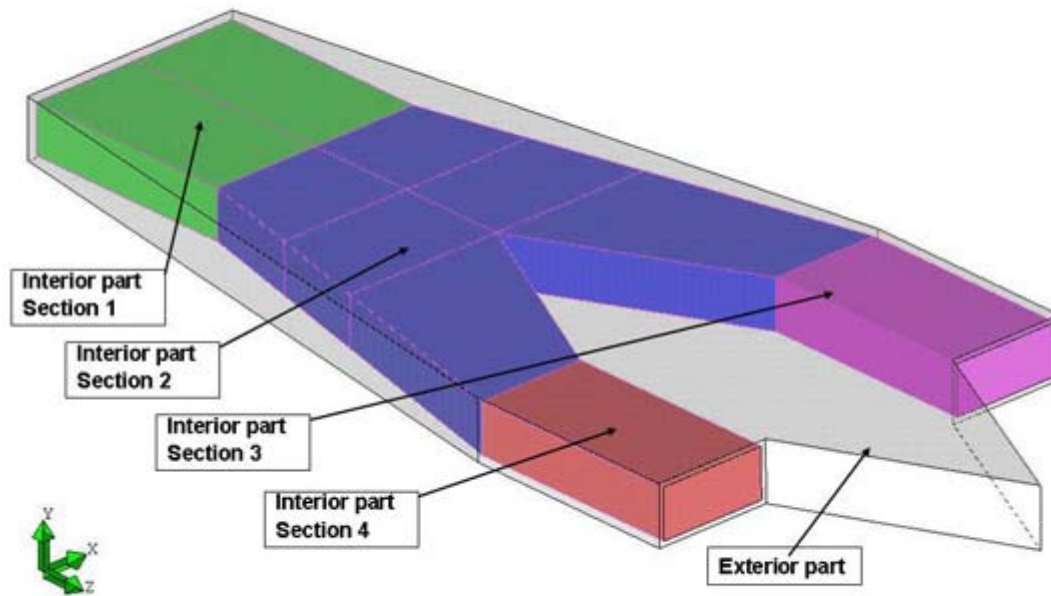


Figure 15: Double intake cavity. Decomposition of the geometry into an exterior part, shown in grey, and into an interior part shown in green, blue, red and magenta. The interior problem is solved in two different ways that is compared in terms of accuracy and computational time. In the first case the whole interior problem (green, blue, red and magenta) is solved in one run and in the second case the interior problem is solved by solving four smaller sub-problems that are merged to one result. Sub-problem 1 is the green part called the section 1, sub-problem 2 is the blue part called the section 2, sub-problem 3 is the magenta part called the section 3, and sub-problem 3 is the red part called the section 4.

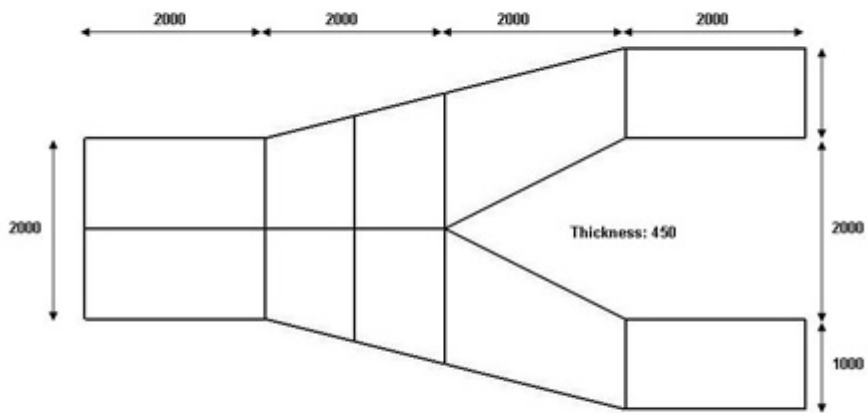


Figure 16: Geometry of the double intake cavity. All dimensions in mm.

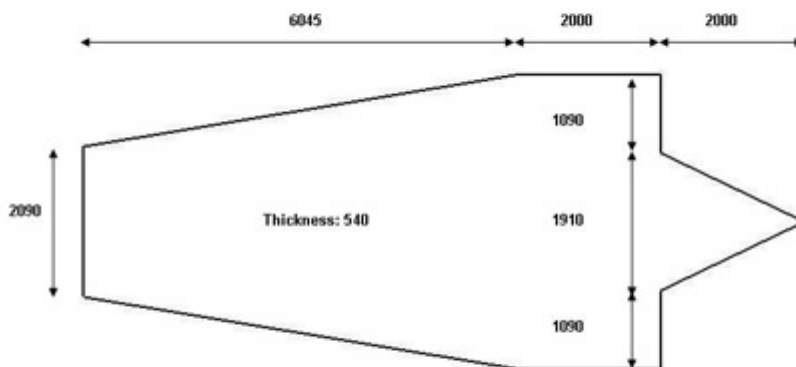


Figure 17: Geometry of the double intake cavity. All dimensions in mm.

Total RCS for the problem for VV polarization is shown in Figure 18 and the total RCS for HH polarization is shown in Figure 19. The full problem simulation result is shown in black, the simulation result from the domain decomposition method with the interior solved in one run is shown in red and the simulation result from the domain decomposition method with the interior solved in four runs is shown in blue. As can be seen the agreement is very good between the different ways to solve the problem.

Cavity RCS as a result from the simulation using the domain decomposition method is shown in Figure 20. As can be seen the cavity contribution decays rapidly away from the entrance of the cavity. The RCS for the problem when the cavity is perfectly matched is shown in Figure 21.

The surface currents for the vertical and horizontal polarizations for plane wave excitation at $\phi=0$ and $\theta=0$ are shown in Figure 23 and Figure 24.

The time for the different computations is shown in Table 3. As can be seen from this table the time to solve the full problem is 96329 seconds. The time to solve the problem using the domain decomposition method with one interior computation is 144579 seconds for the interior part and 7511 seconds for the exterior part resulting in a total time of 152089 seconds. This is slower than solving the full problem and the reason is that one very large MoM problem is solved. Also the MoM solution is obtained using an out-of-core (disc) storage of the matrix which reduces the memory need but increase the solution time. The time to solve the problem using the domain decomposition method with four interior computations is 18954, 32583, 10902 and 10833 seconds for the interior parts and 7511 seconds for the exterior part resulting in a total time of 80783 seconds. In this case the simulation time is equivalent to the simulation time of the full problem. The simulation time of the domain decomposition method could have been reduced even more by decreasing the size of section 2 which takes half the simulation time.

The number of iterations for each right hand side is shown in Figure 22. For the full model computation the number of iterations is much larger than for the decomposed exterior problem. After approximately 80 right hand sides the solution is computed by pure interpolation and no iterations are needed.

This example has demonstrated how the RCS of large open ended cavities such as air intakes and exhausts can be computed using Efield®. The Efield® MLFMM can be used directly on the full problem with the potential problem of slow convergence due to the multiple interactions inside the cavity. The decomposition method described here can be used that enables the decomposition of the problem into several smaller problems which can be solved using different methods, for example Efield® MoM for the interior and Efield® MLFMM or PO for the exterior. The decomposition method enables the computation of cavity RCS and perfectly matched RCS. The decomposition method also has the very attractive property that if design changes are made in the cavity (absorbers, engine and shape) only that interior cavity part needs to be recomputed.

Table 2: Timing results for cavity computations. The simulation was run on an AMD Dual Core Opteron 285 2.6 GHz machine with 16 Gb memory.

Model	Part	Number of unknowns	Method	Number of CPUs	Time (seconds)
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Full	All	207 225	MLFMM	1	96 329
Decomposed	Interior All	83 214	MoM	2	144 579
Decomposed	Interior Section 1	18 954	MoM	2	2 703
Decomposed	Interior Section 2	49 989	MoM	2	32 583
Decomposed	Interior Section 3	10 902	MoM	2	732
Decomposed	Interior Section 4	10 833	MoM	2	642
Decomposed	Exterior	127 506	MLFMM	1	7 511

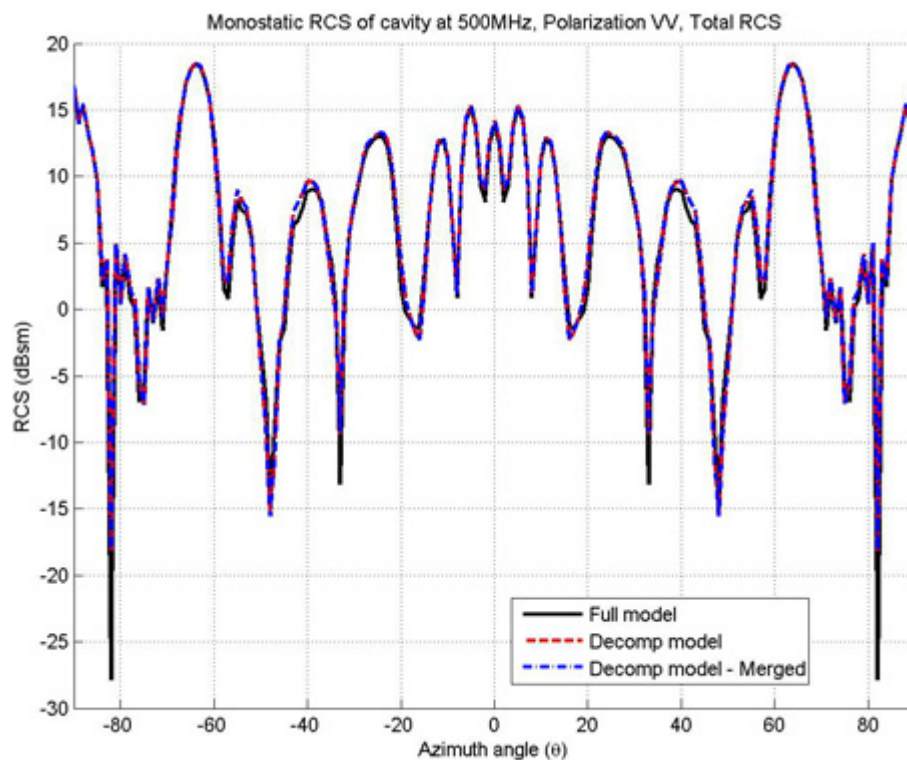


Figure 18: Total monostatic RCS at 500MHz for VV polarization. The full problem simulation result shown in black, the simulation result from the domain decomposition method with the interior solved in one run shown in red and simulation result from the domain decomposition method with the interior solved in four runs shown in blue.

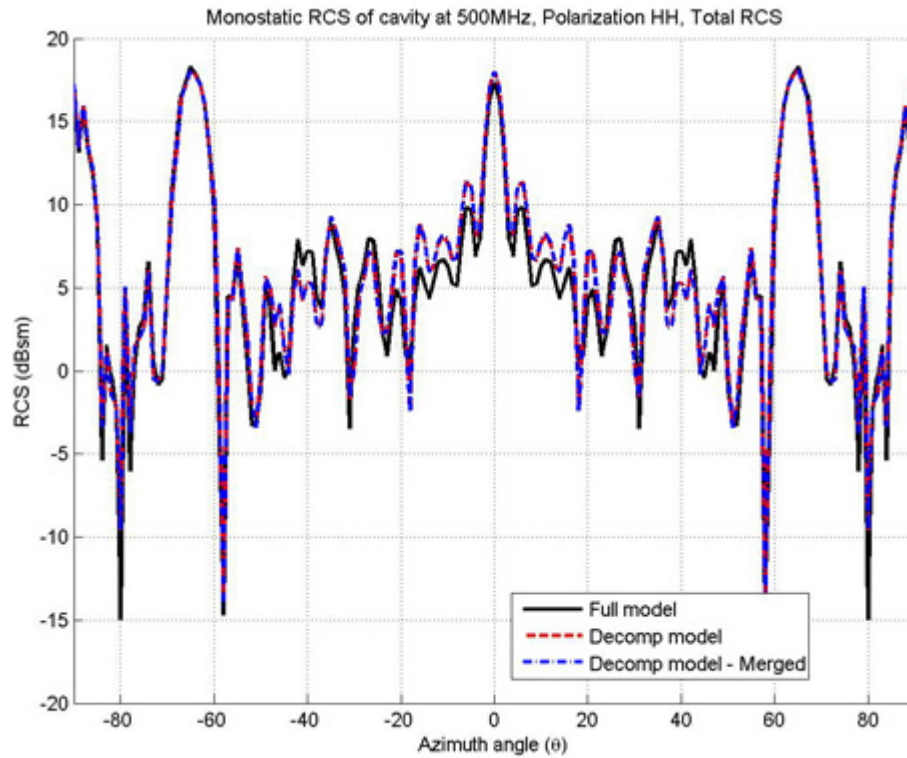


Figure 19: Total monostatic RCS at 500MHz for HH polarization. The full problem simulation result shown in black, the simulation result from the domain decomposition method with the interior solved in one run shown in red and simulation result from the domain decomposition method with the interior solved in four runs shown in blue.

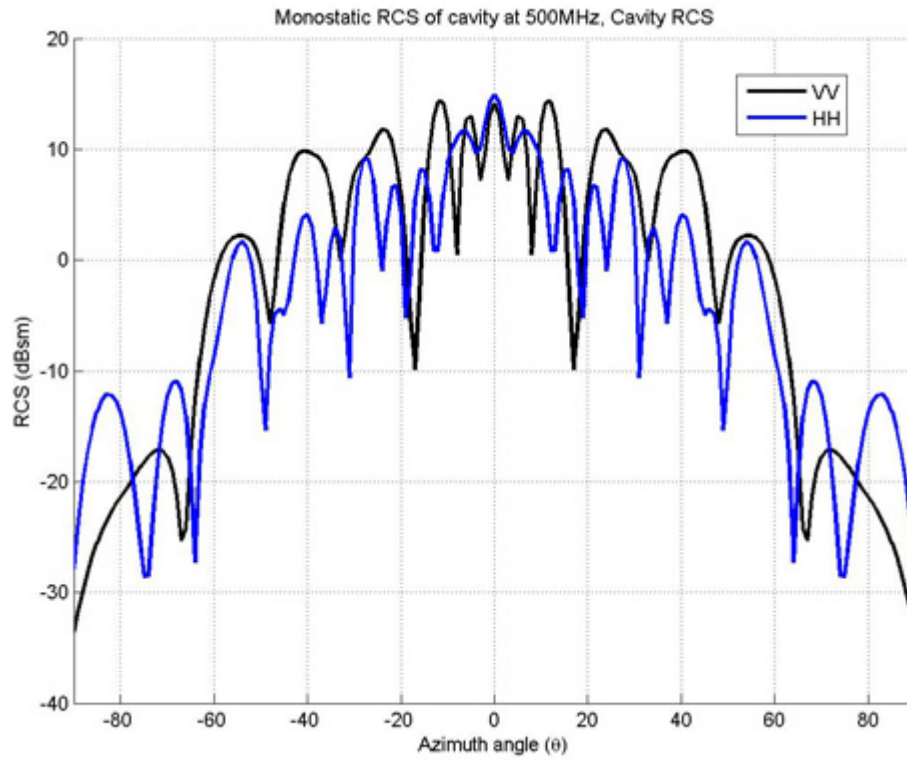


Figure 20: Monostatic cavity RCS at 500MHz for VV and HH polarization.

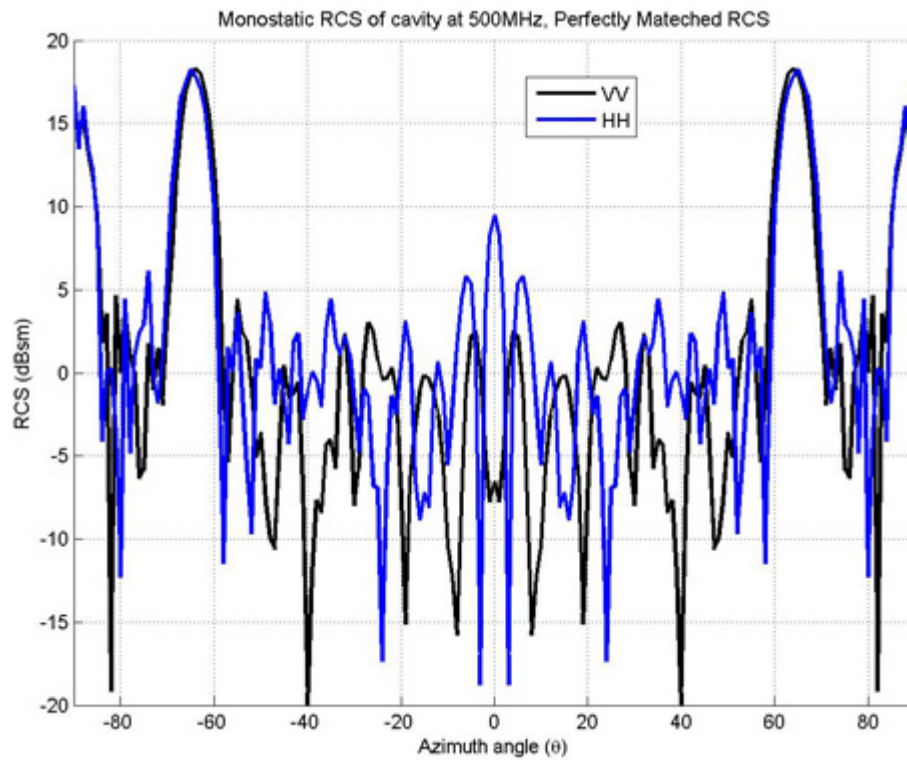


Figure 21: Monostatic perfectly matched RCS at 500MHz for VV and HH polarization.

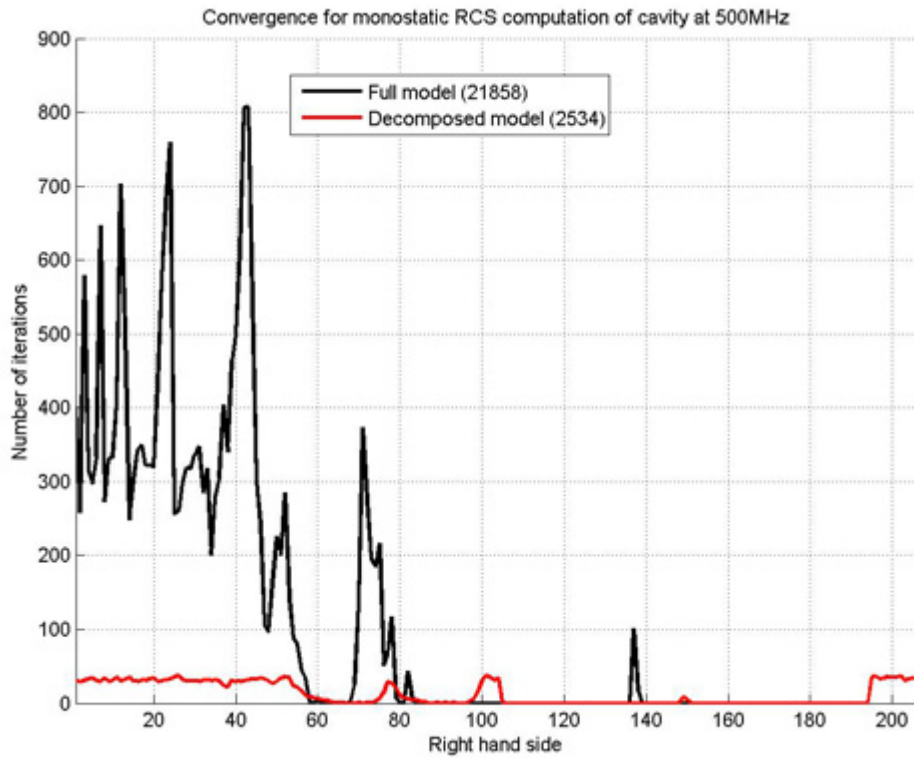


Figure 22: Number of iterations for computation on full model and computation on exterior part of decomposed model.

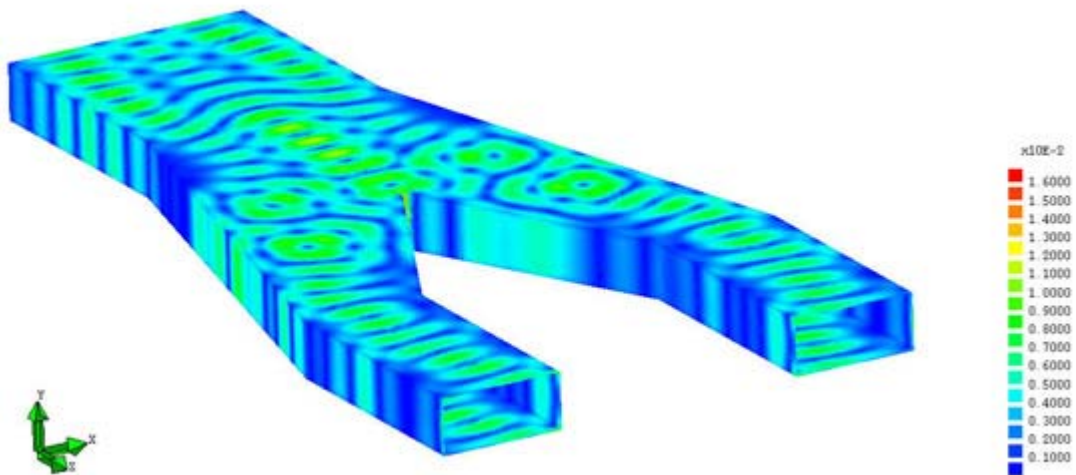


Figure 23: Surface currents of cavity at 500 MHz with vertical polarization for plane wave excitation at $\phi=0$, $\theta=0$. Cavity geometry.

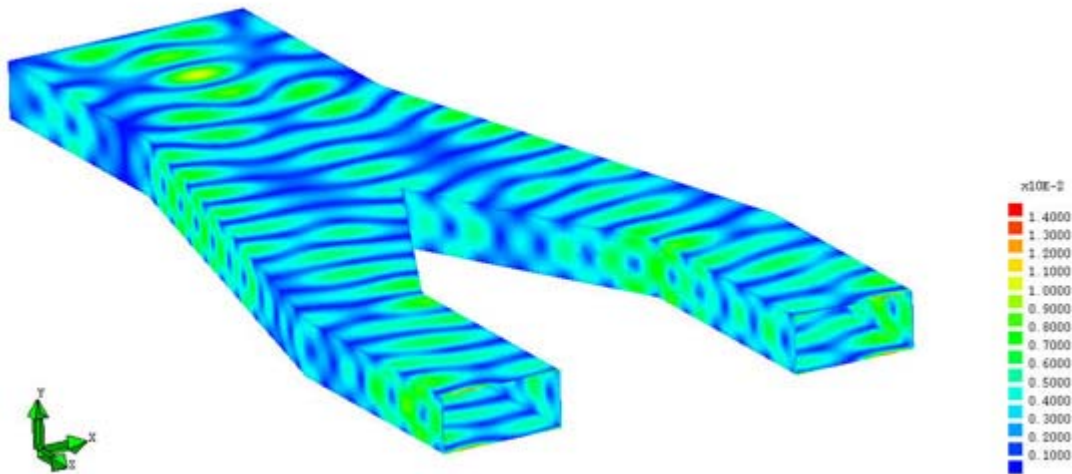


Figure 24: Surface currents of cavity at 500 MHz with horizontal polarization for plane wave excitation at $\phi=0$, $\theta=0$. Cavity geometry.

References

- [1] A. Barka, P. Soudais, and D. Volpert, Scattering from 3-D Cavities with a Plug and Play Numerical Scheme Combining IE, PDE, and Modal Techniques, IEEE Transactions on Antennas and Propagation, vol 48, no 5, 2000.

Appendix: Spherical coordinate system

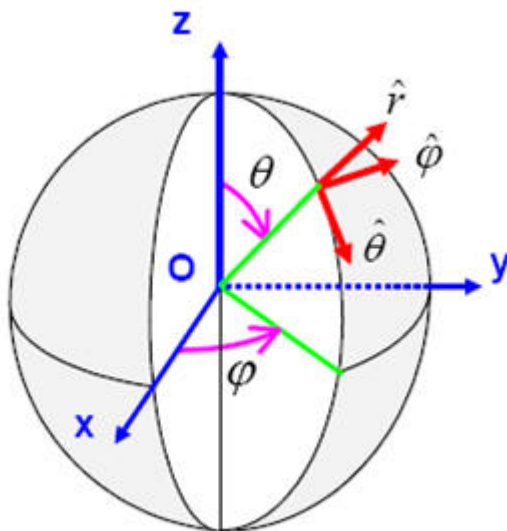


Figure 25: Definition of the spherical coordinate system used.

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