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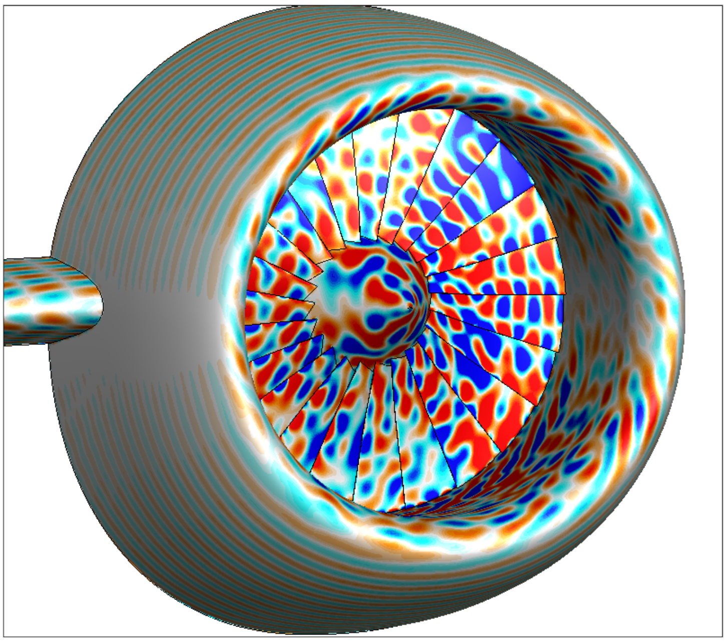
National Aerospace Laboratory NLR

Executive summary

High Range Resolution Profiles for a Civilian Aircraft Inlet

Contribution of NLR



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Knowledge area(s)
Computational physics and theoretical aerodynamics

Descriptor(s)
Radar Cross Sections
Engine inlet Fast multipole

Problem area
Non-Cooperative Target Identification (NCTI) is a concept of great interest to NATO, since it promises the reduction of fratricide incidents. NCTI methods rely on a comparison between the measured target signature to a reference data base. NCTI may be mainly accomplished by *High Resolution Range Profiles* (HRRP's) or 2D *Inverse Synthetic Aperture Radar* (2D-ISAR) images. The data base is populated with experimental data and data from electromagnetic prediction tools.
As prediction tools do not require extensive measurement programs, they in principle hold the promise of generating the data in an efficient way. However, fast and reliable prediction of the radar signature of (air-) targets is an exceptionally challenging problem. It is well known that the scattering from cavities such as engine inlets is an important contributor to the overall radar signature of a fighter aircraft. The intricate physics inside the cavity adds to the complexity of the problem.

Description of work
In the current paper, the HRRP of a civilian engine inlet is computed. These computations serve as a

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demonstration only, verification and validation is the subject of ongoing work. The computational complexity of the simulations is analysed.

Results and conclusions
The computational method is capable of producing HRRP's at realistic frequencies in feasible computing times. Important geometrical features of the engine inlet are visible in the HRRP's.

Applicability
Once validated, the predicted HRRP's can be used to extend the NATO database for non-cooperative target identification.

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Summary

This paper is based on the research conducted by the RTO Task Group SET 138 RTG75/RFT "Electromagnetic Scattering Analysis of Jet Engine Inlets for Aircraft NCTI Purposes" (Oct. 2008-). The main objective of this work is the calculation of the Radar Cross Section (RCS) of inlets occurring on military aircraft, and the subsequent development of High Range Resolution Profiles (HRRP's) to be utilized in Non-Cooperative Target Identification (NCTI). NCTI is a concept of great interest to NATO, since it promises reduction of fratricide incidents. The current report contains NLR's contribution to [3] and describes the methodology and results for the computation of HRRP's for a civilian jet engine.

Contents

Abbreviations

CFIE	Combined Field Integral Equation
EFIE	Electrical Field Integral Equation
GMRES	Generalised Minimum RESidual method
HRRP	High Range Resolution Profile
ILU	Incomplete Lower/Upper factorization
ISAR	Inverse Synthetic Aperture Radar
MLFMA	Multi-Level Fast Multipole Algorithm
MPI	Message Passing Interface
NCTI	Non-Cooperative Target Identification
RCS	Radar Cross Section
RTO	Research & Technology Organization of NATO

1 Introduction

Rapid and reliable identification of (air-) targets by radar means is an exceptionally challenging problem. The various techniques that have been proposed to solve it are roughly divided into two classes: cooperative (often referred to as IFF -*Identification Friend or Foe*- techniques) and non-cooperative techniques (NCTI, *Non-Cooperative Target Identification*) which rely on a comparison between the measured target signature to a reference data base. NCTI may be mainly accomplished by *High Resolution Range Profiles* (HRRP's) or 2D *Inverse Synthetic Aperture Radar* (2D-ISAR) images and the data base is populated with experimental data and data from electromagnetic prediction tools. Using the database, NCTI algorithms will compute the likelihood that a given range profile (for instance, measured in the field) originates from a certain aircraft, based on pattern recognition algorithms. Traditionally, the database is filled with experimental data, the use of simulation data is still in its infancy.

This paper is based on the research conducted by two RTO Task Groups, namely SET 085 RTG49 "Radar signature prediction of cavities on aircraft, vehicles and ships", (Oct. 2004-Dec. 2007) and its continuation, that is, SET 138 RTG75/RFT "Electromagnetic Scattering Analysis of Jet Engine Inlets for Aircraft NCTI Purposes" (Oct. 2008-) The main objective of this work is the calculation of the Radar Cross Section (RCS) of inlets occurring on military aircraft, and the subsequent development of HRRP's to be utilized in NCTI. NCTI is a concept of great interest to NATO, since it promises reduction of fratricide incidents.

It has been shown that scattering from engines is among the most significant contributions to the overall radar signature. When an HRRP from an aircraft is observed for nose-on or tail-on incidences, the scattering behaviour from the engines seems to dominate the response. Bearing this in mind, this group could not avoid the challenge to produce HRRP's of engine inlets obtained via prediction codes.

To validate their algorithms and assess their performance, the Task Group partners initially computed the RCS and developed HRRP's related to the simplified inlet model developed originally in [2]. Numerical results, validated through measurements and cross-checks, have been presented in [1]. However, the geometrical complexity of such a model, along with the computations involved, are much lower than those corresponding to realistic jet engines, which are the scatterers of operational interest to NATO/RTO. Before working on actual aircraft, which is the main objective, it was advisable to apply the algorithms to inlet models of intermediate complexity, such as the "French Channel", and the "Canadian Duct", described in [1]. Finally, similar calculations were performed for actual aircraft types, coded as "alpha", "beta" and "delta". Results for the former two targets are described in [3]; methodology and results for the "delta" target are described in the current report.

The computation of HRRP's is one order of magnitude more expensive than the computation of RCS for a given aspect angle, as a range of frequencies must be considered. This raises the question of the balance between accuracy and turnaround times. The computational method used in the current report represents all (linear) physical phenomena of radar wave scattering. As such, the method is computationally more expensive than more simple methods, such as Physical Optics methods. For low-observable aircraft it is important to be able to represent secondary scattering mechanisms, such as creeping waves, as the primary scattering mechanisms have been reduced significantly by, amongst others, planform design. As the secondary scattering mechanisms are not represented by Physical Optics methods, full-wave methods as used here are required. The increased computational load is deemed acceptable since the computations consist of a large number of unrelated simulations which require little user interaction. Given the lifespan of fighter aircraft, total turnaround times in the order of half a year are acceptable.

2 Numerical method

All RCS calculations, described below, are performed with Shako, which is an NLR in-house developed algorithm for high-frequency scattering analyses for very large objects. The algorithm is based on the boundary integral method, accelerated with a multi-level fast multipole algorithm (MLFMA). A GMRES solver combined with a block ILU(0) preconditioner is used to solve the equations. The preconditioner is based on the near interaction matrix. The algorithm is parallelized using a combination of MPI and OpenMP. Default settings of the MLFMA algorithm are a box size of a quarter wave length and three accurate digits in the series expansion of the Green's function. In the interpolation of the wave directions to the coarser levels an oversampling factor of 1.3 is used. A general description of the MLFMA algorithm can be found in [4], [5], numerical details concerning the Shako algorithm can be found in [6].

The method has been verified against the commercial code FEKO for the RCS computation of fighter aircraft [7]. For shallow cavities the method has been verified against Method of Moments simulations. Validation against experimental data is underway.

3 Geometry

The delta target is the engine of a generic civilian aircraft. The geometry consists of the first set of rotor blades and the cavity is closed behind the blades. Only the part of the nacelle necessary to cover the cavity is modelled: at a short distance behind the back of the cavity the nacelle is cut off and closed with a vertical plane. In this way the essential features of the engine are retained (for the illumination angles considered later) while keeping the problem size manageable. An impression of the geometry is shown in Figure 1. The dimensions of the engine are as follows: the diameter at the rotor fan is 1.118 m, and the depth of the cavity is 0.91m.

4 Results

A high range resolution profile is essentially a one-dimensional spatial representation of a scattering object along the line of sight. For scattering algorithms operating in the frequency domain, an HRRP is obtained by computing the RCS at several frequencies and subsequently applying a discrete Fourier transform to obtain the spatial information. By the very nature of Fourier transforms, the resolution in the frequency domain determines the spatial extent, also known as range; whereas the frequency extent determines the spatial resolution. In more detail, let Δf be the frequency step, let BW be the band width, and c be the speed of light. Then the range resolution s_r , and the total range s_m are determined by

$$s_r = \frac{c}{2BW}$$

and

$$s_m = \frac{c}{2\Delta f} .$$

For the engines considered in [3] it was decided to use a uniform range of 5 meters, implying a frequency step of 30 MHz, and a resolution of 0.05 m, implying a band width of 3 GHz. The central frequency was set at 2.5 GHz, such that the cavity diameter is in the order of ten wave lengths. HRRP's will be computed for 11 illumination angles, between -10 degrees and 10 degrees azimuth at steps of two degrees. The azimuthal angle is measured in the horinzontal plane through the rotor axis with the rotor axis. For HRRP's, both vertical and horizontal polarization need to be considered in order to compute co-polarisation and cross-polarisation images.

The simulations were performed on a series of three grids. For the frequencies up to 2GHz a mesh with 237537 degrees of freedom was used; for the frequencies up to 3GHz a mesh with 468558 degrees of freedom was used; and for the frequencies up to 4GHz a mesh with 797862 degrees of freedom was used. The meshes have been designed such that at the highest frequency the mesh resolution is about one ninth of the wave length. CFIE is solved with 20% EFIE. An impression of the induced current in the engine is shown in Figure 2.

For each illumination angle an HRRP is computed. Figure 3 shows the HRRP at zero azimuth (at zero incidence with the inlet axis). It is clear from the figure that the three main peaks in the HRRP are caused by the engine rim, the rotor, and the reflection of the rotor in the cavity wall. Figure 4 shows the same HRRP combined with the HRRP's at 10 degrees azimuth and -10 degrees azimuth. The peak at the rim for the zero degrees azimuth HRRP splits into two peaks since the two sides of the rim are now at a different distance from the observer. Also note that the two HRRP's at 10 and -10 degrees are not symmetrical due to the orientation of the blades. This is clearly noticeable from the two peaks of the rotor: the amplitudes of the split peaks of the rotor are different at 10 and -10 degrees.

Simulations are run on sixteen 2.667GHz Intel Xeon cores. Total elapsed simulation time for all computations (101 frequencies, 11 angles, two polarizations) is 871 hours (23 minutes on average per RHS). Note that each frequency can be computed separately from the other frequencies, so they can be executed in parallel without any overhead. Figure 5 shows the computing times as a function of frequency. In general, the computation time increases with the frequency, even when using the same mesh. This is mainly caused by the increase in the required number of iterations (Figure 7). The number of iterations for convergence (at a tolerance of 10^{-4}) varies between 100 for the lower frequencies to 450 for the higher frequencies. On the one hand, the more complicated physics at higher frequencies may explain this increase. On the other hand, the preconditioner used in the computations may not be effective for increasing problem size.

The number of iterations also depends on the number of levels in the MLFMA algorithm, albeit more weakly. The minimum box size depends on the wavelength but the actual box size is a fraction of the domain size, where the fraction is one over a power of two. For a given mesh, increasing the frequency will at first keep the number of levels constant as the actual box size is limited by this power of two. At a certain frequency, the wavelength will be become close to one over a power of two of the domain size, the box size will half and an extra level is added. This frequency can be seen in Figure 6, which displays the memory use as a function of the frequency. When a level is added in the MLFMA algorithm, the memory use drops because the number of near interactions drops suddenly. Remember that in the MLFMA algorithm only the matrix coefficients for the near interactions are stored; the coefficients for the far interaction are computed using the fast multipole approximation and computed at each iteration. As the preconditioner is based on the near interaction matrix, one would expect that the preconditioner becomes less effective at the frequency where there is the sudden drop in near interactions. This behaviour is visible at 2.7 GHz (compare Figure 6 and Figure 7), but less visible at 1.3 GHz; the two frequencies where an extra MLFMA level is added. Note that the increase in number of levels is beneficial for the efficiency of the matrix-vector multiplication in the MLFMA algorithm: even though the number of iterations steadily increase around 1.3 GHz, the elapsed time decreases at 1.3 GHz. This no longer holds at 2.7 GHz, as the number of iterations increases too much.

5 Conclusions and recommendations

High Range Resolution Profiles at realistic frequencies have been computed for a civilian engine inlet. Important geometrical features are visible in the HRRP's. The calculations have reasonable turnaround times. Combining the computing times reported here with the times reported in [7] for a complete fighter aircraft without inlet, it is expected that HRRP's of a fighter aircraft for 4 aspect angles with a band width of 3 GHz (0.05m resolution) in the I-band range can be computed in half a year on the current compute resources of NLR.

Given this estimate it is recommended to improve the computational efficiency of the algorithm. This can be accomplished as follows:

- improve the parallel efficiency;
- improve the performance of the linear solver (reduce the required number of iterations), especially for cavity scatterers;
- investigate the efficacy of time domain solvers;
- apply and improve interpolation schemes to estimate HRRP's for aspect angles close to the computed aspect angles.

References

[1] B. Fromentin-Denozière, J. Simon, A. Tzoulis, F. Weinmann, H. T. Anastassiu, D. Escot Bocanegra, D. Poyatos Martínez, R. Fernández Recio, A. Zdunek, and B. Furnivall, "A comparative study of Radar Cross Section computations and High Range Resolution Profiles for a simplified inlet model", *NATO-RTO SET-160 Symposium on NCI/ATR in Air Ground and Maritime Applications Based on Radar and Acoustics*, Athens, Greece, 11-12 October 2010.

[2] H. T. Anastassiu, *Electromagnetic Scattering from Jet Engine Inlets Using Analytical and Fast Integral Equation Methods*, Ph. D. Dissertation, University of Michigan, Ann Arbor MI 1997.

[3] B. Fromentin-Denozière, J. Simon, A. Tzoulis, F. Weinmann, H. T. Anastassiu, H. Schippers, H. van der Ven, D. Escot Bocanegra, R. Fernández Recio, A. Zdunek, and B. Furnivall: Radar Cross Section and High Range Resolution Profiles for a Selection of Realistic Aircraft Inlets, *NATO-RTO SET-160 Symposium on NCI/ATR in Air Ground and Maritime Applications Based on Radar and Acoustics*, Athens, October 11-12, 2010.

[4] Weng Cho Chew, Jian-Ming Jin, Eric Michielssen, and Jiming Song. *Fast and efficient algorithms in computational electromagnetics*, Artech House, 2001.

[5] C. Gibson, *The method of moments in electromagnetics*, Chapman & Hall, Boca Raton, 2008

[6] H. van der Ven and H. Schippers, Mathematical definition document for the multi-level fast-multipole method, NLR-CR-2010-529,2010

[7] H. van der Ven, Verification of a multi-level fast multi-pole algorithm for the radar-cross section prediction of fighter aircraft, NLR-CR-2010-530, 2010.

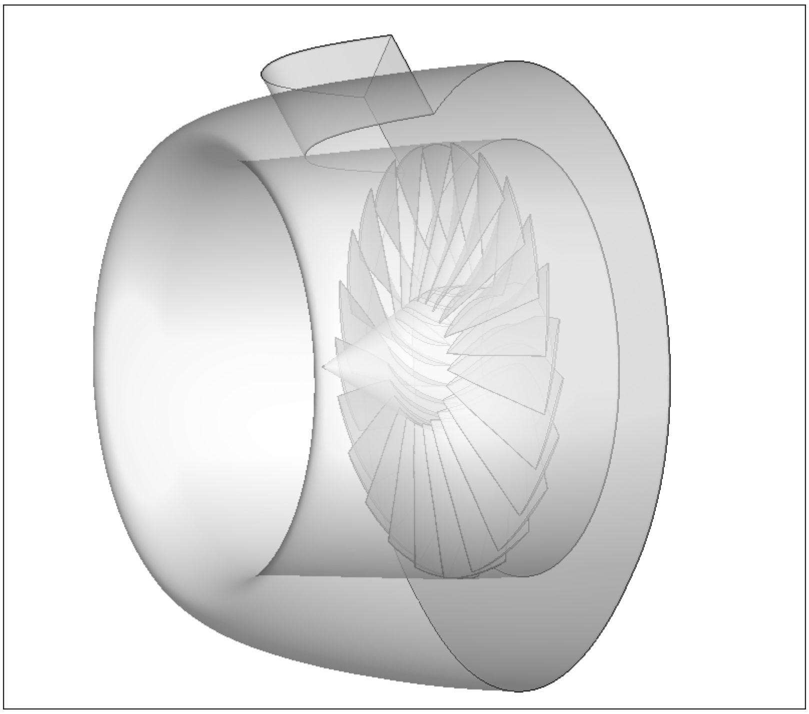

Figure 1 Sketch of the geometry of the "delta" model

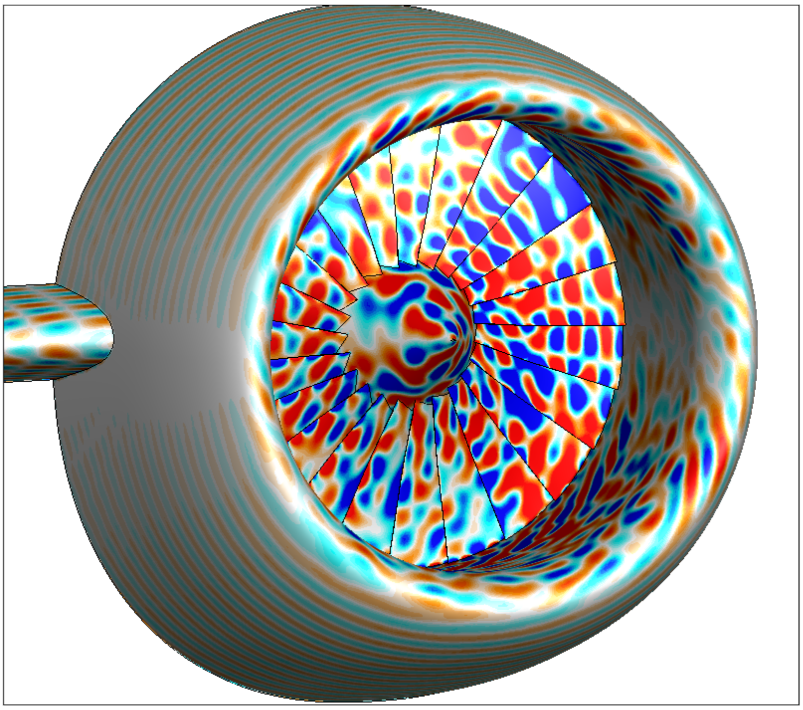

Figure 2 Y-component of the current for an azimuth angle φ=-10° at 4 GHz

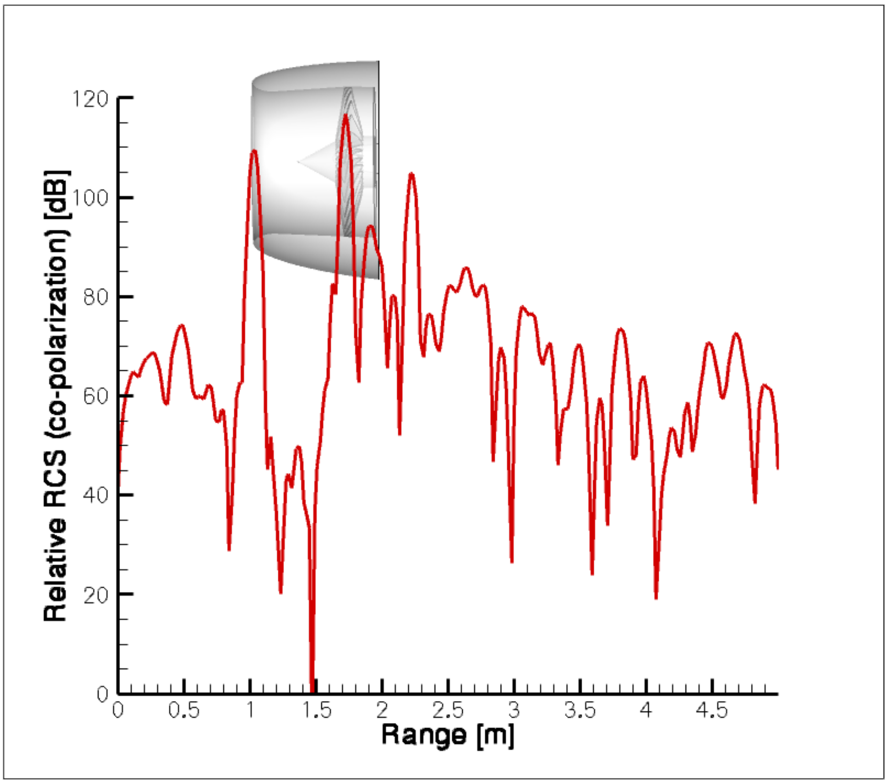

Figure 3 HRRP profile for the "delta" target and VV polarization at frontal illumination angle; with the geometry superimposed

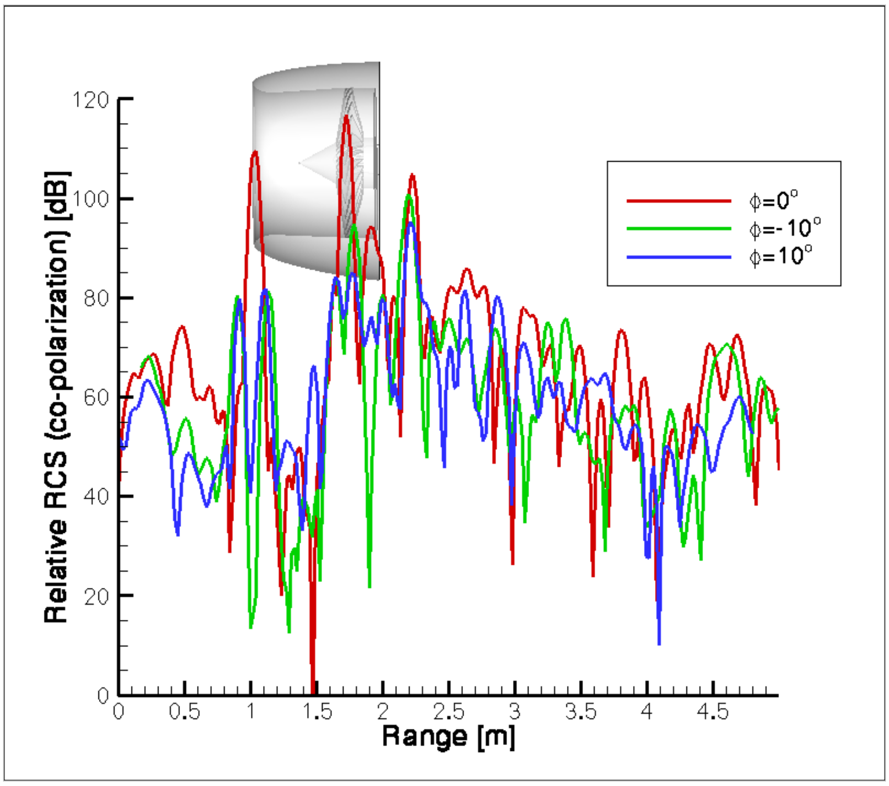

Figure 4 HRRP profile for the “delta” target and VV polarization with the geometry superimposed

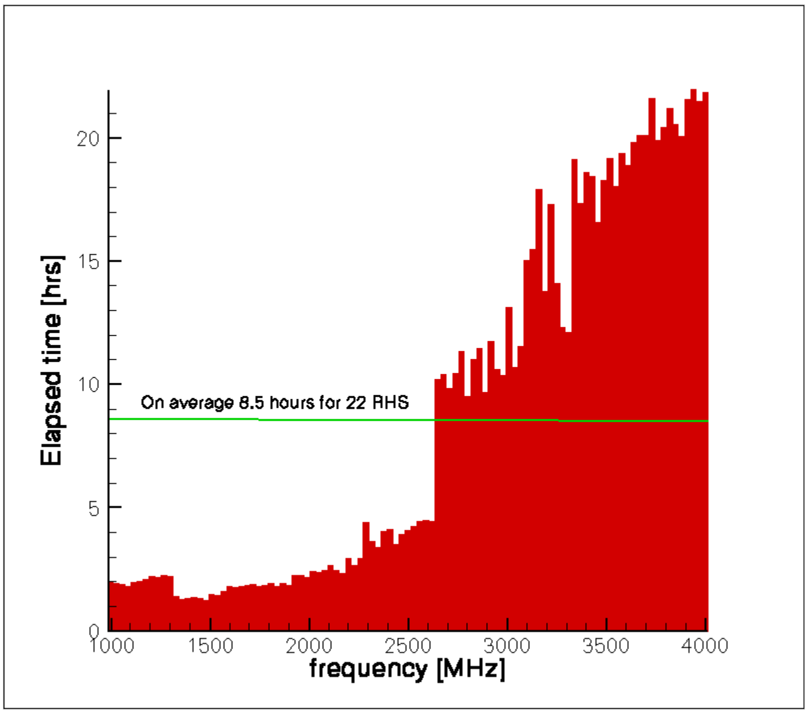

Figure 5 Elapsed computation times as function of frequency

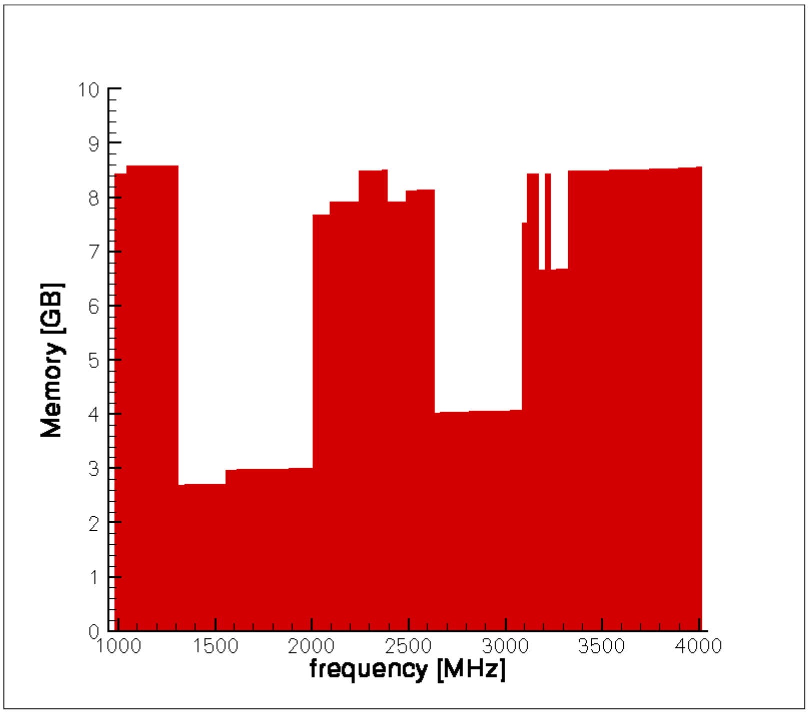

Figure 6 Memory use as a function of frequency

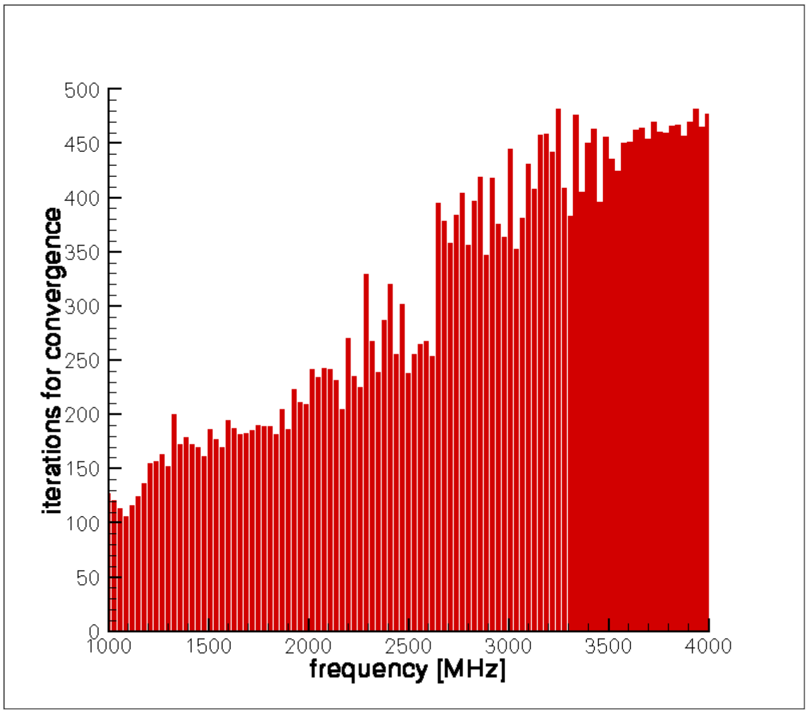

Figure 7 Required number of iterations for convergence as a function of frequency