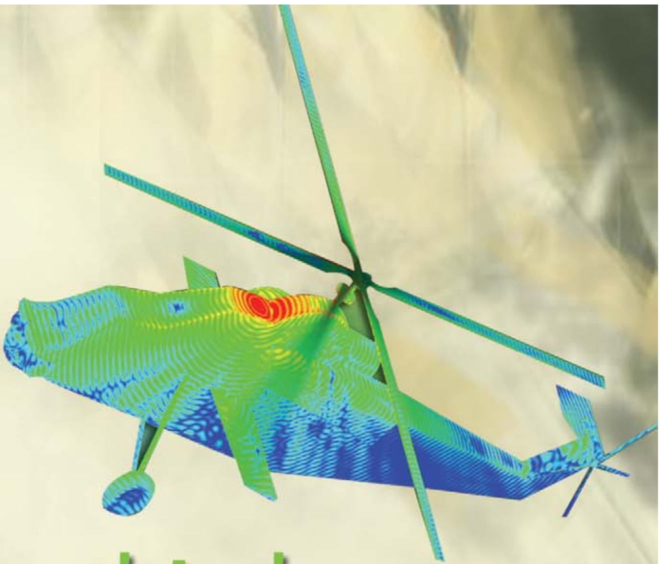

RF Radiation Hazard And Antenna Placement Analysis On Electrically Large Military Platforms

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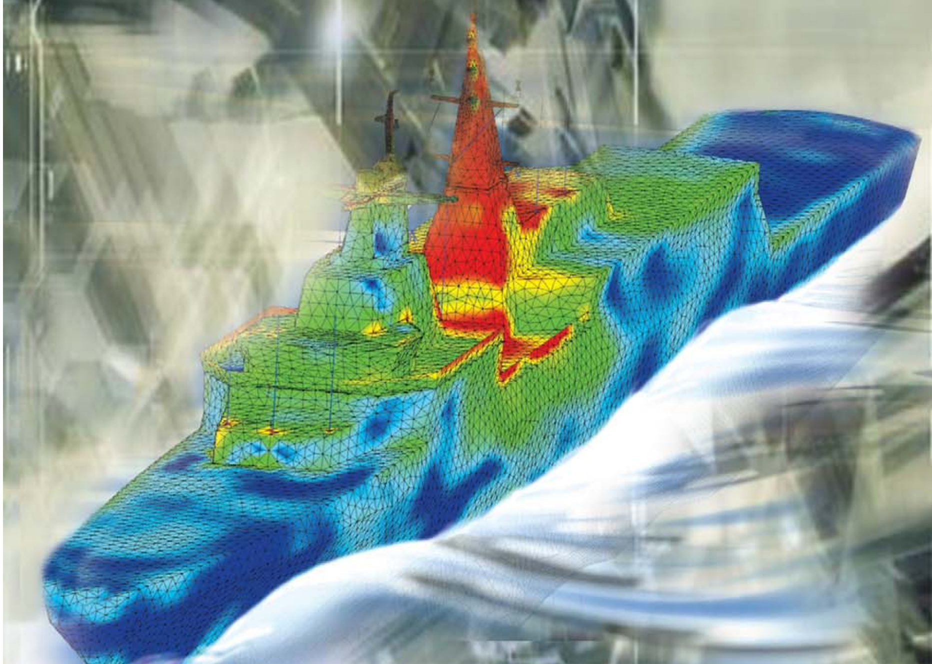


During the design and customization of spatially restricted military platforms, a delicate balance must be struck between maintaining operational specifications and ensuring that RF and microwave systems adhere to electromagnetic (EM) radiation level restrictions. In many instances, sensitive communication systems and armaments must function reliably beside high-power radar and electronic warfare (EW) antennas, while maintaining strict safety standards regarding personnel, equipment, fuel, etc. At RF frequencies, these platforms are typically electrically large (dimensions in the order of hundreds of wavelengths) and represent very large and complex electromagnetic systems.

This paper will explain the difficulties posed by RF radiation hazard assessment and antenna placement analysis on electrically large platforms. It will also explore the concepts on which numerical electromagnetic analysis techniques are based, as well as some of the specific techniques and methods most applicable to antenna placement and RF radiation hazard analysis. In addition, it will demonstrate the capabilities of some computational analysis techniques by application to realistic problems.

Background

There are three tools available to engineers to quantify antenna radiation, coupling, and performance in an operational environment experimental measurements, mathematical analysis, and numerical analysis. Each of these tools has practical limitations that require careful consideration before applying them to problems of the size and complexity typically encountered in large-platform antenna placement and RF radiation analysis.

Direct physical measurement of fields and of the interaction between multiple system antennas in a realistic environment is, of course, the most desirable and reliable tool for any assessment.

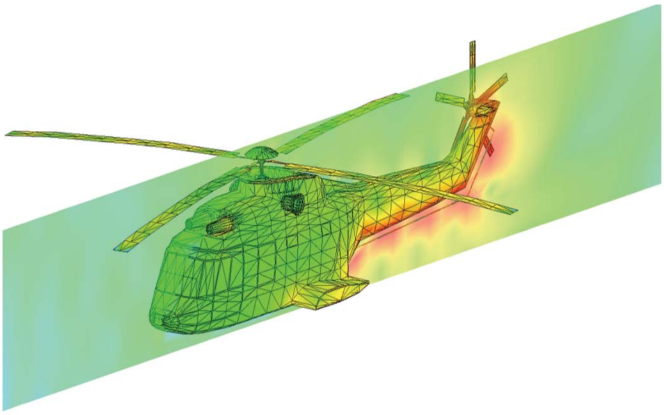


Figure 1: Detailed model of a military helicopter generatedin a computational electromagnetic (CEM) tool.

Experimental measurements are almost always used as final confirmation of analytical or numerical predictions. Coupling between individual radiating structures mounted on an existing or prototype platform is relatively easy to measure, while measurement of far-field radiation patterns and near-field values poses greater difficulties. Characterization of antennas installed on airframes, for example, requires in-flight tests for pattern measurement, which are expensive and allow determination of only roughly sampled patterns (at every 10° or so). If the mounting position of an antenna has to be changed, it may even involve the addition of new mounting holes in the airframe (to the dismay of the aeronautical engineer!).

Any analysis by measurement assumes that physical access to the platform is available and that measurements can be performed using properly mounted antennas. However, this is often impossible during design and prototyping, or for any number of practical or safety reasons. One alternative is the construction of an accurate scale model of the entire platform and all antenna structures for higher frequency representative laboratory measurements. Scaled measurements require considerable effort, and the manufacturing constraints for accurate miniaturization of the structures involved may be prohibitive.

Direct mathematical analysis is only possible in the most simplistic of cases, and conservative approximations are often assumed to reach a solution that is only indicative. Exclusion zones inside which RF radiation levels will exceed permissible exposure levels (PEL) for human or armaments access are, for example, often determined based on analytical reference standards that assume a simple $1/r^2$ drop in the peak radiated power of a spherical plane wave originating at the location of an antenna. Such analytical standards are very conservative particularly when the zones of interest are in the near-field region of radiating antennas. In spatially restricted conditions, basic reference guidelines specifying actual RF field levels and specific absorption ratio (SAR) values may be more appropriate.

To observe these basic reference standards, field measurements in a realistic environment are needed (possibly including measurements inside a representative dielectric body for SAR extraction). Again, these measurements may be very difficult or impossible to perform.

Using commercially available implementations of computational electromagnetic (CEM) techniques, it is possible to consider all interaction between mounted antennas and the entire mounting platform in great detail. The extraction of coupling information and finely sampled radiation patterns as well as the delineation of near-field isosurfaces and SAR values in a totally representative and easily adjusted model of the operational environment is achievable. During and after design implementation, confidence in computational results can be gained by performing only a small set of representative measurements, using computational predictions as a starting point for informed and efficient measurement preparation and planning.

The Foundations of CEM Analysis

CEM methods are based on the numerical solution of Maxwell's laws, which describe and predict the complete electromagnetic behavior of any structure or region given an initial state.

For numerical analysis, it is necessary to create a virtual geometrical representation of the structure of interest and divide this model into a finite number of spatial blocks, or elements. This process is referred to as discretization (depending on the method used, the elements may be 3-D volume blocks or 2-D surface regions). The electromagnetic relations may then be solved (in either a differential or integral form, and in either the frequency or time domain) using numerical integration or differentiation over the discretized region as required. While the relations specified in Maxwell's laws are accurate reflections of electromagnetic behavior, the accuracy of the CEM solution is largely a factor of the error introduced by the sampled numerical solution employed in their resolution. Each of the computational variations (or formulations) that may be used has specific implications in terms of the solution accuracy and computational efficiency.

The most generally encountered CEM formulations, and a representation of where they find widest application, is shown in *Figure 1*.

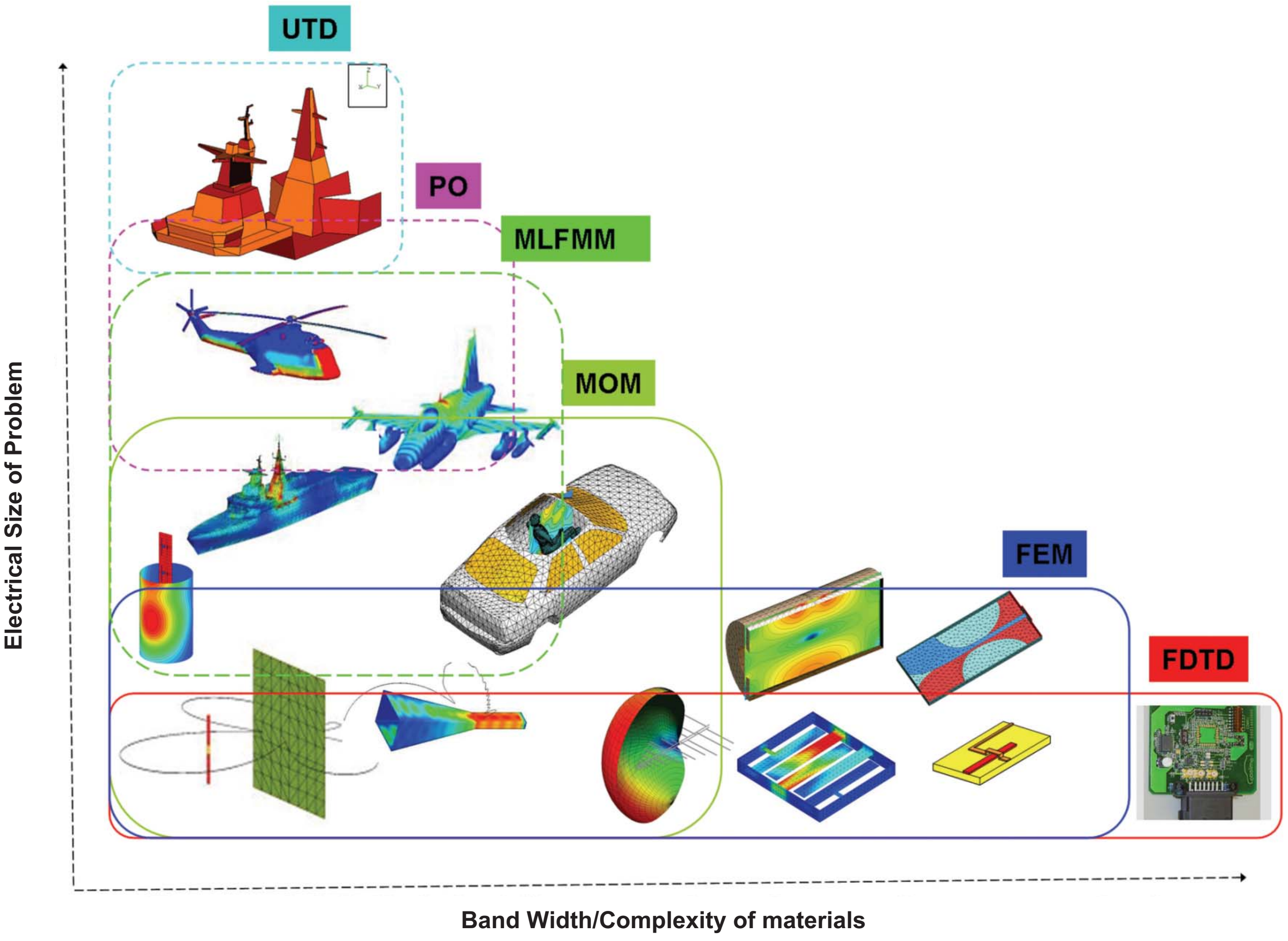


Figure 1: A representation of the main areas of application for CEM formulations.

The major challenge for CEM codes in attempting to provide useful and reliable large-platform antenna placement and RF radiation hazard analysis tools revolves around the resources required to accurately solve problems that encompass spatial volumes of hundreds and even thousands of cubic wavelengths at RF frequencies. The choice of a code should be based on both the applicability of the base CEM formulation used, as well as the availability of complementary techniques that can be applied to improve resource usage.

Techniques Used In RF Radiation Hazard Assessment And Antenna Placement Analysis

A frequency-domain, integral-based CEM formulation, the method of moments (MoM), stands out as the most applicable commercially supported CEM formulation for large-platform analysis. This formulation is well suited to hybridization; where other methods are applied in localized regions. Commercial MoM-hybridized formulations provide the greatest versatility and applicability. Let us consider why integral formulations are more applicable, and the localized hybrid methods that become available for large platform analysis when using the MoM formulation.

Basic Formulations

Differential CEM formulations (e.g. finite difference time domain [FDTD], finite element methods [FEM]) model RF fields directly in 3-D space. This demands the discretization of the entire bounded volume that contains RF fields that may affect, or are of interest in, the analysis. Exceptional resources are required to solve problems that have a large spatial volume at higher frequencies.

Integral formulations like the MoM model RF currents and need only consider portions of the problem where currents flow. Arbitrary field values can then be efficiently derived from the current solution at any point in space as a secondary computational step. This means that integral techniques do not need to apply resources to the modeling of homogeneous propagating space.

Consider the military aircraft shown in *Figure 2*. A 420-cubic-meter box is needed to completely enclose the area around the aircraft in which field values are to be computed. In order to exclusively apply a differential technique, this whole volume will have to be discretized into an average of 1,000 3-D elements per cubic wavelength at the frequency of interest. At 2GHz this translates to

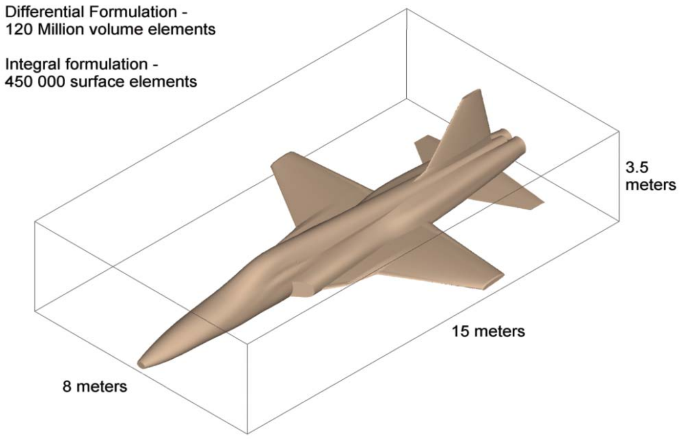
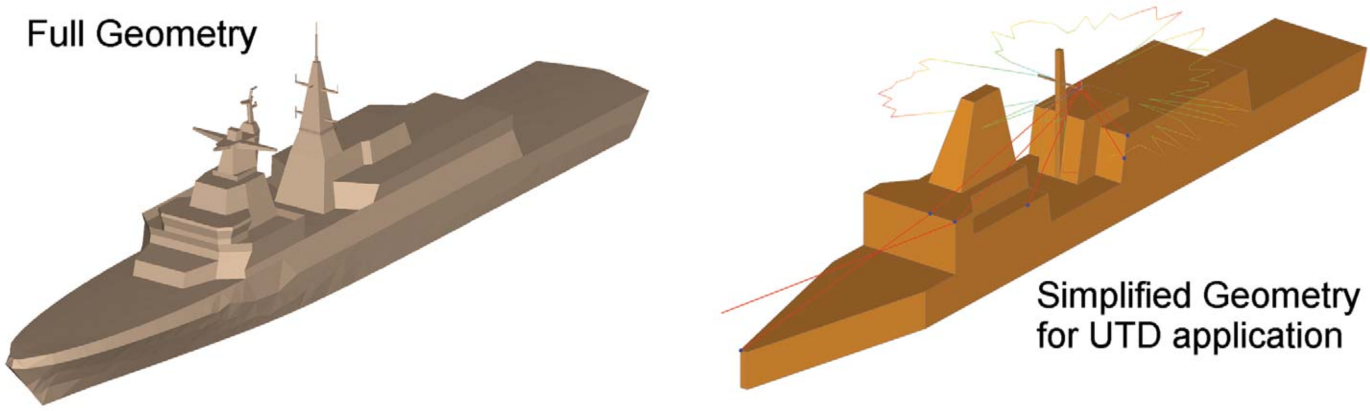


Figure 2: The surface-versus-volume discretization regions for near-field analysis of a military aircraft.

around 120 million volume elements that need to be considered in the computation! The resources required to approach such a problem are considerable. If we consider the same problem using an integral technique, the aircraft surface (100 square meters) would have to be discretized into approximately 120 elements per square wavelength at the frequency of interest. In order to analyze this problem at 2 GHz, the aircraft will thus be divided into around 450,000 elements that must be considered to provide a complete solution.

The per-element resource requirements for differential techniques are far less than for integral techniques. However, for geometries involving large volumes of homogeneous propagation space such as those typically encountered during antenna placement and RF radiation hazard analysis integral techniques can routinely be applied to considerably larger problems than differential techniques. The aircraft used as an example remains a large problem, but can be solved directly with realistic resource requirements using integral techniques.



Necessary geometric simplification of a ship structure for the application of the MoM/UTD (uniform theory of diffraction) hybrid formulation. The approximated radiation pattern of a UHF monopole on the antenna mast, as well as a few of the ray-tracing paths required for UTD-based calculation of far fields, are shown.

There are no commercial implementations of an integral-based time-domain formulation.

Differential formulations do have a role to play, particularly in human RF radiation hazard assessment, were they are most suitable for taking into account localized inhomogeneous dielectric regions like a human. (Integral methods can be applied to analyze multiple and nested dielectric bodies, but are generally less effective than localized differential techniques.) MoM used for efficient free-space field calculations combined with a frequency domain differential formulation (FEM) for direct RF field and SAR computations in localized inhomogeneous dielectric regions therefore delivers a most efficient and versatile CEM tool.

Geometry Reduction And Fast Techniques

Large-platform analysis problems are often too big to be considered with available resources, even if the most effective implementations of full-wave CEM formulations are used. In these cases, complementary methods need to be considered.

The use of partial models (i.e. the exclusion of certain geometries known not to have a significant influence on the results) is often encountered during large-platform CEM analysis. Numerical experimentation is needed to determine which geometry parts can be excluded.

Numerical algorithms can also be used to accelerate CEM solutions and dramatically improve resource usage. The most notable of these so-called “fast techniques” is the Multi-Level Fast Multipole Method (MLFMM) that is applicable to the MoM formulation. By employing fast algorithms like the MLFMM, considerably larger problems can be solved at higher frequencies without any structural or other approximations being required.

There are no commercial fast algorithms currently available for time-domain or for differential-based CEM formulations.

Approximated Formulations

If fast techniques cannot accommodate a problem, approximated formulations may be considered. These approximations involve simplification of both the geometric representation as well as the electromagnetic behavior of the problem and, if applied carefully, can reduce computational resource requirements. The two most common methods used in conjunction with the MoM are physical optics (PO), which computes currents on metallic surfaces based only on the incident field, and diffraction theory

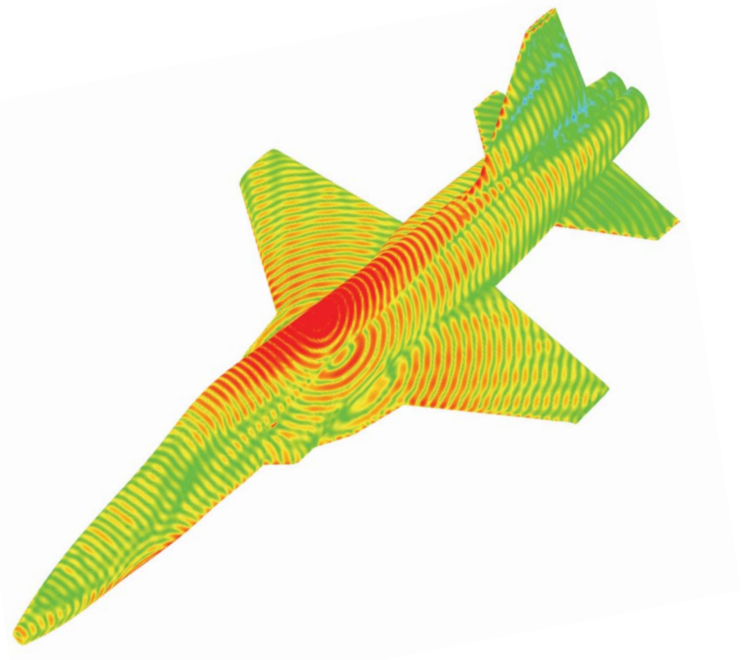


Figure 3a: Multiple-source surface currents and 3-D radiation patterns computed at L-band frequencies for a fighter jet.

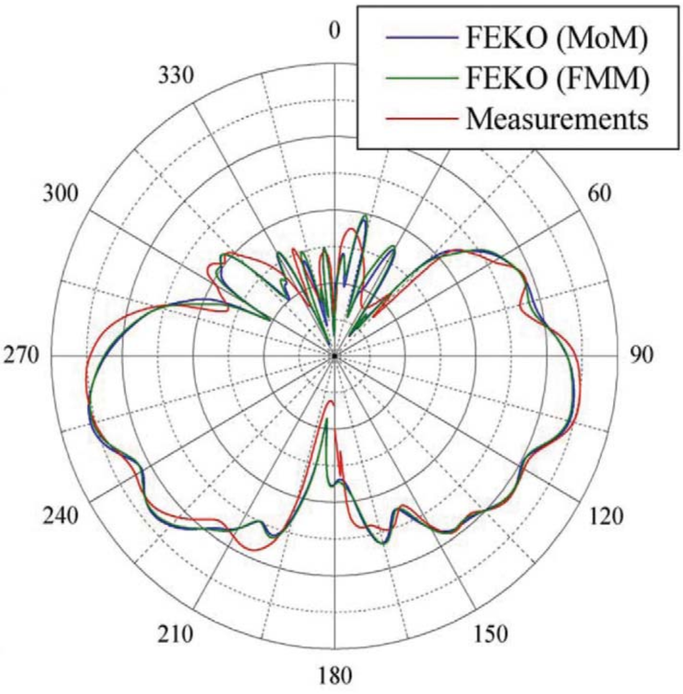


Figure 3b: Comparison between measured and computed patterns for an Lband antenna on an aircraft.1.

(UTD), which considers only ray-based reflection and diffraction from flat, electrically huge metallic surfaces. Both of these techniques are asymptotic frequency-domain formulations and assume that the geometry is electrically very large with respect to simulation wavelength, ignoring lower frequency effects. Application of asymptotic approximations (particularly UTD) places limitations on geometrical structure and can dramatically reduce solution accuracy. The magnitude of these effects should be confirmed by numerical experimentation.

Approximated formulations are most effectively applied as part of a hybrid technique that includes accurate, full-wave solution on and in geometrically accurate regions around radiating structures, while applying the approximations to regions that are electrically far from radiating structures.

Representative Computational results using FEKO
FEKO is a MoM-based CEM tool that provides the functionality required for antenna placement and RF radiation hazard assessment. Methods including FEM, MLFMM, UTD, and PO are implemented in hybrid formulations with the MoM, providing access to powerful tools generally applicable to large-platform analysis.

Antenna Coupling and Radiation Patterns for Military Aircraft
Figure 3a shows surface currents and 3-D radiation patterns for a fighter-jet computed at L-band frequencies using FEKO. MLFMM in the MoM was employed for this computation. Measured radiation patterns agree very well with both the direct MoM and the MLFMM-accelerated MoM CEM solutions for an L-band air traffic control antenna mounted on a larger aircraft as shown in *Figure 3b*. For this case, the classical MoM solution required 8.5 times more memory resources, and 5 times longer run-time than the MLFMM-accelerated case

.RF Radiation Exclusion Zones and SAR calculations on Military Ships
Figure 4 illustrates currents, near-fields, and isosurfaces computed and displayed for a helicopter-mounted antenna at UHF frequencies. The detailed ship and helicopter model are considered completely in the delineation of the displayed boundary of an exclusion zone for the applicable PEL. Arbitrary near-field cuts can easily be computed as shown. MLFMM in the MoM was again used for this analysis. The time and resources required for delineation of such a 3-D exclusion zone by measurement would be extreme. Computational results for antenna coupling on ships have been shown to compare very well with scaled measurements.

Figure 5 shows an inhomogeneous human phantom used to compute near field and SAR values during illumination by a high-power communications array at GHz frequencies. The use of the MoM/FEM hybrid technique was employed here. This technique allows for placement of the phantom in any position relative to radiating structures without increasing resource requirements.

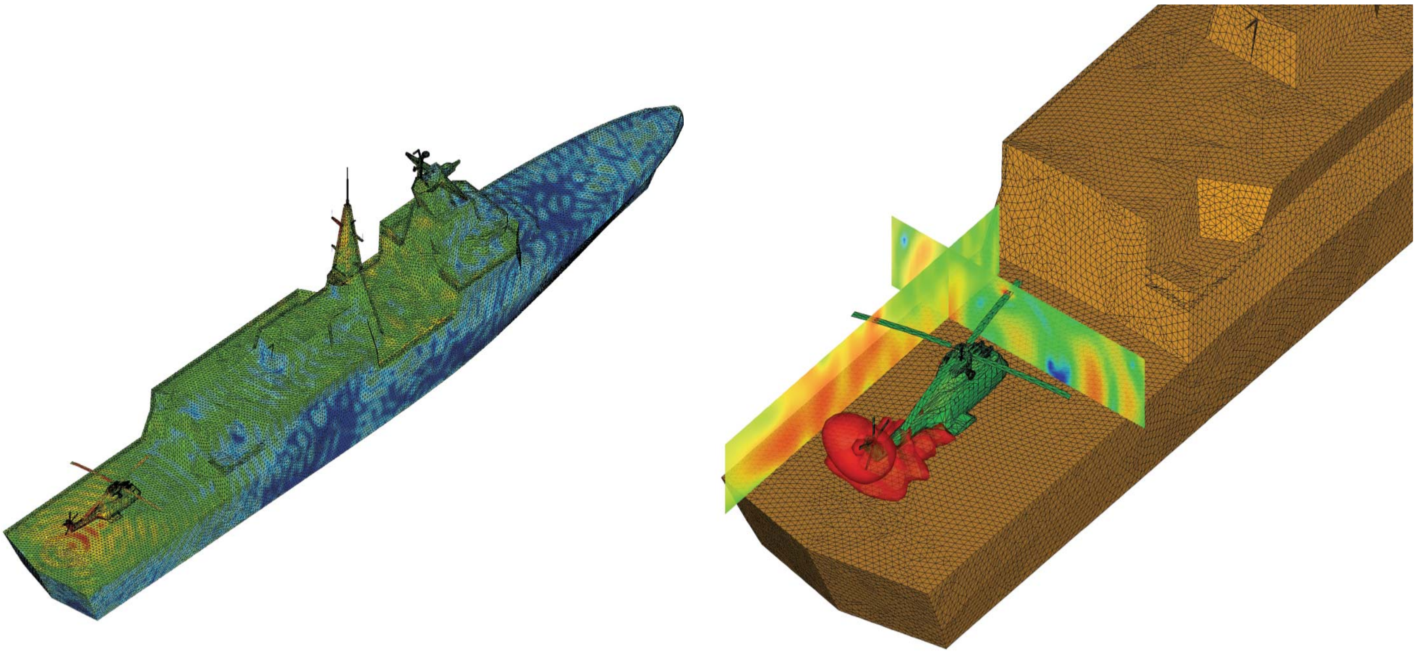


Figure 4: Computed UHF frequency surface currents, radiated near fields, and 3-D exclusion zone for a helicopter landing on the deck of a ship.

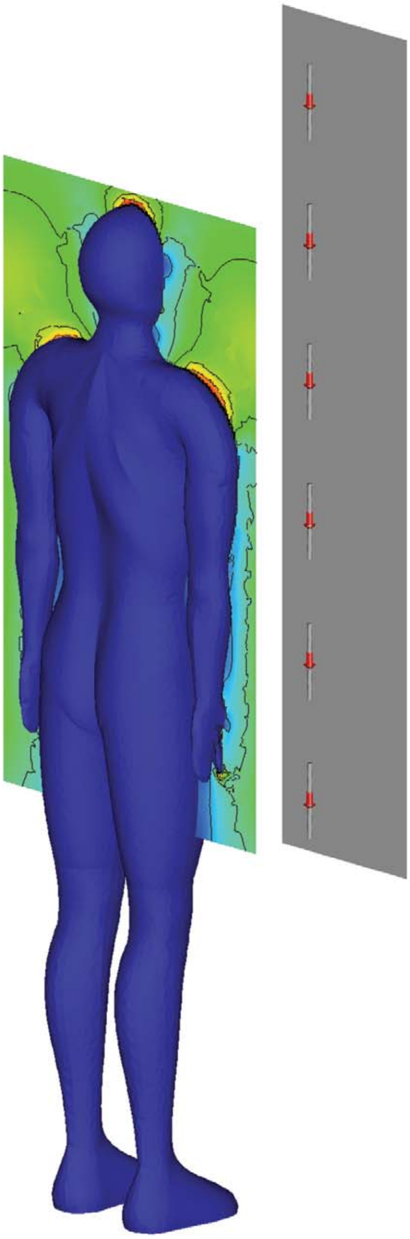


Figure 5: RF fields computed for an inhomogeneous human phantom located near a high-power communications antenna using the MoM/FEM hybrid technique.

Quantified Computational Capabilities

It is very difficult to absolutely quantify the general resource requirements for CEM solution for problems relative to physical size. Resource requirements are influenced by many things, including the frequencies of interest, the applied formulation, complementary techniques used, and a host of factors in the specific methods employed during coding of the numerical routines.

Basic Formulations

In general, resource predictions for classical full-wave techniques are determined based on the number of computational elements, as this number takes both the physical problem size and the solution frequency into account. Unfortunately, the scaling of the resources with respect to the number of computational elements is not linear, but rather close to quadratic or even cubic!

Differential formulations require far less per-element resources than integral techniques, and problems with 3-D element numbers in the order of hundreds of thousands can be solved on a modern desktop PC. Element numbers for 3-D discretization are, however, very sensitive to the bounded computational volume. When problems exceed the resources of a single PC, parallel solutions must be considered.

Integral formulations can be used to solve problems with 2-D surface element numbers in the order of thousands on an average desktop PC before parallel computations, fast techniques, and approximate hybridized techniques become necessary. Element numbers (and therefore also resources) do not scale with the computational volume, but rather with surface Area.

This typically allows consideration of a complete ship structure at several MHz (the actual frequency depends on hardware, RAM, number of processors, etc.). Higher frequency analysis is possible if accelerated and approximated formulations are applied.

Fast Techniques

The application of fast techniques like the MLFMM is possible in the MoM formulation, and does not require advanced knowledge of CEM theory. MLFMM can be applied to any general MoM problem. Typical memory usage for the un-approximated and the MLFMM-accelerated MoM technique for representative military aircraft and ship problems discretized at specific frequencies are shown in *Table 1*. Solution times depend on the number and type of processors used.

Hybrid techniques and Approximations

The resource implications of the application of MoM/FEM, MoM/PO and MoM/UTD hybrid solutions can be predicted only by the direct consideration of a number of geometry-specific factors. The memory requirements in a PO region are roughly proportional to the number of elements in the region (a good rule of thumb is about 370 bytes per element). Requirements to consider the PO-MoM coupling depend on the number of MoM and PO elements

Author's profile

Brian Woods holds B.Eng*(cum laude)* and MScEng*(cum laude)* degrees from the University of Stellenbosch, South Africa in Electrical and Electronic Engineering. He has worked as a full-time researcher at the University of Stellenbosch, focusing largely on the development and analysis of advanced radar technologies. During this period, Brian was also involved in the design, development and commercialization of Ground Penetrating Radar Systems for GeoMole SA, where he obtained experience in the design and implementation of electronic hardware and antennas, as well as in system engineering and production.

Brian joined the EM Software and Systems team in January 2006, where he is currently involved in product support for the North American region and in FEKO applications development.

EM Software & Systems-SA (Pty) Ltd (www.emss.co.za) provides specialist consulting in electromagnetic simulations, using the CEM code FEKO (www.feko.info), which is also developed by the company.