Electromagnetic Problems and Numerical Simulation Techniques

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Abstract: - In this paper, examples of current electromagnetic (EM) problems and available numerical modeling techniques are reviewed. These techniques include the Finite-Difference Time-Domain (FDTD), Transmission Line Matrix (TLM) and the Method of Moments (MoM).

Key-Words: - Computational Electromagnetics, Numerical Simulations, FDTD, TLM, MoM
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1 Introduction

Computer techniques have revolutionized the way in which EM problems are analyzed. EM engineers rely heavily on computer methods to analyze, for example, complex antenna systems, planar microwave devices, EMC/EMI (compatibility and interference) problems, etc. A number of different numerical techniques for solving these EM problems are available. They are mostly based on full-wave analysis, either in the time or frequency domains, where one or two differential equations plus problem-specific boundary conditions are of interest. Each numerical technique is well suited for the analysis of a particular class of EM problem.

EM engineers must be very careful in applying these pure numerical techniques. Although they are powerful and can be applied to variety of EM problems, their output may frequently mislead or be misinterpreted. As long as there are no numerical errors such as *overflow* or *underflow*, computers always give numbers as solutions. The problem is whether these numbers correspond to *real physics* of the problem at hand. EM engineers must always be aware of the assumptions made in the numerical technique that is being used. Under what conditions is this technique derived? What kind of a problem or problems can be handled via this technique? Are there any parametric limitations? What are the accuracy and numerical error limits? Without knowing the answers of these questions it is very dangerous to use these techniques.

Here, three well-known techniques, FDTD, TLM and MoM, are reviewed and applied to variety of important EM problems. Each EM problem is handled via one or two of these techniques so that the results can be compared with each other. The examples presented are listed below together with the most suitable numerical techniques:

- Waveguide analysis (FDTD and TLM)
- EMC/EMI Modeling (FDTD and TLM)
- Cellular phone–human head interaction in terms of biomedical effects and antenna performance (FDTD)
- RCS Modeling (FDTD and MoM)

2 Numerical Techniques in EM

FDTD and TLM are time domain techniques, which have been used for more than a decade. MoM is a frequency domain technique and has been used for nearly thirty years. All three techniques are widely used and well understood. Therefore, only some of their practical aspects are mentioned in this section.

2.1 FDTD Method

This method is based on the discretization of Maxwell' s two curl equations directly in time and spatial domains and dividing the volume of interest into unit (Yee) cells [1]) as shown in Fig. 1.

In applying the FDTD method the following observations should be taken into account:

- The physical volume is subdivided into small cells.
- There are three electric and three magnetic field components in each Yee cell distinguished by (i,j,k) label. The time and spatial discretization steps are Δt and Δx, Δy, Δz, respectively.
- Although field components in each cell are labeled with the same (i,j,k) numbers (such as $E_x(i,j,k)$ or $H_z(i,j,k)$), their locations are different (see Fig.1).
- There is a $\Delta t/2$ time difference between E and H field components in the cell.

- Any object may be simulated by the medium parameters ε, μ, σ.
- Although electric and magnetic field components are updated during the time simulation, voltages and currents in (i,j,k) cell are obtained directly from Gauss and Faraday laws.
- Applying effective absorbing boundary simulations allows open region analysis (e.g., antenna and RCS analysis).
- Narrow and broad band responses may be readily obtained via FDTD simulations.

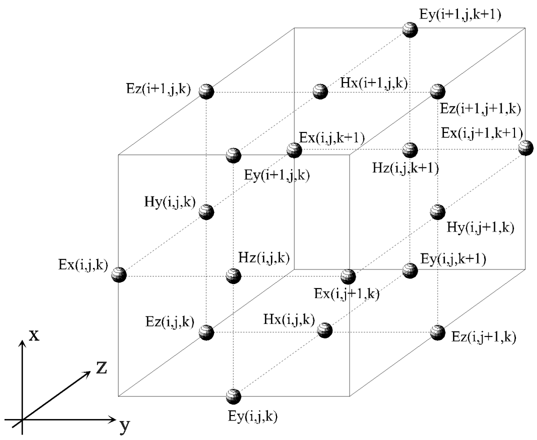

Fig.1: FDTD unit cell in rectangular coordinates

2.2 TLM Method

The TLM [2] is another time domain technique. The Symmetrical Condensed Node (SCN) is the most common version, where the unit cell is reconstructed to overcome asymmetry and asynchronous problems. The SCN-TLM cell for a homogeneous medium is given in Fig.2.

For simulations using the SCN-TLM, these points must be taken into account:

- The TLM method is based on the network theory where voltages and currents are the independent observation parameters.
- The physical environment is sub-divided into small cells as shown in Fig.2. Each cell is distinguished with (i,j,k) label. The label (n) is used to represent the current simulation time. As a result, V(x,y,z;t) is replaced with V(i,j,k;n), where $x= i\times\Delta x$, $y= j\times\Delta y$, $z= k\times\Delta z$ and $t=n\times\Delta t$.
- The total simulation volume extends from (0,0,0) to (X,Y,Z) which is subdivided into $N_x\times N_y\times N_z$ nodes where $\Delta x=X/N_x$, $\Delta y=Y/N_y$ and $\Delta z=Z/N_z$.
- In any direction, the propagation is simulated via two pairs of transmission lines, which do not couple with each other (these transmission lines are totally separated in space).
- Between the nodes, time domain propagation is simulated via the connection of incident and reflected pulses by the scattering matrix. The scattering matrix [S], relating the reflected voltages, V^r to the incident voltages, V^i is a 12×12 matrix for the node structure given in Fig.1, but becomes 18×18 to model any inhomogeneity in the medium of interest[2].
- Lossy structures can be modeled by 21×18 scattering matrix.
- The medium parameters, ε and μ are modeled by open- and short- circuited stubs with the lengths of $\Delta\ell/2$. But, σ can be modeled by infinitely long (matched terminated) stubs[2]. One extra stub per electric field component is necessary for lossy dielectric. The total number of ports is therefore 21.
- Twelve pulses incident upon the node via the link transmission lines, produce 12 reflected pulses. The incident and reflected pulses appear on the terminals of the transmission lines at ports which are numbered and directed according to the voltages shown in Fig. 2.
- 12 voltage pulses given in Fig. 2 describe the Electric and magnetic field components. For example, the pulses contributing to the E_x field are at ports 1, 2, 9 and 12.

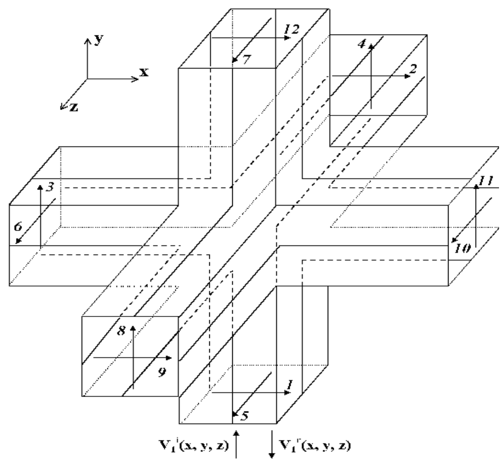

Fig.2: SCN-TLM cell in rectangular coordinates

2.3 MOM Technique

One of the most powerful techniques in the frequency domain is the MoM [3]. The primary formulation of MoM is an integral equation obtained through the use of Green's functions. The technique is based on solving complex integral equations by reducing them to a system of linear equations and on applying *method of moments* (*weighted residuals*).

All *method of moments* techniques begin by establishing a set of trial solutions with one or more variable parameters. The *residuals* are a measure of the difference between the trial and the true solutions. The variable parameters are determined in a manner that guarantees a *best fit* of the trial functions based on a minimization of the residuals.

Depending on the form of the integral equation used, MoM can be applied to

- conductors only,
- homogeneous dielectrics only, or
- very-specific conductor-dielectric

configurations. MoM techniques do an excellent job of analyzing a variety of important three-dimensional radiation and scattering problems. General purpose MoM codes are particularly efficient of modeling wire antennas or wires attached to large conductive surfaces. MoM techniques applied to integral equations are not very effective when applied to arbitrary configurations with complex geometries or inhomogeneous dielectrics. Two typical discrete MoM models are pictured in Fig.3.

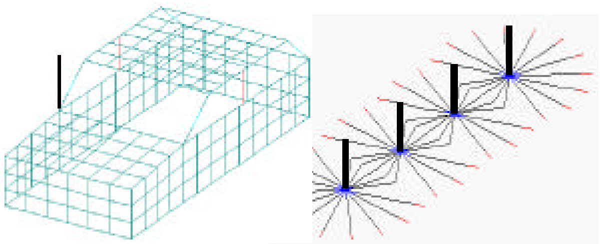

Fig.3: Typical wire-grid models for (a) a vehicle antenna (b) a quadlet array over ground screen

In Fig.3, a vertical wire antenna over the body of a car and a monopole quadlet (four vertical wires) with a ground screen are presented. These two examples are too complex to handle via analytical solutions. Structures such as shown in this figure can easily be modeled via MoM. Major limitations in MoM are the number of segments and diffraction effects.

3 EM Applications

In this section, characteristic examples modeled via these three techniques are presented.

3.1 Waveguide Analysis

Time and frequency domain modeling of wave propagation through rectangular waveguides is a complex problem. The waveguide acts as a high-pass filter, where the cut-off frequency depends on the cross-section. Its frequency characteristics may be controlled via thin capacitive or inductive irises as shown in Fig.4. Here, the time domain pulse propagation through an X-band rectangular waveguide (near cut-off) and the tuning effects of different inside discontinuities are simulated via the FDTD and TLM techniques [4]. In Fig.5, time variation of a Gaussian pulse in an empty waveguide (having 3dB bandwidth of 2GHz around f_0=10GHz center frequency) is plotted.

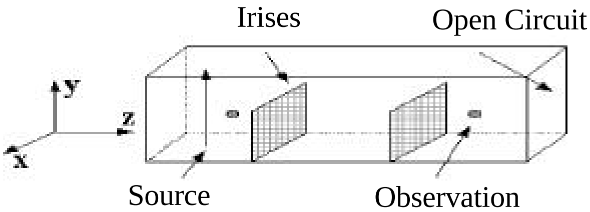

Fig.4: Rectangular waveguide model used in FDTD and TLM calculations

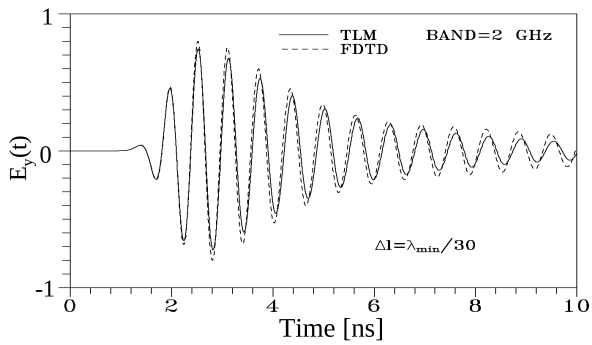

Fig.5: Time variation of a narrow duration pulse around waveguide cutoff

The frequency content of this pulse extends from DC up to 20GHZ (for %10-amplitude degradation). Therefore, components below cut-off (approx. 7.5GHz) do not propagate and diminish within a few wavelengths. On the other hand, multiple reflections occur among the walls of the waveguide. These effects are presented in Fig.5. Trials showed that at least λ_{min}/30 spatial discretisation is required to obtain good agreement between the two techniques. The effects of the two irises placed inside the waveguide (see Fig.4) are given in Fig.6.

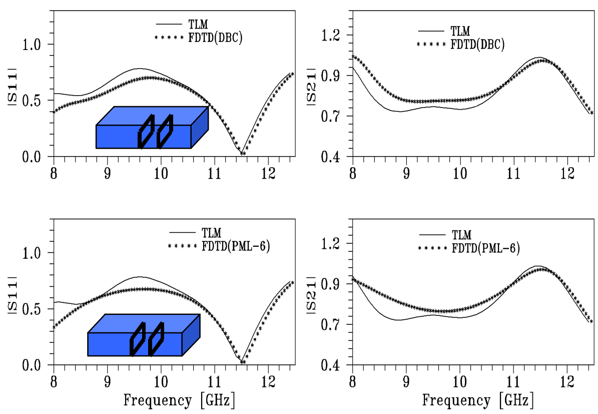

Fig.6: S-parameters calculated via FDTD and TLM

Here, the frequency variations of the S-parameters are calculated via time domain simulation [4]. As shown in Fig.6, the irises control transmission characteristics of the waveguide.

3.2 EMI Modeling

Parallel to the increase in the number of electronic devices that we use, EM Interference (EMI) has become a major EM engineering discipline. Almost all of the EMI problems are extremely complex in nature, and can only be handled via pure numerical techniques. Here, a typical EMI problem is modeled via both FDTD and TLM techniques.

A rectangular box having apertures on its different faces is modeled [4]. Its shielding effectiveness (SE) for a desired frequency band is calculated. SE is the measure of isolation, which can be calculated in two steps:

- First, the field, E(t) of a source inside the box, is calculated at a point across the aperture (outside).
- Then, the box is removed and the same procedure is repeated. The free-space field, $E_0(t)$ is obtained.

The ratio (i.e., $20\log_{10}[(E_0 / E]$, dB) in the frequency domain gives the SE(f) of the rectangular box. If the source is a pulse, then $E_0(t)$ and E(t) are pulse responses, where broad band SE behaviors can be obtained via discrete Fourier transforms. A typical result is plotted in Fig.7.

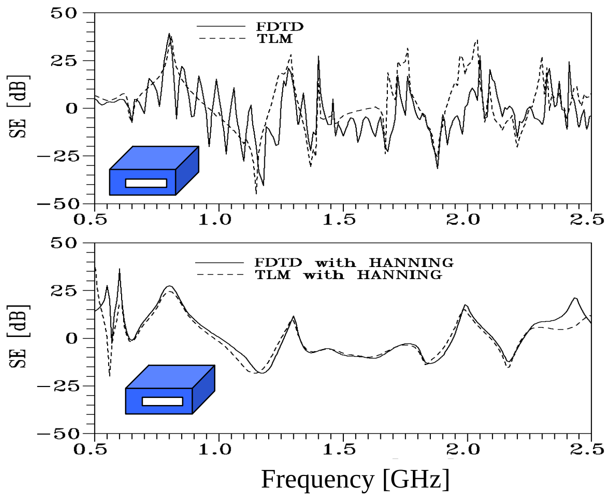

Fig.7: SE versus frequency of a box with aperture

Simulations with pure numerical techniques require great care. This is clearly observed in Fig.7. Here, first, the results of two techniques are directly plotted (top figure). Then, the simulation data is filtered with a Hamming window and plotted again (bottom figure). Because of the ringing effects [4] inside the box, a very long simulation period is required in the time domain. That is the main reason of poor agreement in the first plot. Using long simulation periods in FDTD and TLM is very time consuming. Therefore, instead of this, windowing is applied before Fourier transform to suppress aliasing effects. This example indicates that pre and/or post processing of simulation data may be required in order to obtain reliable results.

Once the algorithm is built and tested, any kind of geometry can be handled via these techniques. This is shown in Fig.8, where the results of SE analysis for multi-aperture cases are presented.

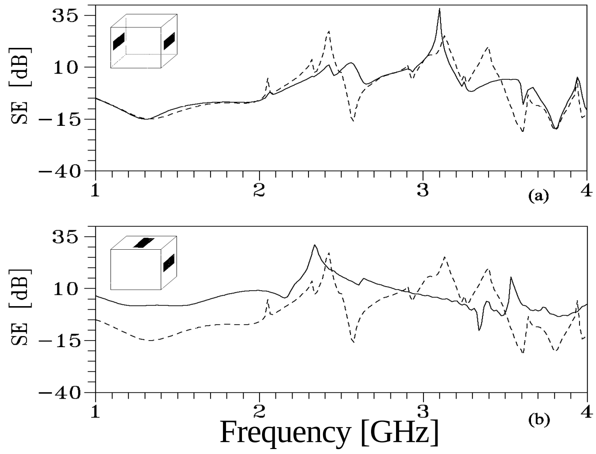

Fig.8: SE versus frequency of a multi-aperture box (solid: multi-aperture, dashed: single-aperture)

3.3 Human Head –Mobile Phone Interaction

Mobile phone-human interaction is another current EM research topic[5-6]. It is important from both human health and antenna performance points of view. A typical FDTD simulation of human head-mobile phone interaction is pictured in Fig.9.

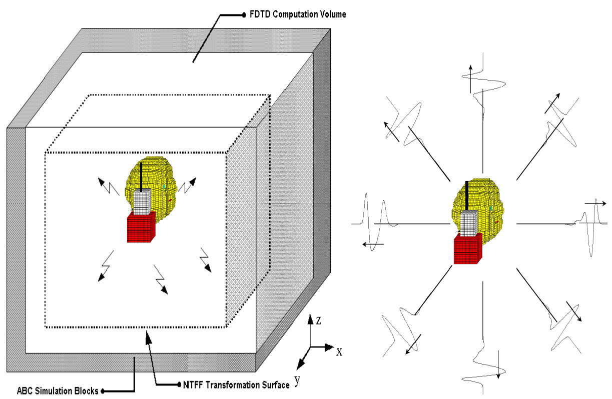

Fig.9: FDTD computation volume and far field extrapolation from the simulated near fields

Total field FDTD code is used in these simulations. The simulation procedure is as follows:

- A discrete model of human head and mobile phone is located inside the FDTD volume and near fields are simulated.
- Radiated power is calculated by applying the surface integration of Poynting vector over a virtual surface.
- Absorbed power is calculated by applying a volume integration of lossy cells (i.e., $\sigma|E|^2$)
- Far fields are extrapolated in time-domain via near-to-far field transformation routines [5].
- Frequency behaviors and radiation patterns are obtained via off-line DFT analysis plus cartesian-polar transformation.

A typical example related to power simulations is plotted in Fig.10. The transient effects and the steady-state regime (which is reached after 4-8 periods) in FDTD volume is clearly observed in the figure.

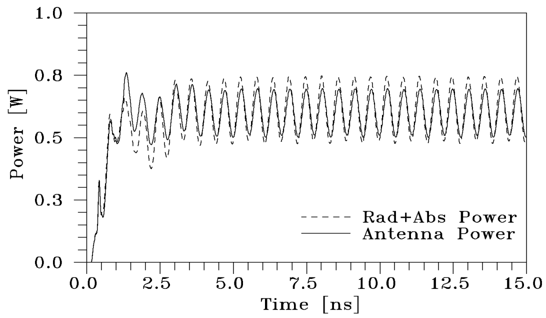

Fig.10: Radiated and absorbed powers versus time

Fig.11 and 12 illustrates performances of two different mobile phone antennas [5].

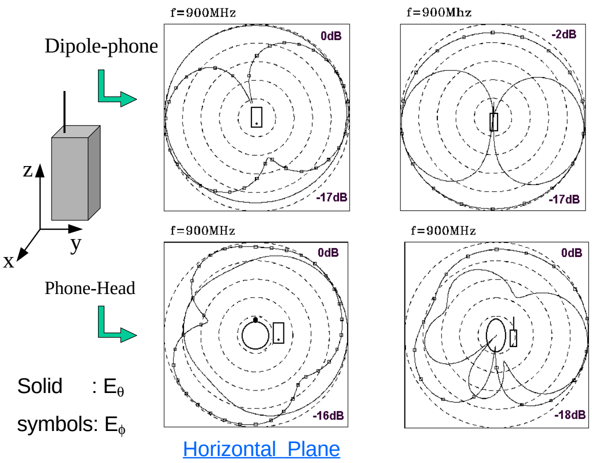

Fig.11: Vertical and horizontal radiation patterns of a quarter-wavelength monopole

As shown in these figures, broad-band antenna characteristics (e.g., voltage, current, power, impedance, gain, radiation patterns) can easily be obtained via a single time domain simulation.

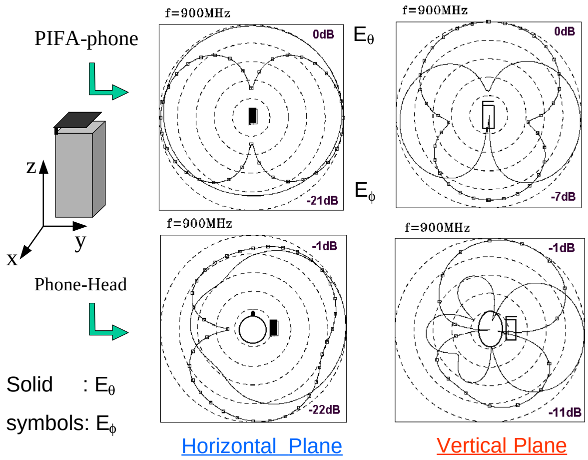

Fig.12: Vertical and horizontal radiation patterns of Planar Inverted F-antenna (PIFA)

It should be noted that, biomedical modeling via these techniques is very difficult. Only Specific Absorption Rate (SAR) of human tissues can be calculated [5]. SAR is a measure of EM energy converted into heat in tissues. Discrete tissues are modeled with their electrical parameters (σ and ε_r), which are supplied by EM measurements. Different EM groups use quite different values. There is also discrepancies among the limits of SAR values declared to be safe by the international health organizations. Simulation results must therefore be carefully analyzed when human health is the concern.

3.3 RCS Modeling

Electromagnetic reflectivity of objects is another major subject area that uses pure numerical techniques. Here, examples are given related to RCS modeling of different targets. The FDTD and MoM techniques are used and their results are compared. In both FDTD and MoM, scattered field based representations are used. Targets are modeled as discrete blocks and as wire meshes in FDTD and MoM, respectively. They are located inside the computation volumes, far fields are obtained all around and mono and bi-static RCS patterns are obtained.

The first example is given in Fig.13. Here, bi-static RCS patterns of a metallic rectangular prism are plotted at different frequencies. Its longest dimension is l=30m (10m×30m×10m) and is illuminated by a vertically polarized EM wave. The illumination is chosen in such a way that that E field is parallel to one of the edges.

It is easy to calculate RCS of complex geometries via these techniques at low and medium frequencies but extremely difficult at high frequencies. As the frequency increases, the number of cells in FDTD and number of wire meshes in MoM for the discrete models increases drastically. Nevertheless, these techniques are especially *good* for RCS modeling in the *resonance regi*me, where the wavelength and target size are in the same order.

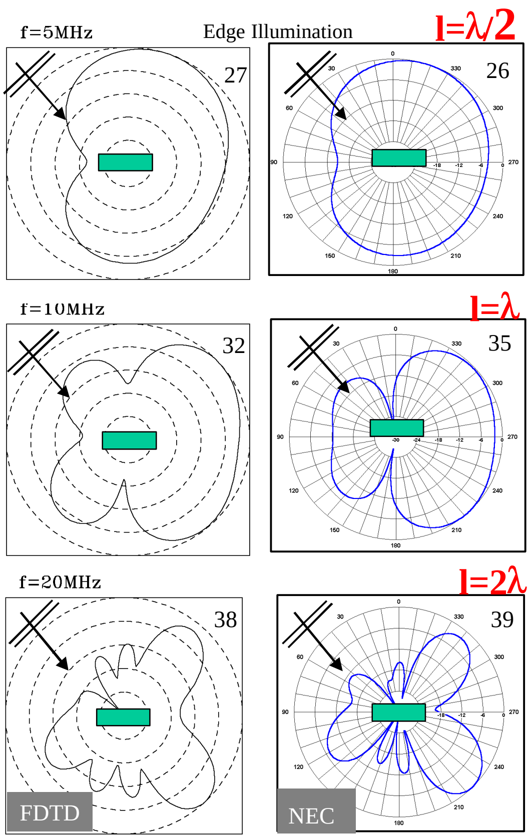

Fig.13: Bi-static RCS behaviors at different frequencies

Frequency variation of the backscatter RCS of this test object is plotted in Fig.14 for the illumination mentioned in the figure. Better agreement between MoM and FDTD results can be obtained if parameters are optimized. Once the parameters are optimized and the limitations and accuracies are tested, any object or group of objects can be used as a target. Then, not only isolated RCS behaviors, but also mutual RCS interaction can be calculated.

4 Conclusion

Examples of current electromagnetic research topics analyzed via powerful numerical techniques, are discussed in this study. The attention that must be paid during the numerical simulations is discussed.

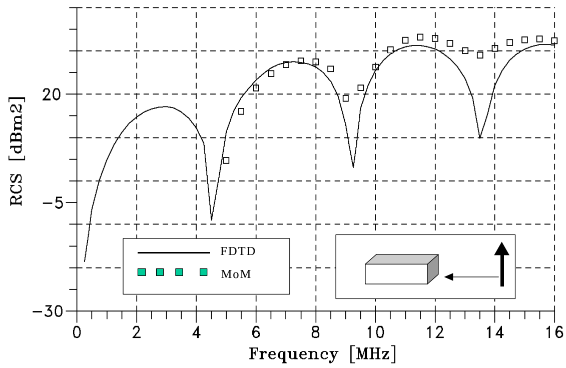

Fig.14: Backscatter RCS versus frequency of a the test target.

Although limited with only idealized geometries, analytical solutions are very important to understand the physics behind the problem at hand. It is only then possible to use pure numerical techniques in analyzing complex EM problems.

The state-of-the-art in numerical modeling is progressing rapidly. On the other hand, practical EM problems are also becoming more and more complicated. It is, therefore, essential that EM engineers should

- have strong analytical background
- use numerical as well as analytical techniques

at the same time.

Finally, it may be concluded that the trend in numerical simulation techniques is towards using some hybrid forms of analytical approximate and numerical methods.

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