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Multi-Scale Simulation Tools For VLF Antennas

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Abstract

Simulations of Very Low Frequency (VLF) antennas are historically performed by using the Method of Moment. The recent developments of thin wire model in Finite Difference Time domain techniques provide attractive tools for simulating VLF in real environment. Test simulations are reported in this paper in order to highlight the advantages and the drawbacks of each method implemented in different software.

1. Introduction

The ability to send order to submerged submarines is one primordial aspect in the defense structure of the most developed countries. VLF bandwidth provides a very long range and a few meter skin depth in water, allowing communication with a submerged and stealthy antenna. The main drawback is the difficulty to study and the size of the antenna systems required.

The systems are composed from several hundreds of meter miniature antennas, powered with hundreds of kilowatts. Their location was judiciously chosen for their [mechanical support, infrastructure] and electromagnetic interest. Most of the actual systems were built during the cold war, without the benefit from computational simulation. Using actual techniques could help us to design new compact and/or efficient VLF antennas.

The simulations of a VLF antenna have some particularities that make them difficult to achieve. The structures are really thin as the cables are often a few centimeters wide for some hundreds of meter long. Those size are still small compared to wavelength of about tens kilometer. The influence of the soil is quite important and needs attentions.

To design a new VLF antenna system, one will have to choose the most suitable simulation tool. Then, we present in this work a brief overview of the most used software and their numerical methods.

One of the most used software for VLF antenna design is probably NEC [1] which was developed by the Lawrence Livermore National Laboratory for the US Marine. NEC uses the Method of Moment (MoM) and can deal with important size conductor structures faster and more precisely than the others. One of the main advantage of the method for the VLF antennas is that the modeling of 1-dimensional structure is quite simple and allows to compute all the cables as thin wire. The commercial software FEKO, also based on the MoM, is more commonly used by the antenna designer community [2]. It provides an accurate solution for VLF simulations. The MoM has a major drawback because it does not deal with dielectric efficiently. It's then quite difficult to take the soil into account accurately without increasing excessively the simulation time.

A new FDTD model was introduced by Holland and al [3] that allows simulation of thin wire with an arbitrarily small radius inside one FDTD cell. The model was extended to an arbitrary oriented thin wire in [4] and more recently in [5]. The FDTD method have some advantage over the MoM as it can perform a simulation over a large frequency band and is far more efficient with dielectrics. The commercial software CST Microwave provides several electromagnetic solvers [7]. Their main focus is the FIT, which is a variant of the FDTD with a thin wire model.

We have adapted the FDTD thin wire model to the TLM method [6], another time domain technique, whose main advantage is that all the field components are computed at the same location and at the same time. This leads to a better representation of the surface between media and then to a better modeling of the ground under a VLF antenna. CST Microwave also provide its own version of the TLM with its thin wire model.

2. Layout

To evaluate the interests and drawbacks of the different methods, we have compared simulations of a simple T-antenna in two different environments. The proposed antenna is based on a 680-meter monopole feed at its feet with two 1.28 kilometers long horizontal cables as top-loading. All cables have a radius of 25mm. The first version considers the ground as a flat perfectly conductor and is depicted in Figure 1. In the second configuration (Figure 2), the antenna is placed in a 2.4km long valley surrounded on three side by 800m large flat hills. Additionally, an infinite dielectric half-space is used. All environment structures can either be made of dry soil (ε_r =3; σ=10^{-4}S/m) or medium soil (ε_r =3; σ=10^{-3}S/m). A 1600x640m² PEC ground plane is placed at the bottom. The valley is 600m deep and 2.56km long to fit antenna dimensions. Cables are maintained by non-represented 80m high towers on each side. Such topology avoids the building of numerous sustainable high masts as in most of the VLF antennas.

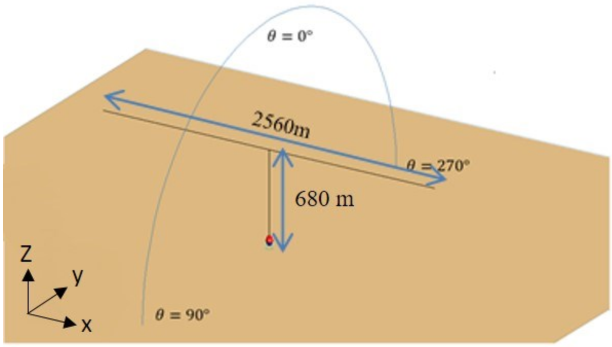

Figure 1. The layout of the T-antenna on the infinite PEC ground

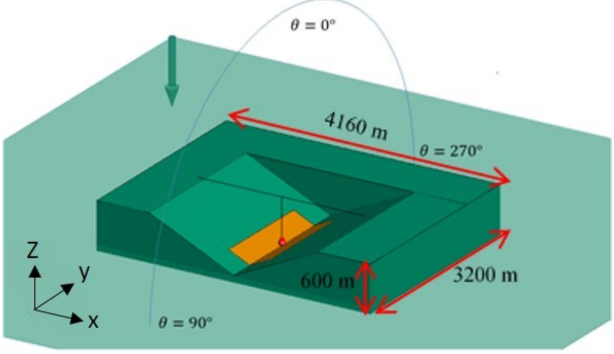

Figure 2. The layout of the T-antenna in the valley

The study is conducted between 20kHz and 40kHz as the antenna resonance is around 30kHz. FEKO simulations have 201 frequency points. The mesh size used in FEKO has to be checked in order to avoid errors. The automatic "fine mesh" is not always sufficiently small for the admittance calculation, especially with higher conductive materials.

Simulation times are given in the Table 1. FEKO and our "homemade" TLM software are implemented on a computer using two Xeon E5-2680 v2 processor (10 cores each) with 64Go of RAM. As CST run on a different computer, we can't compare directly its computational cost. However, as we use time domain method on CST and on our TLM software, same tendency can be expected.

3. Results

3.1 T-antenna on an infinite PEC ground

The absence of dielectric makes such structure easy to compute with FEKO and most of software working with the Method of Moment. All software and methods give similar results with a maximum conductance of 116mS to 130 between 31.2kHz and 31.8kHz and a linear gain between 2.8 and 3 on the ground at 31kHz. The evaluation of conductance maximal value is not accurate due to the limited number of frequency points.

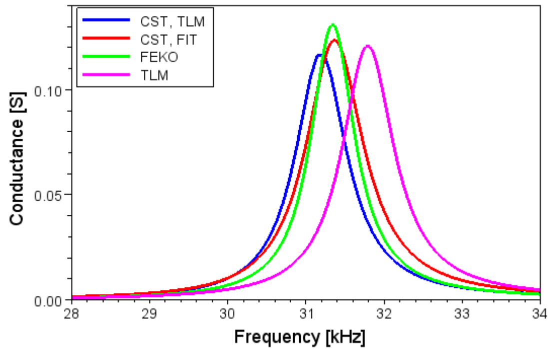

Figure 3. Conductance of the T-antenna on an infinite PEC ground

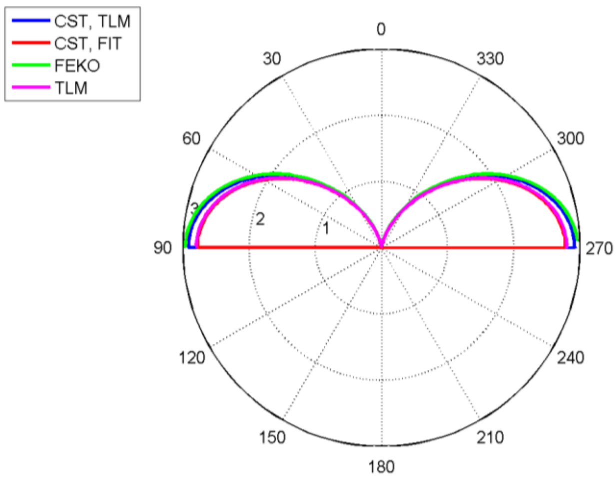

Figure 4. Linear gain of the T-antenna on an infinite PEC ground

3.2 T-antenna in the valley

More problems arrive when dealing with the valley. FEKO simulation CPU time start being long as the MoM is not efficient for simulating dielectric media. It is also necessary to use a thinner mesh than those proposed by the software. The Figure 5 displays the admittance results on a medium soil for the fine mesh proposed by FEKO giving a triangle size around 450m and a custom mesh with triangle size around 250m.The resonance frequency is shifted from

31.0kHz to 28.4kHz, and thereby an error of more than 8% with the automatically chosen fine mesh.

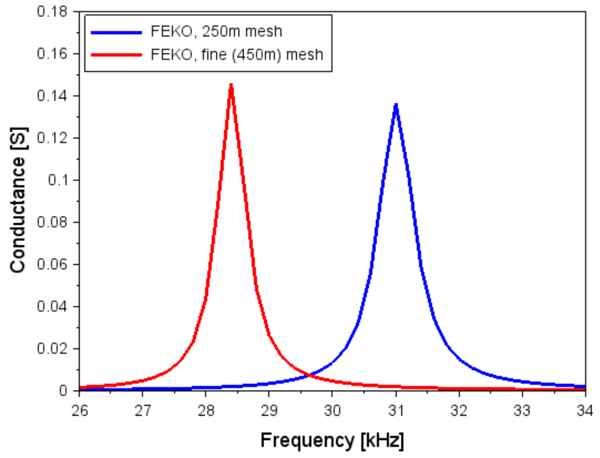

Figure 5. Comparison of the conductance simulated with FEKO for different mesh sizes

The admittance results are satisfactory. On a dry soil (Figure 6), the conductance at the frequency resonance varies between 30.7kHz and 31.3kHz and its conductance value between 121mS and 136mS. On a medium soil (Figure 7), the resonance frequency is evaluated between 31Hz and 31.5kHz and the conductance between 290mS and 325mS.

Linear gain results, on the other hand, are different (Figure 8 and Figure 9). The "homemade" TLM and FEKO give relatively close results: 0.25 and 0.29 at 68° on a dry soil and 1 and 1.1 at 74° on a medium soil. Those configurations cannot be computed with CST as it does not provide tools to design dielectric half-space leading to an inaccurate estimation of the gain. A dielectric block extending 10km around the valley and 1km deep into the soil was used to replace the infinite earth plane. This solution is ineffective as it does not give accurate results and create an important computational cost. We obtain a gain of 0.27 and 0.22 at 59° on a dry soil and 0.89 and 0.78 at 56° on a medium soil.

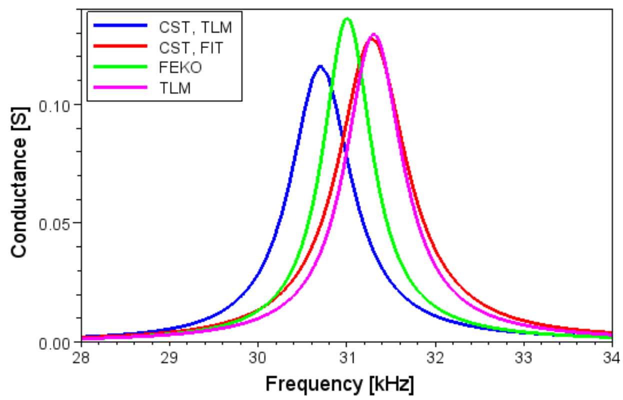

Figure 6. Conductance of the T-antenna in the valley with a dry soil

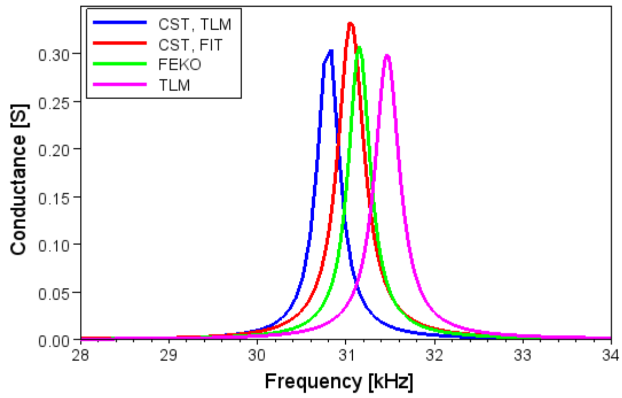

Figure 7. Conductance of the T-antenna in the valley with a medium soil

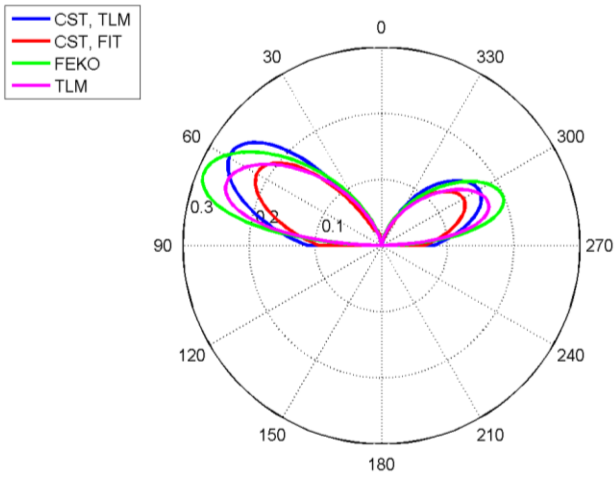

Figure 8. Linear gain of the T-antenna in the valley with a dry soil

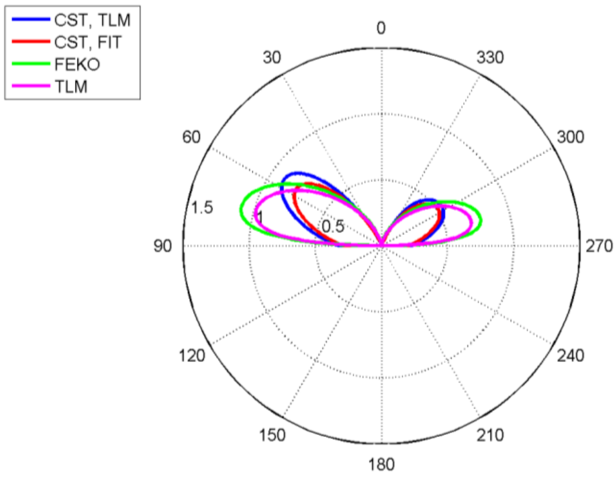

Figure 9. Linear gain of the T-antenna in the valley with a medium soil

	CST TLM	CST FIT	FEKO	TLM
PEC ground	1 min	2 min	1 min	12 min
Dry soil valley	12 min	8 min	3 h	1 h
Medium soil valley	30 min	2 h	10 h	1 h

Table 1 Simulation time

A last comment is that computation time with our "homemade" TLM software is more important than with CST TLM solver. As CST is a commercial software, a lot of optimization works was done to reduce its computation cost. Its main drawback is the lack of infinite dielectric structure leading to increase the resource needed to compute the radiated field diagram. Some works have to be done on our implementation of the method in order to reduce the computational costs.

4. Conclusion

Historically, Method of Moment was the most used method to perform VLF antenna simulation. This method is extremely effective when dealing with large conducting structures and can easily model multi-scale antennas. However, if we want to take the soil more precisely into account, it could be more interesting to use a time-domain method as the model of dielectric complex ground does not increase heavily the calculation time and can easily compute very large frequency band simulation. In other hand, to study VLF antennas, a time-domain software should propose a thin-wire module and a dielectric infinite layer tool.

5. References

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