Optimized Device Design: A Demonstration of Parameterization, Optimization, and High-Performance Computing with Hardware Accelerated FDTD

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Introduction

Computational electromagnetic software packages based on a variety of techniques have been available for many years to the practicing engineer. These tools are used for antenna and microwave circuit design, gauging compliance of devices for biological exposure, and a variety of other tasks. For the most part, these EM software tools were primarily for the analysis or validation of a well-developed design or perhaps for the fine-tuning of a design to improve performance without costly hardware prototyping. In this mode, a representation of the device is entered into the software environment and simulated to give a result for that specific design. When the results do not turn out as desired, the user must modify the device representation in the software and re-run the simulation, possibly repeating this process numerous times, until the desired results are obtained. This approach is helpful to the engineer, but requires user-feedback at each step in the process.

As technology has advanced, tools have been developed that go beyond merely analyzing devices to tools that design devices. These tools allow the user to select basic structures with variable dimensions, size constraints, and performance goals and then iterate automatically until the best possible design is found. The user is freed from the burden of monitoring the progress of each individual simulation and can devote time to other tasks. This evolutionary step in simulation software is improving the productivity of engineers developing next-generation devices in a variety of fields.

There are several components required to convert an analysis tool into a design tool. First is the ability to create a design with variable dimensions which may be adjusted automatically by the software and constrained in a manner that avoids creating an invalid structure. This capability is generally referred to as parameterization, as each variable in the device design is considered a parameter. These variables might be the dimensions of the device, the electrical parameters of the materials used, or perhaps some simulation value such as the frequency of excitation. The next component needed by the software is the ability to modify the parameter values in a logical manner based on an analysis of the output of previous simulations of the design and the goals entered by the user. This is the optimization capability which may be implemented using one of numerous approaches available. Since most optimization techniques require multiple simulations to reach a converged result, and since EM software is computationally intensive, another component needed for the design process is high performance computing. The current state-of-the-art for high speed computing accessible to the typical user is the graphics processing unit or GPU. These powerful hardware boards are the offspring of computer graphics cards but are now designed specifically for highly parallel computations. Fortunately, some methods of EM analysis are exceptionally well-suited for use on these boards and the speed increases possible over typical desktop computer processors are astounding. The complete package with the three components of parameterization, optimization, and high speed computing, combined with the insight of the user, can significantly decrease the design time for a new device and greatly increase the productivity of the engineer.

In this article, we will discuss the each of the components of a design package as implemented in the commercial software XFdtd® 7 from Remcom, Inc. [1]. The software will be used to develop an antenna design for a real application to demonstrate the process and the capabilities of the software. Finally, the simulated performance of the resulting design will be compared to measurements of a fabricated antenna developed for the same design goals.

Design Tool Components

Parameterization is the term typically used to describe the approach of making inputs to a software tool variable rather than static values. For EM software, the inputs can include both the device being simulated and the run parameters for the simulation. As a simple example, consider a dipole antenna with a length and wire radius. Both of these dimensions can be made as parameters and the simulation can sweep over a range of values for each, giving results such as input impedance for each set. A more complex example might be a microstrip circuit with variable substrate permittivity. As the permittivity of the substrate is varied, the line width of the microstrip traces will need to adjust to maintain the proper impedance. This is possible because the expression for a parameter value can be a complicated equation that includes other parameter values – so the value for the line width could be an equation involving the substrate thickness, dielectric value, and desired impedance.

While there are many techniques available for optimization, two methods that are well-suited for EM simulations are Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) [2-4]. These two approaches are global stochastic optimization techniques which give the user the advantage of not needing to have well-selected initial values for the various parameters being swept. Some other methods require precise initial values to avoid finding a local optimization point rather than the global one. The GA approach has the advantage of being able to adjust parameters during the process which can lead to faster convergence. The downside is that the GA method is more complicated than PSO which can make it difficult to set up. It has also been found that when analyzing similar antennas, trends can be found for parameter performance even from less than perfect simulations [5]. This allows the use of somewhat lower resolution models that run faster while performing the optimization. The process may be further aided by the use of Artificial Neural Networks (ANN) [6] which may be trained by running broad band parameterization sweeps with the simulator to allow the network to follow trends regarding different parameters.

As is mentioned above, the optimization of any structure requires many simulations of the software to reach a converged state with the best design. Since EM simulations can take many hours or even days to run, the prospect of running thousands of simulations can make the entire process impossible. While multi-core computers are available to speed up processing, their benefits are limited and do not scale linearly with the number of processors added. A better solution is the general purpose graphics processing unit, or GPGPU. These hardware processing cards have evolved from advanced computer graphics cards and can perform parallel calculations at exceptional rates. These types of calculations are very well suited for EM methods such as FDTD and are becoming commonly available as part of the software. Recently available cards such as the NVIDIA Tesla C1060 carry enough memory (4 GB) to handle many typical EM simulations. They can also be combined into clusters of cards to further increase their computing power and memory capability. While the speed increase over a single core CPU will vary significantly depending on the simulation in question, it is not unreasonable to expect speed increases of 100 times or more. Put in perspective, this means a simulation that might have previously taken eight hours can now be done in as little as five minutes or less. Or conversely, in that same eight hour period perhaps 100 iterations of a design can be simulated rather than one. The possibilities for increased productivity are obvious, so long as the user has the ability to make good decisions about how to parameterize the design for reaching best performance.

Design Example

A real-life design example of a previously-designed and built antenna will be used to demonstrate the optimized design process. Recently a project was undertaken [7] to develop a small, wideband, vertically-polarized antenna for use in near-to-ground situations that would radiate a uniform pattern in the horizontal plane. The antenna is to operate in the 225-500 MHz range with return loss values over that range less then -10dB and VSWR under 2. It is expected to be mounted atop a small, cylindrical sensor approximately 9 inches (23 cm) tall with a radius between 4 and 6 inches (10 and 15 cm). Several varied models of antenna were investigated including conformal patches and a mono-cone design. The best candidate proved to be a broad band sleeve monopole (BBSM) consisting of a cylindrical monopole partially surrounded by a hollow sleeve and topped by a circular cap. A basic example of the BBSM antenna is shown in Figure 1 where the bottom cylinder represents the sensor and the antenna is mounted above this.

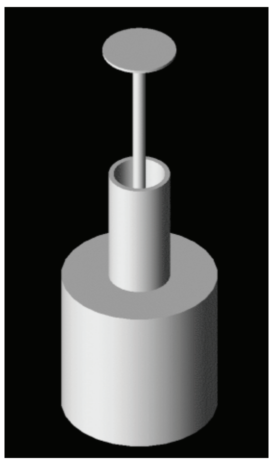

Figure 1: A typical broad band sleeve monopole antenna shown above a cylindrical base.

A prototype of this antenna, shown in Figure 2, was fabricated based on early simulations that produced acceptable performance in free space. The fabricated antenna used a wire skirt to represent the sensor since at that time the composition of the sensor was not defined. An assumption was made that the sensor body would either be metallic, or if not, the sensor could be enclosed with the wire skirt to produce similar performance to a solid metallic sensor base. The original design simulations indicated good performance over the entire frequency range although a matching inductor was added at the feed to improve performance over the entire band. When the prototype was measured, the performance when the antenna was suspended in the air was similar to the simulations, although slightly worse. The resulting measurements for the VSWR (shown in Figure 3) were acceptable. When the antenna was placed on the ground, as it would in actual use, the performance did not meet the design goals for all frequencies but was acceptable (see Figure 4). For the measurements, "ground" meant a concrete floor in the lab rather than actual terrain.

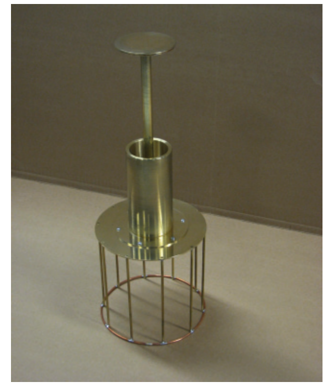

Figure 2: A photograph of the initial prototype antenna fabricated for the project using design parameters generated with a manual optimization approach.

Using the PSO technique combined with the hardware accelerated simulations, our goal is the redesign of this antenna for better performance, particularly for the case of the antenna

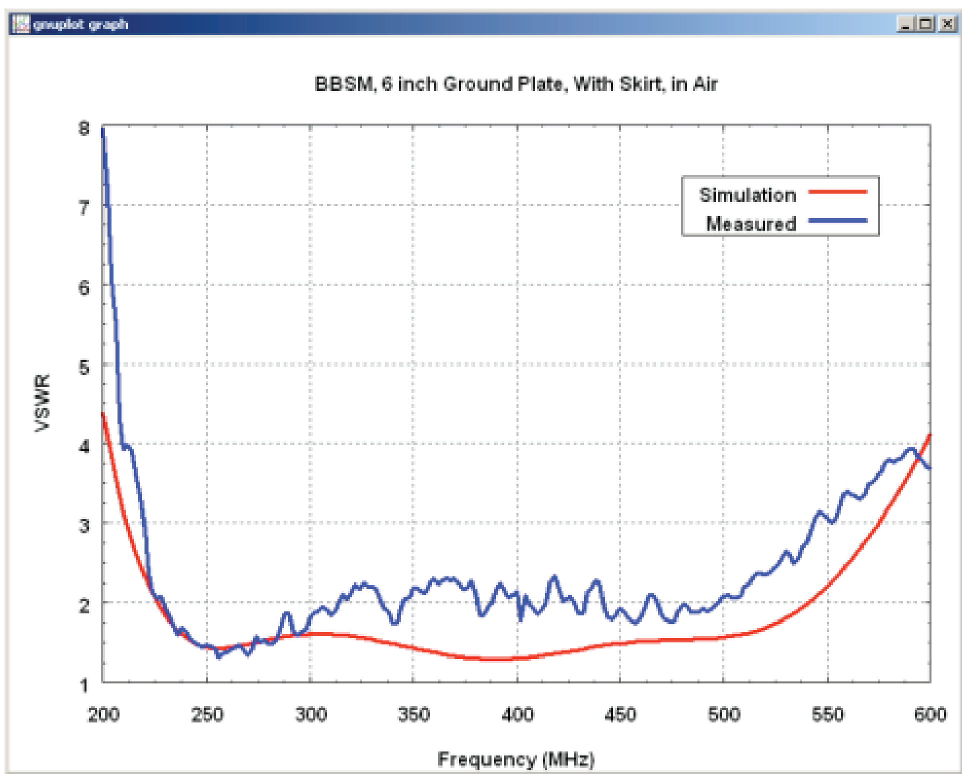

Figure 3: The measured VSWR performance of the fabricated antenna compared with the simulated results for the antenna in free space. The measured results are quite close to the design specifications and are a reasonable match to the simulated results.

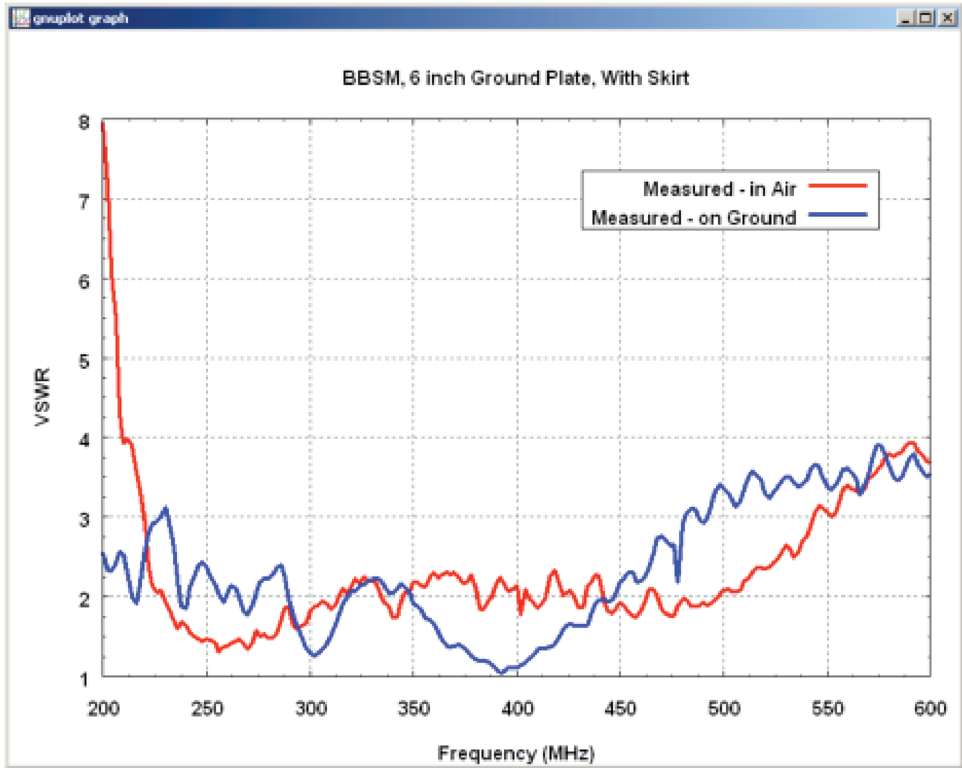

Figure 4: The measured VSWR results for the fabricated antenna in free space and when placed on the ground (ground here is a concrete slab). The "in air" results were within specifications over the entire frequency range while the "on ground" results produce a higher VSWR over the high end of the frequency range.

on realistic ground that includes loss. We'll begin using a script that was developed to optimize the feed location of a patch antenna [8] for best return loss performance at a single frequency. The script was modified to increase the number of variable parameters from one to five. The return loss performance is used as the goal (S11<-10dB) over the range of frequencies of interest (225-500 MHz). In the script the return loss is tested at five frequencies that span the range of interest. A drawing of the antenna is shown in Figure 5 with the variable parameters indicated. The original values for these parameters are chosen based on the prototype

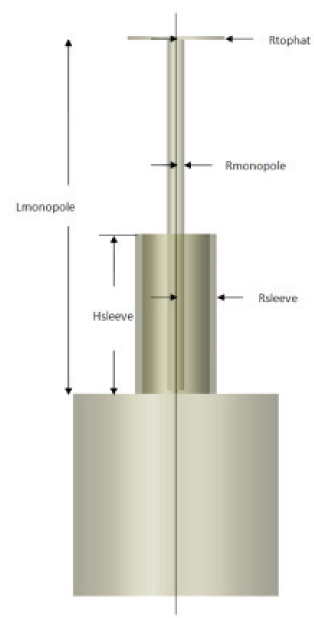

Figure 5: An outline drawing of the antenna with the variable parameters listed.

design that was first built and are shown in Table 1. In the table, the thickness of the circular plate on top of the monopole (the "top hat") is listed as Htophat and is kept fixed at 0.3 cm. Also the thickness of the cylinder surrounding the monopole (the "sleeve") is kept fixed at 0.5 cm. As the sensor base is not a part of the antenna design that can be modified, those values (Rbase and Hbase) are also kept fixed. The other parameters are allowed to vary over defined ranges which are shown in Table 2.

Parameter	Dimension (cm)
Lmonopole	26
Rmonopole	0.635
Hsleeve	11.9
Rsleeve	3
Rtophat	3.6
Rbase	7.6
Hbase	15
Htophat	0.3
Rsleevethick	0.5

Table 1: Original parameter values for the antenna based on the prototype design.

Parameter	Min. Dimension (cm)	Max. Dimension (cm)
Lmonopole	20	40
Rmonopole	0.25	1.0
Hsleeve	5.0	19
Rsleeve	2	7
Rtophat	1	5

Table 2: Allowed ranges of each parameter in the script.

The design process for this antenna will consider four situations: the antenna in free space, the antenna on dry ground (relative permittivity = 4.0, conductivity = 0.001 S/m), the antenna on medium ground (relative permittivity = 8.0, conductivity = 0.01 S/m) and the antenna on wet ground (relative permittivity = 25, conductivity = 0.02 S/m). The goal will be to develop a single antenna that will function for all ground cases. As the optimization script is based on the PSO approach and the particle movements are random, several simulations will be performed to find averaged results for the designs for each case. While the optimization approach is global, our goal is loose enough (S11 < 10dB) that there can be multiple solutions. By running the script repeatedly, the results from each successful trial can be averaged. Because of the random nature of the particles and the need to run repeated simulations, a random number generator is used that will use a different seed at each execution to avoid arriving at the same solution every time. This random number generator is seeded by the current system time to ensure different random number sequences. For one part of this study some timing tests will be done on different platforms and in that case the random number generator will be seeded with the same number to ensure consistent performance.

Before beginning the design process, timing tests will be done on a computer with multiple processors and on two different hardware platforms. The multiprocessor computer is a Dell Precision T5400 with an 8 core Intel Xeon 5405 processor at 2.0 GHz and 8 GB of main memory. The hardware cards are an NVIDIA Quadro FX 1600M with 512 MB of memory and an NVIDIA Tesla C1060 with 4 GB of memory. For the initial test, the antenna in free space will be used with the parameters set for the original prototype design as shown in Table 1 which results in a problem space of 77x77x127 FDTD cells using 63 MB of memory. An outer boundary condition using seven uni-axial perfectly matched layers (UPML) is applied to absorb fields at the edges of the problem space. The FDTD mesh has variable cell sizes ranging from 2.92 mm up to 5 mm. The excitation is a broadband pulse, the stored output data includes voltage, current, power, impedance, and S-parameters at the single input port and the convergence criteria for the problem is a decrease in total energy in the computational space of 30dB down from the peak.

As this initial test problem is quite small, the efficiency with an increased number of processors is expected to be poor. This is evident in the results of Table 3 where it can be seen that increasing the number of processors beyond six actually increases computation time. In simulations with the hardware cards, the performance is shown to improve significantly, although because of the small problem size and the extremely short calculation time, the speed increase is not maximized. The performance increase from the GPU card is reduced due to the non-hardware tasks such as initialization of the variables and the file writing required.

Processor	Run Time (sec)	Speed Factor
1 CPU	235	1.0
2 CPU	108	2.2
4 CPU	74	3.2
6 CPU	54	4.4
8 CPU	163	1.4
Quadro	38	6.2
Tesla	7	33.6

Table 3: Performance times of the antenna design in free space.

As a second test involving a larger problem, the antenna is placed on a rectangular slab of the wet ground material resulting in a slightly larger problem of 141 x 141 x 186 FDTD cells with cell sizes varying from 1.5 mm up to 10 mm. In this case the calculation required about 253 MB of memory, which is still a small problem, but the largest required for this design scenario. Due to the wet ground, the simulations ran for about twice as many steps in time before reaching convergence as compared to the antenna in free space case. The results are shown in Table 4 and it can be seen that now the performance continues to improve as more processors are used and the results for the hardware cards are slightly better than the free space.

In other test cases for much larger geometries which use significantly more memory than the antenna design shown here, the performance of the Tesla card has been shown to be over 100 times faster than a single processor. While our performance here is less than half that amount, it is still significantly faster than the eight core processor. Given that during the optimization process, several hundred simulations will be run for each trial, and about 40 different trials will be made, the increase in performance will save many days of computer time. For all simulations that follow, the Tesla card will be used.

Processor	Run Time (sec)	Speed Factor
1 CPU	2253	1.0
2 CPU	1144	2.0
4 CPU	739	3.0
6 CPU	642	3.5
8 CPU	588	3.8
Quadro	318	7.1
Tesla	57	39.5

Table 4: Performance times of the antenna design on a rectangular slab of wet ground material.

Our first design case is the antenna in free space. As was mentioned previously, the random nature of the particles in the PSO approach and the loose restriction on our design goal make numerous possible solutions available, so five different designs will be developed and averaged. In general, more than five trials are likely to be required to reach a good design, but for the purposes of this article, five seems a reasonable number to demonstrate the approach. The problem set up is identical to

Parameter	Run 1 Dimension (cm)	Run 2 Dimension (cm)	Run 3 Dimension (cm)	Run 4 Dimension (cm)	Run 5 Dimension (cm)	Averaged Dimension (cm)
Lmonopole	34.2	32.9	37.1	34.2	29.2	33.5
Rmonopole	1.0	0.7	0.7	1.0	0.5	0.8
Hsleeve	17.0	16.5	14.6	17.0	16.5	16.3
Rsleeve	4.8	4.4	4.9	4.8	3.8	4.5
Rtophat	3.7	2.5	1.1	3.7	4.6	3.1
Executions	36	37	49	36	93	

Table 5: Resulting parameter values from each of the five optimization runs for the antenna in free space. The averaged parameters are shown in the right column.

that performed earlier in the timing run and each of the random trials starts with the original design parameters as shown in Table 1. For the particle swarm optimization, a maximum of 35 iterations with eight particles will be allowed. This results in a maximum of 280 simulations before the script will end. The results for our five designs are shown in Table 5 with the averaged results given in the last column. The optimized parameters vary significantly in some cases between runs, such as monopole lengths ranging from 29.2 cm up 37.1 cm. So, clearly there is a lot of freedom in adjusting the parameters for the free space case. The number of executions shown in the bottom row indicates how many FDTD simulations were required before the goal (S11 < -10dB) was reached. The converged result is reached fairly quickly as the maximum number of executions is 93 and most of the trials are complete in less than 40 executions. The return loss results from each of the five trials are shown in Figure 6 and while all can be seen to meet the goal of being less than -10dB, each is unique.

This averaged parameter optimization generates a significantly different design than the original prototype antenna, especially in terms of the length of the monopole as can be seen in Figure 7 where the antennas are compared side-by-side. Over the design frequency range the VSWR remains below 1.7, which is similar to the results produced by the original design, so the two antennas are functioning in a similar manner despite their distinct appearance. The main difference is the

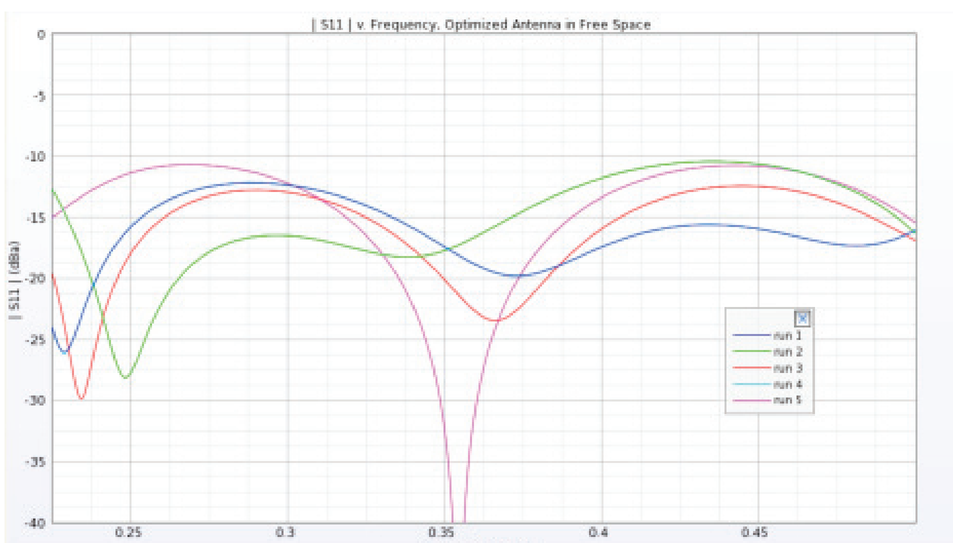

Figure 6: The return loss results for each of the designs in free space are unique while also meeting the goal of being below -10dB over the frequency range of interest.

height of the optimized antenna; it is significantly greater than the original which is not desired considering that this antenna/sensor combination is supposed to be covert when in operation. Given this start though, we'll now attempt to optimize the antenna over the different ground types to see how the parameters change.

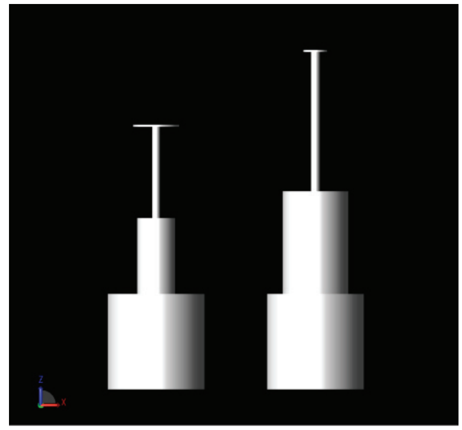

Figure 7: A comparison of the original antenna design (at left) and the optimized design for the antenna in free space (right) formed from the average of the five design trials. While the performance of the antenna over the frequency range of interest is similar, the dimensions of the antenna are quite different.

To simulate the antenna over ground, a rectangular slab is added to the simulation under the antenna in the FDTD simulation. The slab dimensions are 1 x 1 x 0.1 meter and the absorbing outer boundary condition is placed in contact with the slab to cause it to appear infinite to the calculation. The optimization process is repeated with the parameters of the ground slab set to those of dry earth and the resulting parameters for each simulation are shown in Table 6. Here again the monopole length of the averaged parameters is longer than the original

Dry Ground Parameter	Run 1 Dimension (cm)	Run 2 Dimension (cm)	Run 3 Dimension (cm)	Run 4 Dimension (cm)	Run 5 Dimension (cm)	Averaged Dimension (cm)
Lmonopole	37.9	29.2	23.9	36.4	26.4	30.8
Rmonopole	0.8	0.4	0.7	0.4	0.4	0.5
Hsleeve	15.4	16.7	14.0	16.6	15.1	15.6
Rsleeve	4.7	2.9	3.8	3.5	2.8	3.5
Rtophat	1.8	4.2	5.8	1.6	4.6	3.6
Executions	180	49	21	44	48	

Table 6: Shown are the parameter results for the optimization of the antenna design over dry ground. The averaged parameters are shown in the right column.

design while some of the other parameters are fairly close to the original values. Also again, the simulations reached convergence in relatively few executions, indicating that the design goals are not difficult to reach. The appearance of the optimized antenna over dry ground is similar to that developed for free space.

The optimization of the antenna over medium ground was much more difficult. When this case was simulated the optimization script reached a converged result in only one case out of the five. As this wasn't considered a good set of data for designing the antenna, modifications to the optimization script were made to increase the chances of finding a good design. After observing the parameter values from the first five runs, the variable range of the parameters Lmonopole, Rsleeve, and Rtophat were increased to allow for further expansion in the direction the previous results seemed to indicate were appropriate. For these runs, the lower bound of Lmonopole was decreased from 20 cm to 15 cm, the lower bound of Rsleeve was decreased to 1 cm, and the upper bound of Rtophat was increased to 7 cm. After several more executions of the optimization script, a converged result was still not found. At this point, the script was edited again to increase the number of iterations to 50 from 35 and the number of particles per iteration to 10 from eight while retaining the increased parameter ranges. These changes then produced two additional runs with convergent results which are shown in Table 7. At this point after doing nine trials the optimization was stopped and the results for the three convergent runs were averaged.

Medium Ground Parameter	Run 3 Dimension (cm)	Run 8 Dimension (cm)	Run 9 Dimension (cm)	Averaged Dimension (cm)
Lmonopole	22.4	20.3	20.2	20.9
Rmonopole	0.3	0.3	0.5	0.35
Hsleeve	14.0	14.8	13.3	14.0
Rsleeve	2.4	2.3	2.7	2.4
Rtophat	5.0	6.0	6.6	5.9

Table 7: Parameter values obtained for the antenna over medium ground optimization trials.

For the last case of the antenna over wet ground, the optimization proved to be even more challenging than for the antenna over medium ground. The initial five optimization trials did not produce any convergent results after running the maximum number of executions. These simulations used the modified ranges for the parameters Lmonopole, Rsleeve, and Rtophat developed during the medium ground optimization, but the number of iterations and particles was set to 35 and 8, respectively. In subsequent simulations, the range of the parameters was changed to allow ranges of Lmonopole from 17 to 45 cm, Hsleeve from 5 to 20 cm, Rsleeve from 1.8 to 7.6 cm, Rmonopole from 0.25 to 1.5 cm, and

Rtophat from 1 to 15 cm. These parameter ranges made it possible for invalid geometries to be created since in some cases the sleeve and monopole could overlap. To account for this possibility which will lead to wasted simulations, the number of iterations and particles was increased to 50 and 14 respectively. Even with all of these changes, no trial was performed that reached a convergent result after 14 trials, however one trial did produce an S11 result that was less than -10dB for nearly the entire frequency range. Clearly the increased permittivity of the wet ground slab presented a significant challenge to the antenna performance. The single marginally-convergent result for the antenna on wet ground was deemed to be the best possible and is shown in Table 8.

Wet Ground Parameter	Run 7 Dimension (cm)
Lmonopole	20.4
Rmonopole	0.3
Hsleeve	16.5
Rsleeve	2.1
Rtophat	7.0

Table 8: Shown are the only convergent design parameters for the antenna on wet ground.

After reviewing the results from the four cases (free space, dry ground, medium ground, and wet ground), it's clear that the free space and dry ground designs are quite different from those on wet and medium ground. Attempting to average the parameters obtained from each of these cases gives a design that doesn't perform well. However, since the free space and dry ground cases were somewhat flexible in the design, it was found that the average of the wet ground and medium ground cases does perform well in both free space and over dry ground. These averaged values were chosen as the final design and the parameter values are shown in Table 9.

Parameter	Final Design (cm)
Lmonopole	20.66
Rmonopole	0.33
Hsleeve	15.27
Rsleeve	2.30
Rtophat	6.42

Table 9: Shown are the final design parameters obtained by averaging the optimized parameters for the medium and wet ground cases. While these parameters did not consider the free space or dry ground values, the resulting design performs well for those cases as well.

A comparison of the original and final antenna designs is shown in Figure 8 which shows that the optimized antenna is shorter than the original with a higher sleeve and a much larger top hat radius. The return loss and VSWR for the final design are shown in Figures 9 and 10 and both are shown to be within the design limits for all cases at nearly all frequencies. Only the wet ground case at low frequencies has a return loss that does not comply with the goals, and even then the S11 plot is less than -9 dB.

When contrasted with the simulated and measured results for the original design shown in Figures 3 and 4, the new antenna that was optimized for performance over real ground should perform better. Also, the optimized design as simulated does not require any additional matching circuitry to obtain good performance over the entire frequency range.

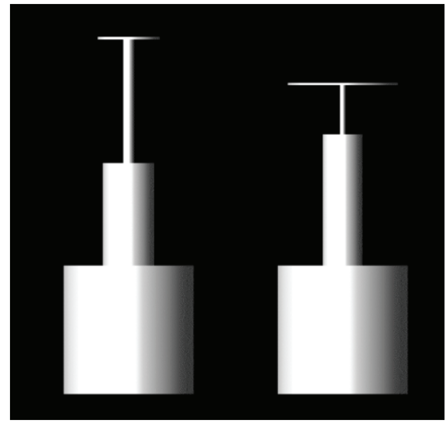

Figure 8: Shown are the original design (left) and the final optimized design (right) created by averaging the antennas developed for use over medium and wet ground. The optimized design presents a shorter profile, which is desired and performs well over all three ground types and in free space.

Another goal of the design was to have reasonable gain in the horizontal direction. The final design was simulated in both free space and over a perfectly conducting infinite ground plane and antenna gain patterns were generated at several frequencies that spanned the range of interest. The patterns are shown in Figures 11 and 12. As can be seen, the gain in the horizontal direction is around 2dB except for the top end of the frequency range for the free space case where the gain is lower. As the antenna is radially-symmetric, the pattern is uniform with azimuth angle.

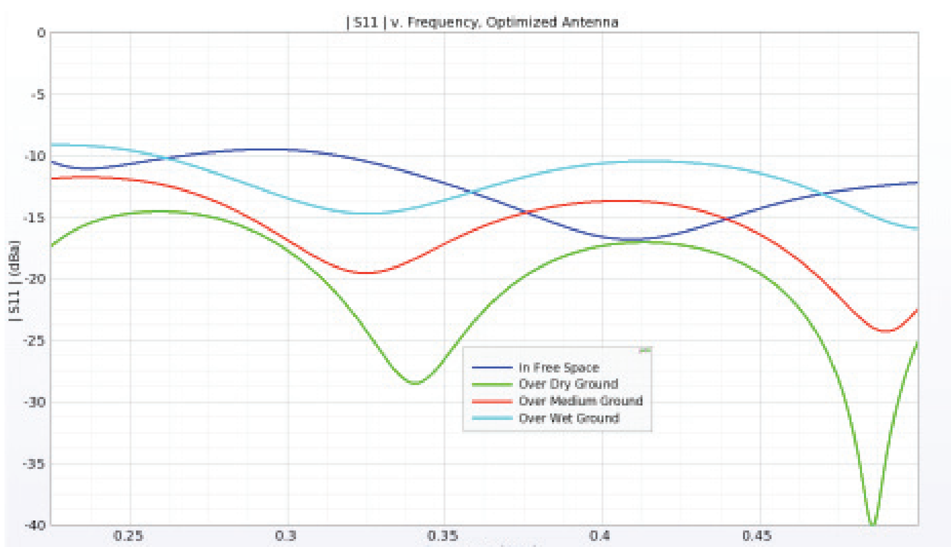

Figure 9: The return loss for the optimized design is well within specifications for the dry and medium ground cases. For wet ground, there is a slight drop in performance for the frequencies below 250 MHz.

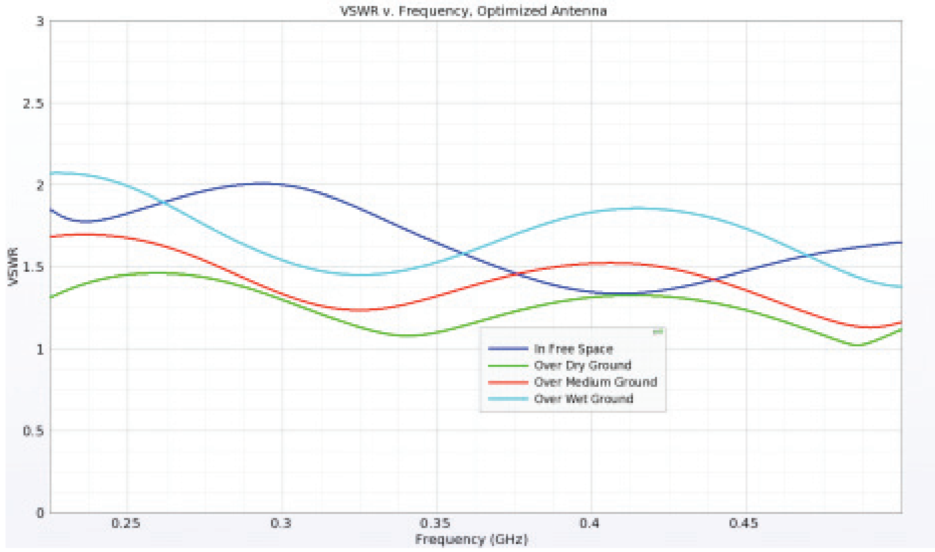

Figure 10: The VSWR plot is under 2 for most cases and frequencies. The performance over wet ground at low frequencies is very slightly above the design threshold.

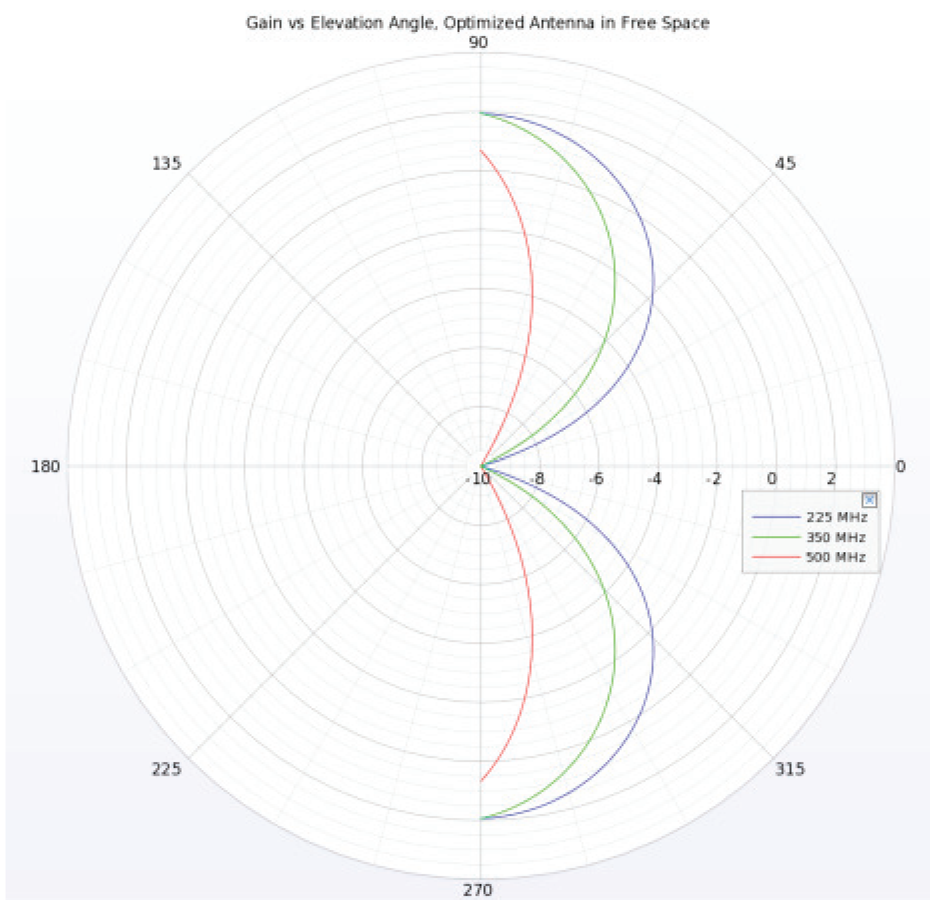

Figure 11: Far field gain patterns for the optimized antenna in free space show that antenna has reasonable gain in the horizontal direction, as desired.

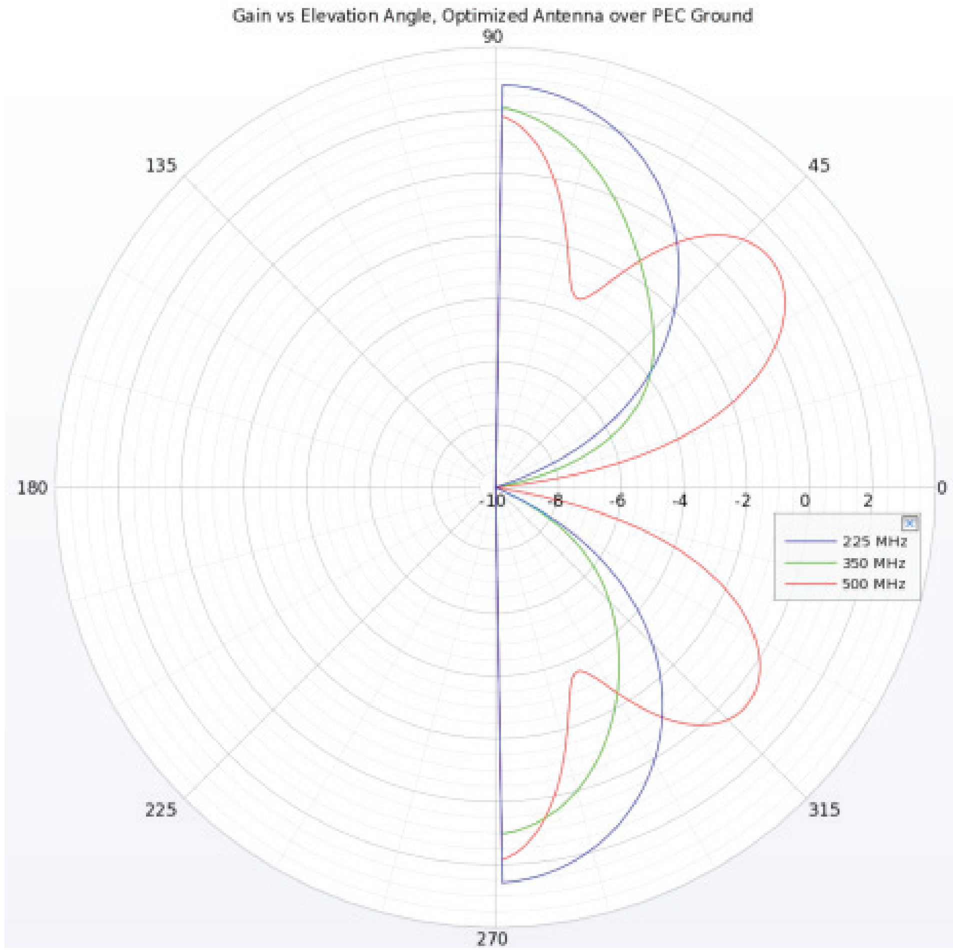

Figure 12: In this plot the gain is shown for the antenna over a perfectly conducting ground plane. Here the gain in the horizontal direction is around 2dB for all frequencies of interest.

Summary

An electromagnetic solver with automated optimization capabilities is a powerful tool for the practicing engineer. Much of the burden of setting up and repeatedly running simulations is removed since the calculations are performed in large part without user-intervention. When combined with extremely fast solvers in the form of GPU hardware, the turnaround time for projects can be significantly reduced.

In this paper a demonstration of how an electromagnetic design software tool can be used to solve a typical problem was given. Here the test case was a simple antenna design that started with a set of goals and a basic antenna structure. The output was a well-functioning antenna design ready for fabrication. The process was significantly aided by the ability to run the simulations on a powerful GPU hardware solver which reduced the processing time in this case by a factor of about 40. The software and the process are general and can easily be applied to a wide range of applications in microwave engineering and beyond.

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