Collaborative Research: Compact Microwave Imaging System Based on Antenna Array of Dielectric Resonators for Breast Cancer Detection

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ABSTRACT:

The University of Arkansas is collaborating with universities all over the world to devise a new method of breast cancer detection using microwave technology and advanced imaging. The possibility to use gold nanoparticles as an enhancement agent of the contrast between the tumor and the healthy tissue is the motivation behind sending a student to the University of Technology of Troyes in France for three months. To explore this idea, the DDSCAT code was investigated for its capabilities and analyzed for its accuracy in scattering calculations. The results obtained showed the DDSCAT to be a flexible code, which offers potential to further research of the breast cancer detection. Despite the encouraging results, more extensive analysis is needed to determine exact precision, resolution, and CPU times for targets with increasing complexity. The student was excited to work on a multi-disciplinary project and be exposed to new trends in technology as well as the surrounding culture. As a result of the research experience, she is motivated to pursue a graduate career in electrical engineering.

INTRODUCTION

Past research in breast tumor detection using microwaves has shown a contrast between healthy breast tissue and cancerous breast tissue when microwaves are applied. However, recent studies, performed on women of all ages, have shown a poor contrast with healthy and unhealthy tissue, making a tumor difficult to detect. The Department of Electrical Engineering at the U of A is currently conducting research that mixes biology and microwaves in the area of breast tumor detection. The current NSF research award no. ECS-0524042 focuses on developing a new method of detecting breast tumors using microwave-imaging techniques. Unlike the mammogram, this approach proposes a non-invasive, non-ionizing method to attain more accurate results and earlier detection. To improve the contrast of a breast tumor with surrounding healthy tissue, a method using gold nanoparticles has been proposed. The gold nanoparticles can be functionalized biochemically to "stick" to cancerous tissue. It is expected that this contrast enhancement will facilitate the microwave imaging process of the tumor, from the scattering information generated from its interaction with an incident field. This former research and new idea motivates the PI, Magda El-Shenawee, to send Lauren Megee, a senior in Electrical Engineering, to study at the University of Troyes (UTT) under the supervision of Demetrio Macias from May 18, 2008, to August 13, 2008.

Although different rigorous and approximation methods have been proposed to study the interaction between electromagnetic fields and matter, during her stay in Troyes, the student investigated incorporating the modeling capabilities of the DDSCAT into the overall research project. The software is based on a discrete dipole approximation (DDA) and was developed by Drain and Flatau [2] and is "a very flexible and general technique for calculating the optical properties of particles of arbitrary shapes. The DDA replaces the solid particle by an array of *N* point dipoles, with the spacing between the dipoles small compared to the wavelength. Each dipole has an oscillating polarization in response to both an incident plane wave and the electric fields due to all of the other dipoles in the array; the self-consistent solution for the dipole polarizations can be obtained as the solution to a set of coupled linear equations." [2] With the success of gathering an enhanced microwave reflection from spherical particles using the DDSCAT to model the reflection, extensive research can be performed to implement complex shapes. By utilizing the complex shapes the code offers, these shapes can be used to more accurately represent a breast tumor.

The research of the student will be carried out at the Laboratory of Technology and Optical Instrumentation (LNIO) at the University of Technology of Troyes because it offers many resources to study nanotechnology, plasmonics, and other advanced topics incorporating near-field optics. Additionally, the expertise of the researchers at the UTT is advancing the employment of nanotechnology within the proposed research project. The host mentor and researchers at the UTT have extensive experience with codes based on similar theory to the DDSCAT and advised the student as she assessed its functionality.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The DDSCAT code developed at Princeton University is free software based on the DDA. Although the operational principles of the DDSCAT are published elsewhere, it is convenient to briefly describe them before showing the results of our numeric experiments. The code uses a cubic lattice composed of *N* dipoles to approximate the target volume. Various target geometries, generated by the dipole arrays, can be represented [1]. Once the target geometry has been selected, it is necessary to represent the volume with an adequate number of dipoles. A function of the surface irregularity *f(N)*, is used to find minimum points of *N* dipoles [2]. The computing time of the software is related to the square of the number of dipoles [2]. By locating the minimum points of the function *f(N)*, an adequate number of dipoles can be obtained to compose the target geometry without sacrificing CPU time.

The DDSCAT contains two executables, ddscat and CALLTARGET, which can be manipulated to achieve the desired number of dipoles. The ddscat executable obtains its input parameters from the file ddscat.par. This file sets up target shape, polarization, wavelengths, effective radii, and number of dipoles. Setting the target shape parameters accordingly and leaving the lattice separation set at unity in the subroutine reapar.f obtains the desired number of dipoles. The CALLTARGET executable is a user interactive program used to generate targets based on user input of interdipole separation and target shape. The program produces an ASCII output file, target.out, which must be passed into the ddscat.par file under the target shape option [1]. Both methods to generate dipole arrays are effective because both are based on the same governing principles mentioned in reference [1].

Within the input file, ddscat.par, the iterative solver is selected. Two iterative solvers are available with the DDSCAT code, the Preconditioned BiConjugate Gradient with Stabilitization (PBCGST) and the Complex Conjugate Gradient (PETRKP). The accuracy of the scattering efficiency factor, Qsca, is dependent upon the accuracy of the solver used. To evaluate the accuracy of these solvers, we considered an example from Figure 1 of reference [3] with the refractive index, m=6 and one point was selected at the highest peak of the graph. Using the ddscat executable, ddscat.par was set up to generate a sphere with an affective radius of 6.33μm, one wavelength corresponding to the selected point, *N*=1045 dipoles, and the PBCGST solver. The number of dipoles is a minimum value obtained from the *f(N)* function in reference [2]. The dielectric material was set to m=6 in the diel.tab file. Polarization was set for both incident and orthogonal polarization and three orientations were implemented to obtain more accurate results. With an increase in the number of orientations CPU time increases. Therefore, a small but adequate number of orientations were selected. When the target contains multiple orientations, the target is rotated in the frame to capture different points of the microwave reflection to increase the accuracy of the calculations. Two polarizations and three orientations produced six values of Qsca, which were averaged and obtained from the output file w00r00kori.avg. The ddscat.log_000 contains the number of iterations and error per iteration. The fractional error over number of iterations was graphed for six curves to show the accuracy of the Qsca values obtained by using the PBCGST solver and can be seen in Figure 1 a) and b). In Figure 1 the error curves corresponding to the orientations are separated into Figure 1a and Figure 1b for easier viewing due to the non-linear behavior of the curves. The PETRKP solver was compared to the PBCGST solver by observing its error over iterations. The same input parameters were used to obtain the accuracy of the PETRKP solver and it can be seen in Figure 2. Six plots representing six cases, three orientations and two polarizations, are shown in Figure 2. However, the plots of curves 1st, 2nd, 4th, 5th and 6th are almost identical. The plot that represents the second orientation and the first polarization is shown as the 3rd curve (dashed lines). Both solvers presented unique results that were analyzed for the best accuracy.

Once the accuracy of the scattering efficiency factor was determined and an appropriate solver analyzed, the DDSCAT was also tested for overall accuracy. To do this a graph was selected so the DDSCAT output could be measured against theoretical results. The ddscat.par file was set up to generate the graph in Figure 1 of reference [3] with a refractive index, m=6, using the PETRKP iterative algorithm. The number of dipoles was kept at *N*=1045 to reduce CPU time. Instead of using one point, this time many wavelengths were used to create the entire behavior of the graph. The error between the DDSCAT approximation graph and the Mie theory graph was calculated, and CPU time was analyzed.

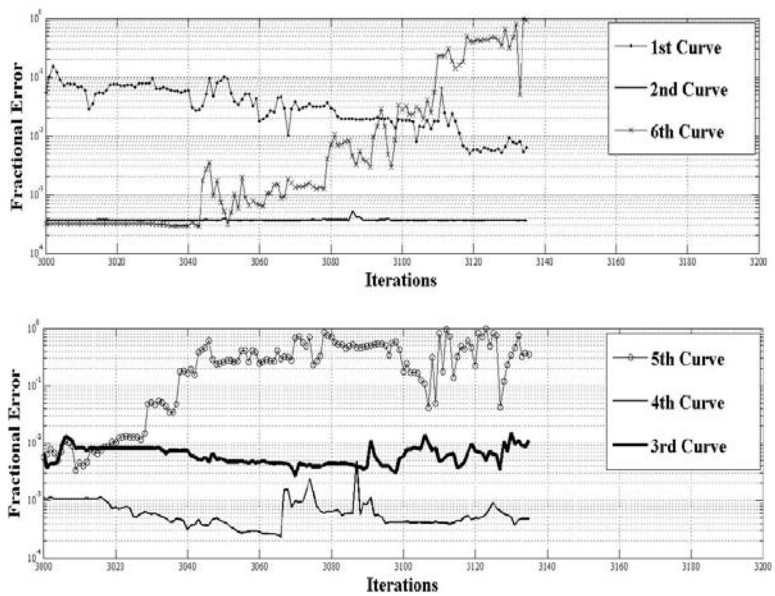

Figure 1. a) and b) Error of PBCGST Solver vs. Number of Iterations

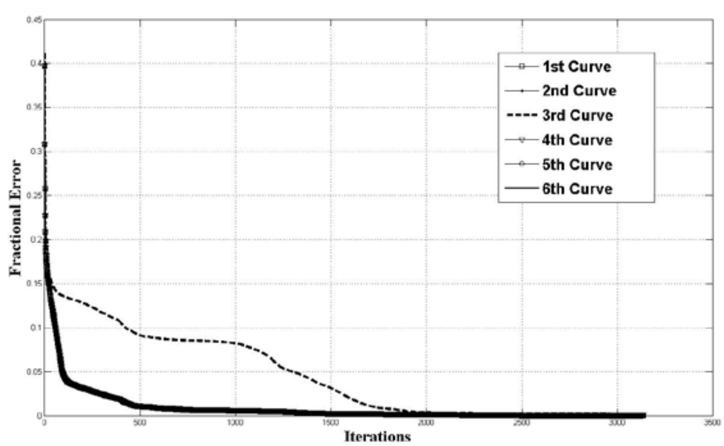

Figure 2. Error of PETRKP Solver vs. Number of Iterations

BROADER IMPACTS OF THE INTERNATIONAL TRAVEL

By participating in the IREE opportunity in France, the student was able to work on a multi-national and multi-disciplinary team that combined unique perspectives from the physics at the UTT and engineering at the U of A to achieve one main goal. By working on a diverse team, the student's communication skills and academic knowledge were improved. Before participating in the IREE the student's background consisted of only one course in Electromagnetics. Throughout the research experience the student's academic horizons were broadened to advanced topics in electromagnetics and optics, which are the foundation of the overall project. Learning this material was a challenging and rewarding experience for the student, which sparked an interest in her to pursue advanced studies. The student also traveled to the University of Bourgogne at Dijon, France, to visit optics laboratories and listen to presentations about cutting edge technology with optical antennas. Current technological progress at both the UTT and the University of Bourgogne focuses on nanotechnology using optics properties. These areas of research revealed to the student a worldwide perspective in new and advancing technologies.

With the expertise of her host adviser and US mentor and increasing knowledge of new scientific material, the student was able to obtain information about the DDSCAT code and show the code's potential for future use in the overall research award. The flexibility of the DDSCAT makes it applicable in many areas. Using the code to model gold nanoparticles inside of the breast tissue as well as healthy and unhealthy breast tissue is one of the future methods we hope to implement with the DDSCAT. The code also contains methods to model many different dielectric materials and complex shapes. Although the DDSCAT was shown to hold potential, more research must be done to determine the exact capabilities, precision and limits of the algorithms.

Along with gaining vital research experience, during the student's three-month internship in Troyes she met international students from over ten different countries as seen in Figure 3. This was her first time to travel overseas, and she was exposed to many different languages, cultures, and customs. Her eyes were opened to the perspective international students have concerning the United States of America and its political policies. Recognizing the impact the United States has on the world politically, created a conviction to vote and ameliorate consciousness of current events and foreign policies. Socializing with international students gave the student the opportunity to learn about foreign education programs and the importance of languages. Most of the international students studying at the UTT speak at minimum three languages. This realization is a catalyst for challenging the student to pursue the study of a foreign language. Exposure to people from different countries was a rewarding experience that created a more accepting attitude of culture and customs different from American traditions.

The culture of France is very rich and founded on the enjoyment of life and relaxation. This principle can be found by simply experiencing a French meal. It is typical to spend at least two hours enjoying a meal and the company of colleagues or friends. These practices are in complete contrast to the alacrity found in the daily American life.

Because of the richness of French culture, traveling and sightseeing was a very enjoyable experience. From the famous artwork on display in many museums in Paris, the student's creative side was inspired, and she began using her free time outside of research to sketch. By visiting medieval French towns and large cities like Paris, engineering research was contrasted with learning the history of France and appreciating the creative genius in its art and architecture.

The history of France has compelled the student to further study history, and it is her newest interest and hobby.

All of the student's experiences served to improve her perspective of the world and knowledge of engineering, history, culture, art, and politics. She will apply this new perspective to accept, learn from and enjoy different cultures as she comes into contact with them in future opportunities, and she will continue to fuel her interest of art and history with further personal study.

Figure 3. UTT International Student Trip

DISCUSSION AND SUMMARY

The accuracy of the DDSCAT code was analyzed for its potential use to enhance the imaging of breast tumors. The tests performed with the DDSCAT evaluate the accuracy of the scattering efficiency factor based on the iterative solvers and the overall accuracy compared to Mie theory. Two iterative algorithms were compared by plotting the fractional error versus number of iterations. The PBCGST solver showed large fluctuation in error over iterations. Two of the curves contained large error at the last iterations revealing a problem with the Qsca values. The curves with large fractional error at the final iterations were discarded because the Qsca values were negative. These negative values have no physical meaning because Qsca is always positive due to the squared modulus of the scattered field. Using the PETRKP solver obtained the most desired results. The number of iterations versus fractional error was graphed for the PETRKP solver and showed the error decreasing exponentially with increasing iterations. All six curves followed this behavior, and many of the PETRKP curves lay on top of each other. No negative Qsca values were found when using the PETRKP solver. Because of this and the decreasing error over iterations, the PETRKP solver obtained the most accurate Qsca values. Both solvers have different advantages; however, to obtain precise results using either solver, the calculations of the algorithms must be done with double precision. Currently the DDSCAT is executed with single precision. Although the PETRKP solver requires longer CPU time than the PBCGST, the PETRKP was used when comparing the DDSCAT approximation method with Mie theory due to its accuracy. Further research must be done to increase the precision of the algorithms and explore the accuracy and CPU time with increased number of dipoles and effective radii.

Before producing a graph to compare with the analytical solution, examples from the user manual were explored and reproduced. The examples produced in reference [1] were correctly obtained and compared to Mie theory with small overall error [1]. The knowledge obtained from exploring the user manual examples was applied to produce the example in Figure 1 of reference [2]. A comparison of the accuracy between the DDSCAT method and the analytical Mie method is still under investigation. The research performed with the DDSCAT code did not obtain a graph with overall behavior similar to Figure 1 in reference [2]; however, the behavior of the first peak in Figure 1 of reference [2] was obtained. The reason correct behavior was not obtained by the DDSCAT was explored, but no definite explanations concluded. One hypothesis investigated to improve the behavior was to increase the number of dipoles. This hypothesis could not be thoroughly tested due to the increasing CPU time needed. A comparison of the DDSCAT to Mie theory is needed to generalize the overall use of the code and further prove its advantages. Because of reason, research is ongoing.

Exploring the depths of the DDSCAT code exposed the student to many challenges and advanced topics in engineering and physics. The challenging experience motivated the student to think outside the box and dig deeper into the scientific background of the code. The overall IREE experience impacted the student academically and socially. Her knowledge of electromagnetics, optics, and programming has been expanded as well as her perspective of research. The rewarding aspects of research have convinced the student to pursue graduate studies in electrical engineering where she can continue to work on multi-disciplinary projects. Socially the student was able to interact with people from all different backgrounds. A new appreciation for many cultures and languages resulted from her time spent in France. The student feels she has gained a more open mind toward other cultures and was enriched by the surrounding French culture. The student developed a persisting interest in history and art while studying in Troyes. By traveling more she hopes to learn more history of the world, and she is excited to work on other mutli-national teams in the future.

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BRIEF BIOGRAPHIES OF RESEARCHERS

Lauren Megee is currently a senior at the University of Arkansas. She is majoring in Electrical Engineering with a minor in Mathematics. She is a member of the Honors College and an officer of Eta Kappa Nu electrical engineering honor society. She is working under Dr. El-Shenawee for her honors thesis in the area of breast cancer tumor detection.

Magda El-Shenawee worked as a Research Associate in the Center for Electro-Optics at the University of Nebraska where she focused on the problem of enhanced backscatter phenomena. In 1994, she worked as a Research Associate at the National Research Center, Cairo, Egypt, and in 1997, she worked as Visiting Scholar at the University of Illinois at Urbana-Champaign. In 1999, she joined the MURI team (Multidisciplinary

University Research Initiative) at Northeastern University, Boston. Currently, Dr. El-Shenawee is an Associate Professor in the Department of Electrical Engineering at the University of Arkansas, Fayetteville. Her research areas are rough surface scattering, computational electromagnetics, subsurface sensing of buried objects, breast cancer modeling, numerical methods, and microstrip circuits. Dr. El-Shenawee is a member of Eta Kappa Nu electrical engineering honor society.

Demetrio Macias received the B.S and M.S in Electrical Engineering from the National Autonomous University of Mexico in 1993 and 1998, respectively. In 2003 he received the PhD. degree in Physical Optics from the Center for Scientific Research and Higher Education of Ensenada, Baja California, Mexico. In the same year, he joined the Laboratory of nanotechnology and Optical Instrumentation (LNIO) at the University of Technology of Troyes in France, where at present he is Assistant Professor. His current research interests include the modeling and solution of direct and inverse problems in Near-Field Optics and plasmonics.