Applied Computational Electromagnetics Society

Newsletter
Volume 23 – No. 2
ISSN 1056-9170

September 2008

APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY (ACES)

NEWSLETTER

Vol. 23 No. 2 September 2008

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Editor's comment

Another issue comes round with the usual cry of 'where did the summer / winter (delete, as appropriate, depending on hemisphere) go?'

You will have noticed (at least I hope you noticed) that the Newsletter has gone to two issues per year rather than three. This is as a result of another change that I hope you also noticed which is that the Journal has gone to four issues a year. We hope that these changes will be good for the ACES community. On that note, you will see in the Newsletter that the contents pages for the most recent two issues of the Journal are reproduced. Please feel free to copy / print these are pass them on to colleagues whom you feel may be interested in any of the papers published there.

On the topic of copying, the final ACES 'flyer' is reproduced in this Newsletter and you are more than welcome to copy and distribute this to colleagues you think may be interested in the work and the aims of ACES.

Please feel free to contact me with comments about the Newsletter particularly suggestions for what you would like to see here.

Finally, if any ACES members are giving or arranging meetings or talks between now and March, please send me a brief review so I can include that in the next issue and if you are giving or arranging talks or meetings from March 2009 onwards, please send me a brief synopsis (including venue and timing details) and a contact email address, so I can include this information in the March issue.

Best wishes

Alistair

apd@dmu.ac.uk

Applied Computational Electromagnetics Society

News

Time is very short for nominations for ACES Fellows for this year. Please read the next page and think whether there is someone you would like to nominate, either this year or next. Also, meet your new Board of Directors members. Finally, here is the ACES flyer for you to uses should you wish to pass this on to colleagues.

Election of ACES Fellows

As you will know, a new class of membership has been introduced, namely Fellows. Congratulations again to the first class of Fellows:
Dick Adler
Atef Elsherbeni
Allen Glisson
Osama Mohammed
Andy Peterson
Doug Werner

I am sure you will recognize these names through their hard work and dedication to ACES as well as their technical contributions to computational electromagnetics.

To find out more about the ACES Fellow committee, or if you feel that a member of ACES has demonstrated exceptional achievements in computational electromagnetics and that these achievements would be well rewarded with elevation to the grade of Fellow. please contact Professor Andy Peterson(Peterson@ece.gatech.edu). Fellow nominations must be submitted through the "Fellow Nominations" page on the ACES website.

The deadline for submission has been extended to the the 30th September, so time is very limited for nominations for 2008. However, if you read this in time, and you would like to make a nomination, please get in touch with Andy as quickly as you can. If time does not permit this, nominations for the following class of fellows can be submitted at any time up to the end of September 2009.

To guide your thinking and suggestions, the Bye-laws state that:

The grade of Fellow is bestowed by the BOD upon a person with exceptional achievements in computational electromagnetics, including ACES publications, and extensive service to ACES. The candidate, the nominator, and the references must be members of ACES in the nomination year and the year this honor is bestowed.

The Awards and Membership Committee provides a list of recommended candidates to the BOD. At the Fall BOD meeting, the BOD votes to approve the list. ACES Fellows will be officially announced in the March Newsletter and will be recognized at the following ACES conference awards banquet.

Board of Directors Elections

You will, no doubt, already know the results of the Board of Directors' Elections. Thank you to all those who voted. As a reminder, the new members of the Board are as follows. Their term ends in 2011.

Andy Drozd.

Andrew L. Drozd is President and Chief Scientist of ANDRO Computational Solutions, LLC

Andro1@aol.com

Alistair Duffy

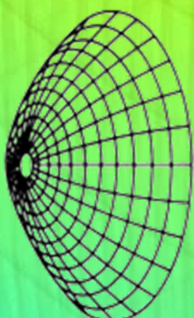
Alistair Duffy is Reader in Electromagnetics at De Montfort University (DMU), Leicester, UK and Head of the Engineering Division in the School of Engineering and Technology.

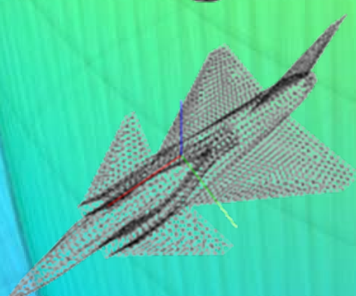
apd@dmu.ac.uk

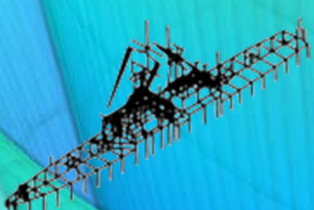
Atef Elsherbeni

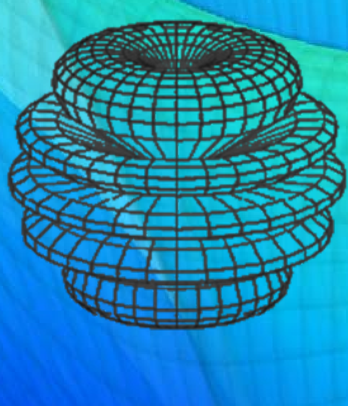
Atef Elsherbeni is Professor of Electrical Engineering in the Department of Electrical Engineering, University of Mississippi.

atef@olemiss.edu







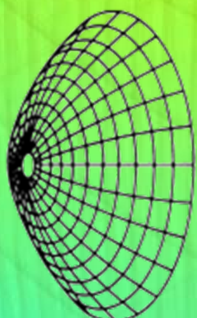


Applied Computational Electromagnetics Society Journal

http://aces.ee.olemiss.edu

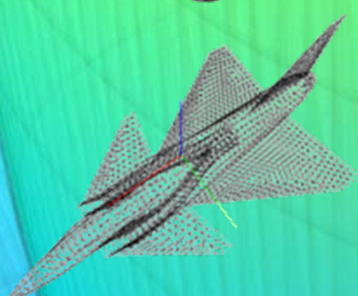
The Applied Computational Electromagnetics Society (ACES) Journal is devoted to the exchange of information in computational electromagnetics, to the advancement of the state of the art, and to the promotion of related technical activities.

The ACES Journal welcomes original previously unpublished papers, relating to applied computational electromagnetics. All papers are refereed.



The scope of the Journal includes, but is not limited to:

- Numerical solution techniques, optimization, and innovation;
- Technological innovation in Electromagnetics;
- Identification of new applications for electromagnetics modeling codes and techniques;
- New materials;
- Biomedical effects of EM fields;
- Integration of computational electromagnetics techniques with new computer architectures;
- Code validation.

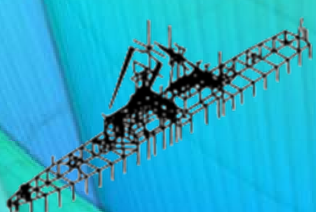


Some recent papers that have appeared in the journal are:

- *A. Taflove, "A Perspective 40–year history of FDTD Computational Electromagnetics," vol. 22, no. 1, pp: 1-21, March 2007.*

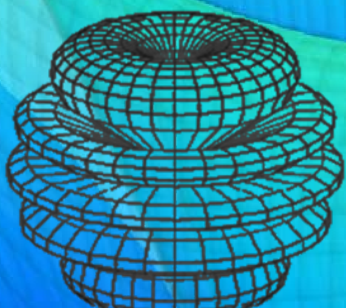
- *J. L. Volakis, K. Sertel, and C. Chen, "Miniature Antennas and Arrays Embedded within Magnetic Photonic Crystals and Other Novel Materials," vol. 22, no. 1, pp: 22-30, March 2007.*

- *S. M. Ali, N. K. Nikolova M. H. Bakr, "Semi-analytical Approach to Sensitivity Analysis of Lossy Inhomogeneous Structures," vol. 22, no. 2, pp. 219-227, July 2007.*



The ACES Journal is scheduled to be published six times annually. The electronic copy of the journal is available at no charge to ACES members.

Editor-in-Chief: **Atef Elsherbeni (atef@olemiss.edu)**



Applied Computational Electromagnetics Society

Around ACES

I was so pleased with the response to the response about the interview with Andy Drozd that I asked the same set of questions to two other ACESians I have known for quite some time: Bruce Archambeault and Liz Davenport. I am sure you will find their responses as interesting as I did.

Natialia Nikolova is another name that will be familiar to many ACES members. She has very kindly let us into her place of work: McMaster University.

Meet the ACESians

Bruce Archambeault

Where were you born and brought up, where do you live now and what circumstances brought you there?
I was born/raised in Manchester, NH (north-eastern USA). About 11 years ago, I moved to North Carolina to get away from the harsh winters and to have more sailing time throughout the year.

What did you read at university, which university(ies) and why this (these) subjects?
I did all of my university work as an adult with a family. I received my BSEE degree from the University of New Hampshire, then my MSEE at Northeaster Univ (Boston). I went back to University of New Hampshire for my PhD in Computational Electromagnetics. I find it hard to believe (after my initial experiences with EM as a BSEE and MSEE student) that I ended up specializing in EM! I think there must have been a fair amount of beer involved in that decision! Honestly, I was frustrated by the lack of understanding that most people seem to have concerning EMI/EMC, and wanted to learn CEM so I could make things more understandable and less magical.

What is your current job and what does it entail? What are you most proud of achieving?
I work for IBM in Research Triangle Park, NC. I was recently promoted to IBM Distinguished Engineer, which gives me a corporate wide mandate to 'improve the technology' where ever I can. I lead a number of other EMI/EMC people in EMI/EMC tool development as well as high speed (fullwave) Signal integrity (SI) tool development.

If you weren't doing this job what would your ideal occupation be? What are your abiding passions?
I like to teach. So if I was not doing this job, I might find a university where I could teach without the hassles associated with the need to get research funding and all the normal 'tenure track' things I hear about from others at universities.

One of my most abiding passions is to make sure users of CEM tools know the tool's limitations, and does the appropriate validation. It appals me how many people purchase expensive software, and then just blindly believe they get the correct answer. I am fond of saying that these tools will give a very accurate answer to whatever question the user asks. But did the user ask the questions they *thought* they were asking?

If you were abandoned in an underground laboratory with no immediate chance of release and with the opportunity of only using one numerical technique, which technique would you want to use and why? What 'big problem' would you want to spend your time trying to solve with your modelling?
I am a firm believer that as engineers we need to use a tool box approach, and use the right tool for the right job. So a variety of simulation techniques are required! But to stay within the constraint of your question, I would probably select FDTD. This technique is the most flexible (in my opinion) so it can be used for nearly anything.

As far as which big problem I would attempt to solve? I honestly do not have one….I work on many different problems, and I would expect that I would continue all these little problems and then bring them together.

If you had a 'one shot' time machine to bring someone from any period of history to keep you company in the underground laboratory, who would you choose and why?
someone with a big shovel to help me get out? I guess for pure conversation, I would select Michangelo (if we could communicate). I think he had more different ideas that were ahead of his time than anyone else I can think about.

Any interesting stories or anecdotes?
This is a true story that happened to me while getting near the end of my PhD studies … While taking the last advanced EM class that I needed for my degree, the professor decided to find the scattering off a circular metal disk. We started with Maxwell's equations, and planned to find the equivalent electric and magnetic currents on the disk, then the fields from those currents. I felt that I understood the math as well as the 'why' for a good part of the derivation. However, at one point, I realized I had lost track of why we were doing these steps. The step-by-step math made sense, but I could not see how this related to the problem we were trying to solve. However, I did not dare ask the professor, since *I* was supposed to know EM, at least, *if* I ever wanted to graduate!

After another class of simply copying the work he wrote on the board into my notebook without understanding, I was getting very nervous. On the third day, the professor was late so I asked the guy next to me for some help. He also did not have a clue what was going on. In fact, no one in the class knew what was going on!

Finally, when the professor appeared, I was brave enough to ask him about what we were doing and why (since it was not only me that did not understand!) He backed up to a point where we needed to integrate from "-a" to "+a" and the formula we were integrating had it's variable in the denominator. Since integration is simply moving along a path, and we would pass through zero on the way from "-a" to "+a", and since we can not have zero in the denominator, he had decided to go from "-a" to minus-infinity, then come back from plus-infinity to "+a"! (I did not know the minus-infinity and plus-infinity were connected!)

So all this work was simply to do an integration along the way to the final answer. So I put my pencil down, and told the professor that to let me know when he gets back to electromagnetics! And I would resume taking notes. He did not like that comment, of course. But if professors would simply tell the students that they need to go into "mathematical hell" for a while, I think EM would be much less scary!

Meet the ACESians

Liz Davenport

Where were you born and brought up, where do you live now and what circumstances brought you there?
I grew up in Croydon, Surrey – a boring place which at the time lacked the amenities of central London because it was too close, but was too far away to access them easily, especially if you're a teenager. Escaped to Bristol University, loved the city & stayed there.

What did you read at university, which university(ies) and why this (these) subjects?
Physics- I became interested at school, and never really thought seriously about doing anything else.

What is your current job and what does it entail? What are you most proud of achieving?
I'm a senior scientist in the mathematical modelling department at the BAE SYSTEMS Advanced Technology Centre, Filton. I work in the electromagnetics group where we're interested in modelling radar returns, installed antenna performance & EMC problems. The main part of my job involves development of software for predicting system EMC performance. I provide the technical input, validate and test the code, train & support new users, and try to prevent the software engineers from overspending.

Achievements? I saved the life of Sooty, my children's hamster, by rescuing her from the innards of the dishwasher.

If you weren't doing this job what would your ideal occupation be? What are your abiding passions?
I suppose my ideal job would be a university lecturer 30-40 years ago!

If you were abandoned in an underground laboratory with no immediate chance of release and with the opportunity of only using one numerical technique, which technique would you want to use and why? What 'big problem' would you want to spend your time trying to solve with your modelling?
The choice of modelling techniques is definitely like swings and roundabouts. Boundary elements are great for predicting scattering from structures, for both antennas and radar cross sections, so long as the scatterer is a good conductor. But if it's made from other materials, then the maths becomes more complex and things start to slow down… Finite difference has the advantages of speed and simplicity- indeed the fastest and simplest method, for both run time and meshing. However it does lack geometrical flexibility, which leads us to

finite elements. These are brilliant for conforming to the structure you're modelling, so long as you can afford to wait until next year for the results. And don't think that buying a bigger better computer will help, the next problem will always be too big for it and the current code will decline to compile. Maybe the best technique to use is the one you're most familiar with – you know where the heffalump traps are!

What 'big problem' would I want to solve? My professional interest, from the EMC viewpoint, is in internal fields in structures such as aircraft and ships, over a wide range of frequencies. The EMC specifications go up to 18GHz, and occasionally 40GHz, so the models are potentially electrically very large. I don't think that conventional CEM is the way to go for such problems, especially if you take into account all the variations in the possible configurations. Cables can follow slightly different routes, connectors and gaskets can change, particularly after use and maintenance, even dimensions and sub-units can vary between different equipments that are nominally the same. A CEM model only gives the right answer for the configuration you've chosen to model. I think the way ahead lies in statistical electromagnetics. So I might prefer to spend my time in the bunker developing ideas in this field, rather than number crunching.

If you had a 'one shot' time machine to bring someone from any period of history to keep you company in the underground laboratory, who would you choose and why?

This answer has nothing to do with work. I'd like to meet my great-grandfather, who was born in 1834, the seventh of ten children, and was working as a mill-hand in a Lancashire cotton factory in 1851. By 1860 he'd become a clergyman in the genteel spa town of Tunbridge Wells in Kent. I want to know how he achieved this. What educational opportunities were offered, and grasped, by him? How hard did he have to work, and who helped? All questions I'll never find the answers to!

Any interesting stories or anecdotes?

No – unless you want a detailed account of the rescue of Sooty from the dishwasher.

The Electromagnetics Research Team at McMaster University

RESEARCH FOCUS AND ACHIEVEMENTS

Our electromagnetics research team is part of the Department of Electrical and Computer Engineering at McMaster University, Canada. It comprises two laboratories: the Simulation Optimization Systems (SOS) Research Laboratory[1] and the Computational Electromagnetics (CEM) Research Laboratory.[2]

Our team is engaged in leading-edge research in electromagnetics-based computer-aided analysis and design of high-frequency structures as well as inverse imaging for the purposes of biomedical diagnostics and non-destructive testing.

The SOS Research Laboratory, headed by Prof. John W. Bandler and founded more than two decades ago, paved the way to the world's first statistical modeling/yield-driven design technology used within major CAD/CAE products. Collaborations, notably with Optimization Systems Associates Inc. (OSA), founded by Bandler, were vital. They made possible the creation of OSA's RoMPE™, HarPE™ and OSA90/hope™, featuring the world's most powerful harmonic balance optimization engines, as well as Empipe™, Empipe3D™, EmpipeExpress™, ***empath***™ and the breakthrough Space Mapping and Geometry Capture technologies. The Empipe family became the foundation of Agilent HFSS Designer and Momentum Optimization. The world's most advanced family of L_1, L_2, Huber, and *minimax* optimizers were implemented. Pioneering developments include design centering, optimal assignment of tolerances, postproduction tuning, and production yield enhancement.

Since 1993, the SOS Research Laboratory has focused on the Space Mapping technology, which it pioneered. This led to the development and exploitation of the user-friendly Matlab-based system called SMF (Space Mapping Framework). The Space Mapping technology, together with surrogate-based modeling and optimization, have grown to become a major research thrust in modern engineering optimization.

The SOS Research Laboratory is currently recognized as a world leader in the theory and applications of the optimization of complex engineering systems.

The CEM Research Laboratory was founded in 1999 and since then has built an international reputation for its leading-edge research in the areas of computer-aided electromagnetic analysis and design. Research is directed by professors Natalia K. Nikolova and Mohamed H. Bakr. On average, the group has 10 full-time graduate students and 2 postdoctoral fellows.

The CEM group works in collaboration with a number of research and industrial partners, notably, Research In Motion (RIM), Intratech Inline Inspection Services, DRDC (Defence Research and Development Canada), Royal Military College, University of Victoria, etc. Projects include microwave imaging for medical diagnostics, radiation hazard evaluation, magnetic flux leakage techniques for nondestructive testing, novel numerical approaches to high-frequency (microwave and photonic) structure analysis, sensitivity analysis for design optimization and inverse problem solutions. Our students are currently actively involved in the design and fabrication of ultra-wideband antennas for microwave imaging as well as a photogrammetry system for surface shape acquisition aiding inverse imaging. They master the theory and practice of electromagnetic simulation, optimization and image reconstruction.

The CEM Research Laboratory has pioneered the development of the first general sensitivity solvers, which work together with commercial and in-house electromagnetic simulators to produce response sensitivities with practically no computational overhead. The sensitivities are used in design optimization and image reconstruction driven by electromagnetic simulation leading to dramatic acceleration of these iterative procedures. With the aid of the computationally cheap sensitivities, yield and tolerances of complex structures are now estimated within seconds. Modeling based on electromagnetic simulation is also made faster and more reliable since the system behavior is described not only through its responses but also their gradients in the parameter space.

RESEARCH FACILITIES

Our research facilities are equipped with vector network analyzers (3.8 GHz, 50 GHz, 110 GHz, 4-port 20 GHz with a 16-port test-set), spectrum analyzers, high-speed oscilloscopes and high-speed arbitrary waveform generators. We have access to the anechoic chamber, the electromagnetic interference chamber and the specific absorption rate measurement facilities at RIM.

[1] http://www.sos.mcmaster.ca/
[2] http://www.ece.mcmaster.ca/faculty/nikolova/cgi-bin/ceml.cgi

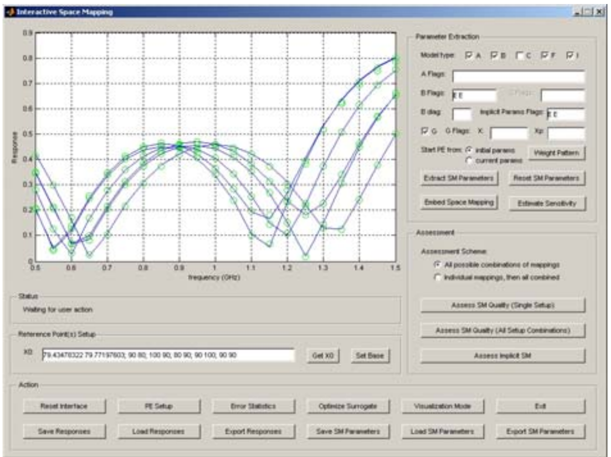


Fig. 1. Space mapping framework (SMF) user interface.

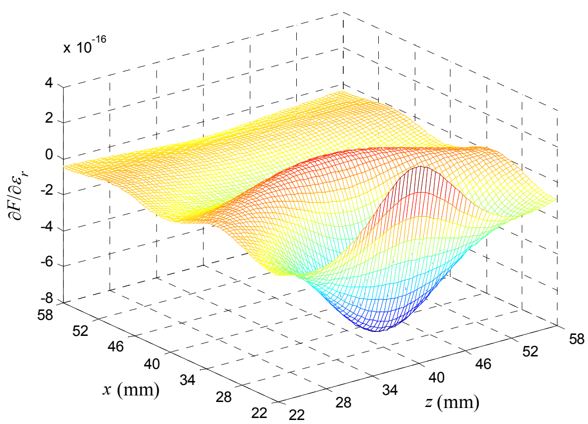


Fig. 2. Permittivity Jacobian map at 4 GHz in an *x-z* cross-section of a breast model derived from a time-domain field solution obtained with Quickwave-3D. The minimum indicates the presence of a small scatterer (tumor simulant).

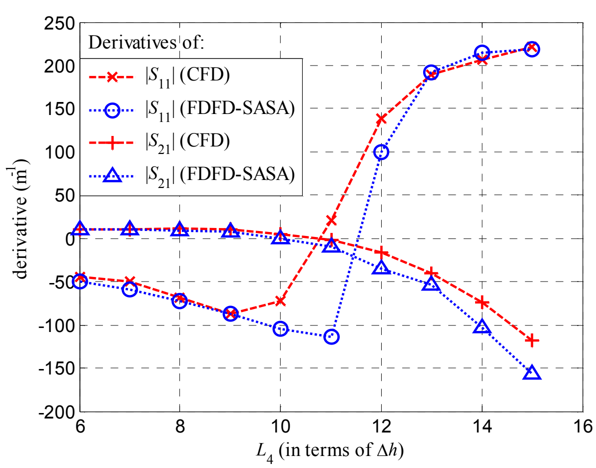


Fig. 3. Derivative curves for the *S*-parameter magnitudes of a waveguide filter calculated from field solutions obtained from a simulation with Ansoft HFSS. The plot validates our results (marked FDFD-SASA) with response-level central finite differences (marked CFD). Derivatives are with respect to a shape parameter L_4 for a sweep of L_4.

Commercial high-frequency CAD packages include: Ansoft HFSS and Maxwell, EMSS FEKO, Remcom XFDTD, Faustus Mefisto-3D Pro, Agilent ADS and Momentum, Sonnet ***em***; QWED Quickwave-3D, etc. We have a powerful computational 12-node Blade cluster. Each of the nodes can handle problems with memory requirements up to 32 GB of RAM.

PROJECTS

Some of the current research projects include:

- Matlab-based Space-Mapping Framework (Fig. 1)
- Sensitivity analysis of high-frequency structures (Figs. 2 and 3)
- Microwave imaging for breast cancer detection (Figs. 4, 5 and 6)
- Antenna design for the microwave imaging system for breast cancer detection (Fig. 7)
- Photogrammetry-based surface reconstruction for arbitrary 3-D objects aiding microwave imaging (Fig. 8)
- Antenna design for minimum specific absorption rate (SAR) of modern handset wireless devices
- SAR evaluation of handhelds (Fig. 9)
- Pipeline inspection based on magnetic flux leakage measurements (Fig. 10)
- Modeling and design of photonic structures (Fig. 11)
- Magnetic tracking system for biomedical applications
- Noise-based radar for concealed weapon detection

Our projects are funded by government research councils and industrial partners.

Fig. 4. *S*-parameter measurement of a breast phantom.

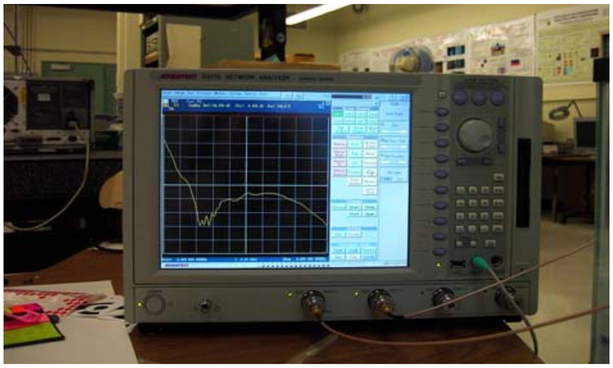


Fig. 5. The 4-port 20 GHz vector network analyzer (Advantest) used in the phantom measurements shown in Fig. 4.

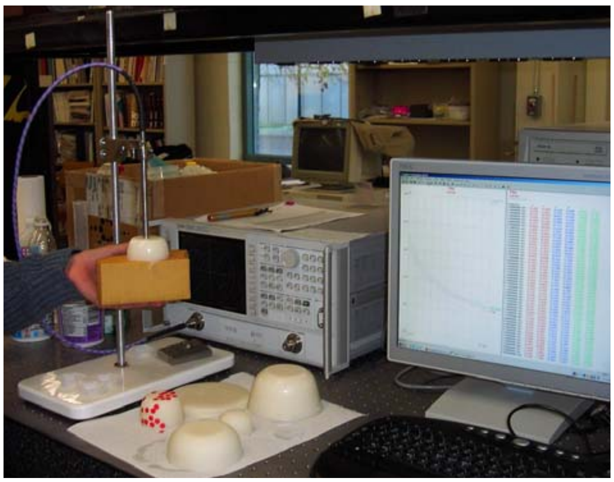


Fig. 6. Measuring the complex permittivity of breast phantoms with Agilent's Dielectric Probe 85070E.

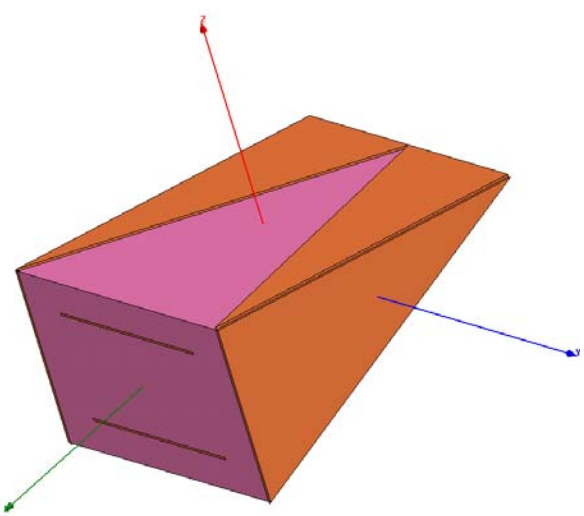


Fig. 7. A solid view of the CAD model of a novel ultra-wideband TEM-horn antenna for breast-imaging measurements.

OUR PROFESSORS

Prof. Bandler studied at Imperial College London and received the B.Sc.(Eng.), Ph.D., and D.Sc.(Eng.) degrees from the University of London, England, in 1963, 1967, and 1976, respectively. He joined McMaster University, Canada, in 1969. He is now Professor Emeritus. He was President of Optimization Systems Associates Inc. (OSA), which he founded in 1983, until November 20, 1997, the date of its acquisition by Hewlett-Packard. He is President of Bandler Corporation, which he founded in 1997. He is Fellow of several societies, including the IEEE, the Royal Society of Canada, and the Canadian Academy of Engineering. He received the Automatic Radio Frequency Techniques Group (ARFTG) Automated Measurements Career Award in 1994, and the IEEE MTT-S Microwave Application Award in 2004.

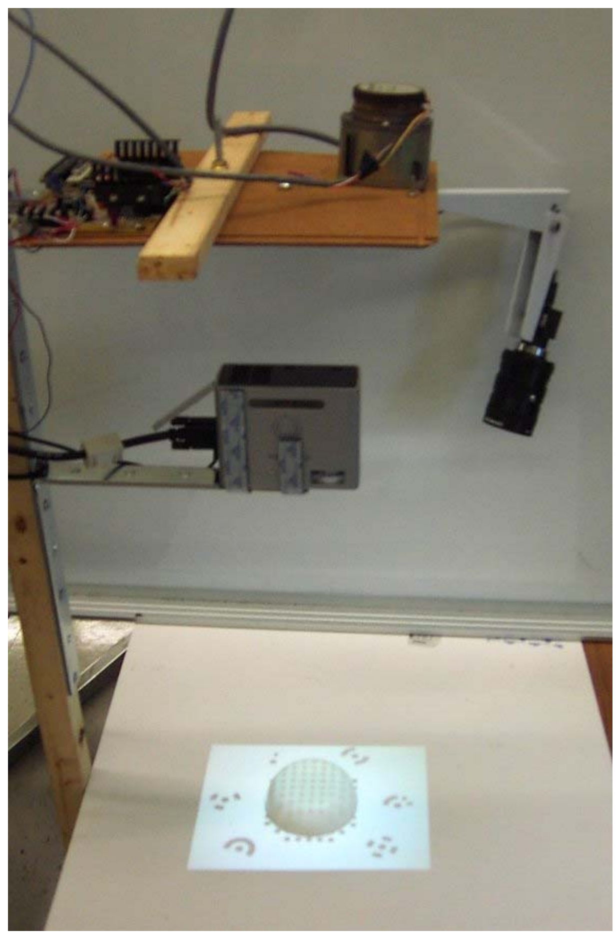


Fig. 8. Photogrammetry system for surface shape acquisition. The knowledge of the shape of the object whose interior is imaged through microwave *S*-parameter measurement enhances greatly the speed and the convergence of the reconstruction algorithm.

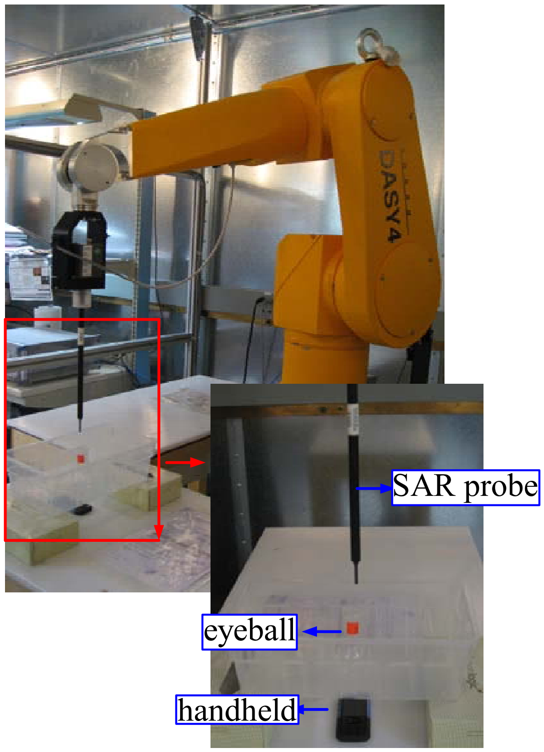


Fig. 9. SAR measurement robot with our human-eye phantom.

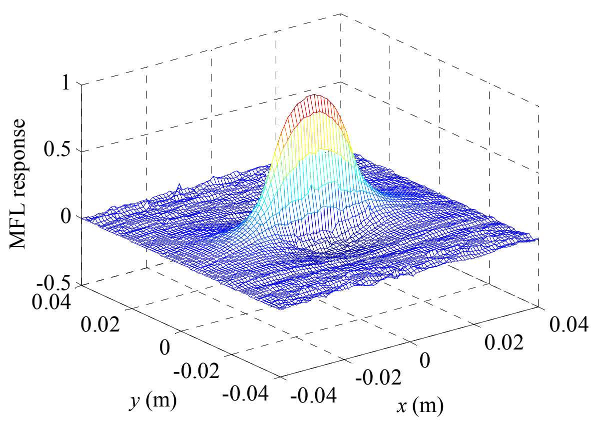


Fig. 10. The magnetic-flux-leakage (MFL) signal clearly indicates the presence of a crack in the wall of a steel gas-line pipe.

Prof. Bakr received the Ph.D. degree from McMaster University, Hamilton, ON, Canada, in 2000. In November 2000, he joined the Computational Electromagnetics Research Laboratory, University of Victoria, Victoria, Canada, as NSERC Post-Doctoral Fellow. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, McMaster University. His research areas include computer-aided design and modeling of microwave circuits and photonic devices, neural-network applications, and bio-electromagnetism.

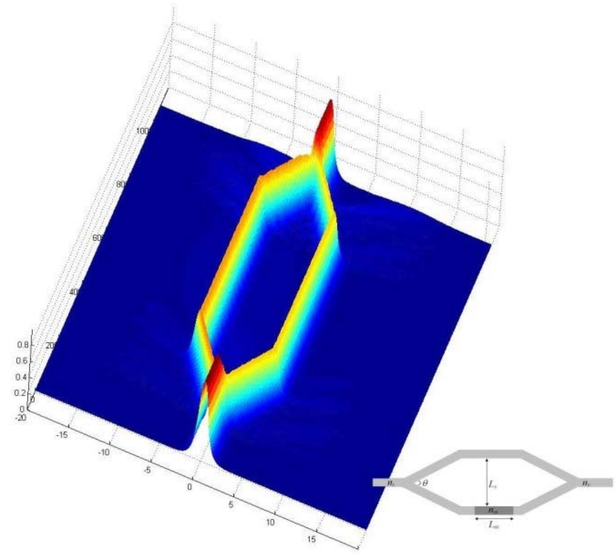
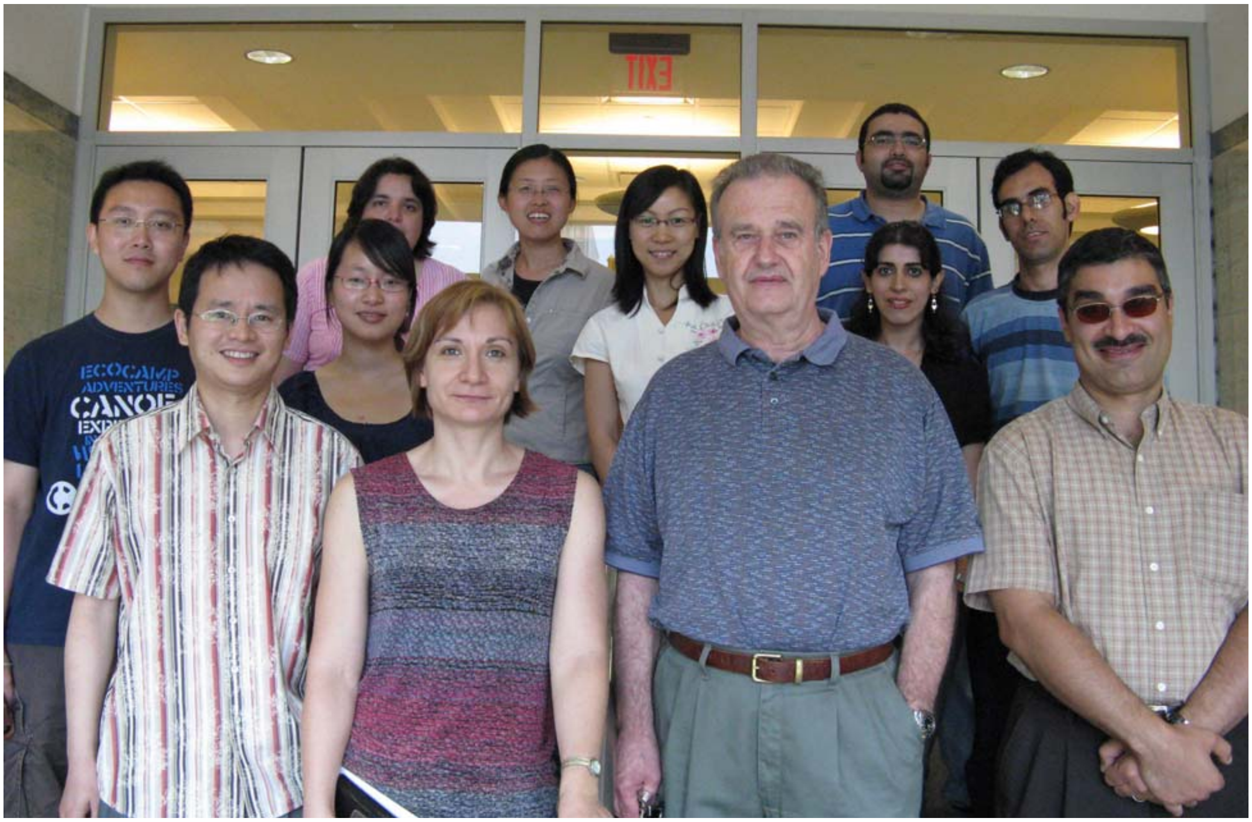


Fig. 11. Mach-Zehnder modulator ("On" state).

Professor Nikolova received the Ph.D. degree from the University of Electro-Communications, Tokyo, Japan, in 1997. From 1998 to 1999, she held a Postdoctoral Fellowship of the Natural Sciences and Engineering Research Council of Canada (NSERC), during which time she was initially with the Microwave and Electromagnetics Laboratory, DalTech, Dalhousie University, Halifax, Canada, and, later, for a year, with the Simulation Optimization Systems Research Laboratory, McMaster University, Hamilton, ON, Canada. In July 1999, she joined the Department of Electrical and Computer Engineering, McMaster University, where she is currently an Associate Professor. Her research interests include theoretical and computational electromagnetism, high-frequency analysis techniques, computer-aided design of high-frequency structures as well as inverse-problem solutions. Dr. Nikolova held a University Faculty Award of NSERC from 2000 to 2005. Since 2008, she is a Canada Research Chair in High-frequency Electromagnetics. She is a senior member of the IEEE, a correspondent of the International Union of Radio Science (URSI), a member of the Applied Computational Electromagnetics Society (ACES) and the ACES Board of Directors.



Members of the electromagnetics team at McMaster University in July 2008. From left to right: 1st row – Dr. Qingsha Cheng (research associate), Prof. Natalia Nikolova, Prof. John Bandler, Prof. Mohamed Bakr; 2nd row – Kai Wang (M.A.Sc. student), Xiaying Zhu (M.A.Sc. student), Li Liu (Ph.D. student), Maryam Ravan (post-doctoral fellow), Reza Amineh (Ph.D. student); 3rd row – Aastha Trehan (M.A.Sc. student), Jie Meng (M.A.Sc. student) and Mohammed Swillam (Ph.D. student).

Applied Computational Electromagnetics Society

Publications update

Another very successful ACES conference has passed and we are looking forward to 2009. The contents of the most recent couple of issues of the Journal are presented: remember, you can access the papers through the ACES website.

The ACES Conference 2008

This year, the Conference was held at Niagara Falls. Your intrepid Newsletter Editor was unable to attend this year (not so intrepid after all!). However, all the conversations I have had with people who did go confirm how successful it was with a good blend of technical papers and both technical and social networking. If you did not manage to go either, please check out the ACES website or the March issue of the Newsletter for a list of papers; also, you will find the welcome message from Natalia and Mohamed interesting.

See you in Monterey next March?

Message from the General Chairmen

On behalf of the ACES 2008 Organizing Committee, we welcome you all to the 2008 Applied Computational Electromagnetic Society (ACES) Conference in Niagara Falls, Canada.

ACES originated from a Computer Modeling/Electromagnetics Workshop, which was held at the Lawrence Livermore National Laboratory on March 19-22, 1985, with the title "First Annual Review of Numerical Electromagnetics Code (NEC) Applications." The primary goal of the Workshop was to initiate a forum for exchange of information about computer modeling tools like the Numerical Electromagnetics Code (NEC).

ACES was officially launched on March 19, 1986. Since then ACES has grown rapidly and now offers high quality services to its members: the Newsletter, the ACES Journal (cited in ISI), and the annual Conference, providing the means to exchange information about electromagnetic computational codes and their performance in real-world applications.

The annual ACES Conference is increasing the number and level of participants every year, becoming the best recognized international symposium on computational methods in electromagnetics. Until 2003, the ACES Conference was held in California (mostly at the Naval Postgraduate School). Since 2004, the conference has been held in different locations in the United States. In 2007, for the first time in ACES history, the Conference took place in Europe, in the charming city of Verona, Italy. This year, the Conference takes place in Niagara Falls, Canada, one of the most beautiful and attractive places in the world.

The ACES 2008 Conference features invited keynote lectures from university and industrial research centers. These talks address the present challenges and the future trends in applications of computational electromagnetics which range from industrial electronics, antenna and *communication system design to medical applications and the design of novel materials of unusual properties. The conference is organized in three and a half days of parallel sessions and a day of short courses. For the first time this year, the ACES Conference organizes a day of Vendor Training Sessions where representatives of the computational-electromagnetics software industry offer parallel training sessions to conference attendees. It is our hope that these sessions will benefit greatly all users of commercial electromagnetic software and will provide a forum for discussion among experts.*

We would like to recognize the people whose efforts made ACES 2008 a success. We express special thanks to the Technical Program Chair, Prof. Atef Elsherbeni, and to Prof. Osama Mohammed, the Chair of the Local Arrangements and Social Program. We recognize the efforts of Dr. C.J. Reddy and Prof. Amir Zaghloul who solicited contributions to the short-course program, to the vendor training program and who promoted the ACES Conference through publicity and a network of contacts. Our thanks go to Prof. Erdem Topsakal and his team of reviewers for the Student Paper Competition, who had exceptionally hard task this year. Many thanks go to our five administrative assistants—they volunteered their time to take care of numerous technical and administrative jobs which make a Conference run smoothly.

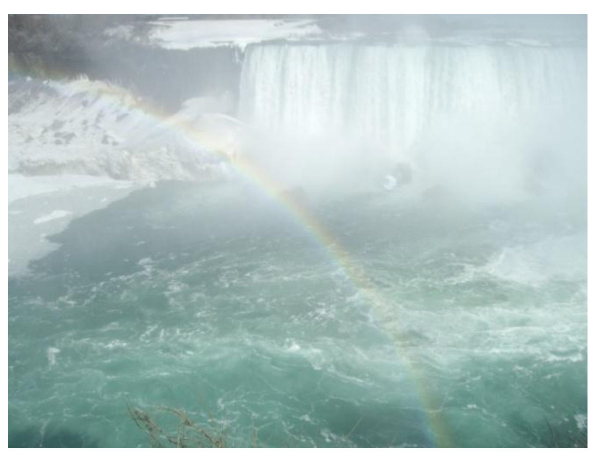
The ACES Conference has traditionally relied on the efforts of dedicated professionals and experts to organize sessions and invite high-quality contributions. This year, we have more than 30 session organizers to whom we extend our greatest thanks—your efforts made ACES 2008 possible and brought contributions of the highest quality!

Much appreciation goes to the ACES 2008 sponsors! The support from the software and communications industry is an important indicator for the significance of what we all do.

While at ACES 2008, enjoy the beauty of early spring in the Niagara Falls region. To more than 18 million visitors annually, the Niagara region is many different things. Most notably, it is the spectacle of Niagara Falls. The Canadian "Horseshoe" Niagara Falls are 180 feet high (about 60 meters) and 2,500 feet (833 meters) wide. Together with the American Falls, they form the second largest falls in the world (after the Victoria Falls in Africa). But Niagara is also the aroma of grapes and the taste of exquisite wines. Niagara boasts the best ice-wineries in the world. To families, Niagara is great theme parks, most notably the numerous attractions of Clifton Hill, which is walking distance from the Conference hotel. To newlyweds, Niagara is the honeymoon capital of the world. To history buffs, Niagara is 20 historical museums, two reconstructed forts, and the historic charm of Niagara on the Lake. To gambling enthusiasts, Niagara is Casino Niagara, Niagara Fallsview Casino Resort and the Fort Erie Racetrack and Slots.

We wish you all productive and enjoyable stay in Niagara Falls!

Natalia K. Nikolova and Mohamed H. Bakr, General Chairs ACES 2008



ACES
Applied Computational Electromagnetics Society

ACES Web Site: ***http://aces.ee.olemiss.edu***

CALL FOR PAPERS

The 25th International Review of Progress in Applied Computational Electromagnetics (ACES 2009)
March 8 – 12, 2009
Embassy Suites Hotel, Monterey, California

On the momentous occasion of the 25th Review, the ACES symposium is returning to Monterey, California in March, 2009. The international ACES symposium serves as a forum for developers, analysts, and users of computational techniques applied to electromagnetic field problems at all frequency ranges. The symposium includes technical presentations, software demonstrations, vendor booths, short courses, and hands-on workshops.

Papers may address general issues in applied computational electromagnetics or may focus on specific applications, techniques, codes, or computational issues of potential interest to the Applied Computational Electromagnetics Society community. The following is a list of suggested topics, although contributions in all areas of computational electromagnetics are encouraged and will be considered.

SUGGESTED TOPICS

Integral Equation Methods
Differential Equation Methods
Fast and Efficient Methods
Hybrid and Multi-Physics Modeling
EM Modeling of Complex Mediums
Modeling Electrically Large Structures
Inverse Scattering and Imaging Techniques
Optimization Techniques for EM-based Design
Asymptotic and High Frequency Techniques
Low Frequency Electromagnetics
Computational Bio-Electromagnetics
Printed and Conformal Antennas
Modeling and Performance of RFID Systems
Wideband and Multiband Antennas
Dielectric Resonator Antennas
Phased Array Antennas
Smart Antenna and Arrays
EBG and Artificial Materials
Nanotechnology Applications
Frequency Selective Surfaces
MEMS-NEMS and MMIC
EMC/EMI Applications
Propagation Analysis
Remote Sensing Applications
RF and Microwave Devices
Modeling and Analysis of TeraHertz Antennas
High Performance Computing
Parallel and GPU Computations
Modeling and Applications of Metamaterial
Modeling and Analysis of Small Antennas

All authors of accepted papers will be invited to submit an extended version of their paper or papers for review and publication in a special issue of the ACES Journal.

SYMPOSIUM STRUCTURE

The international ACES Symposium traditionally includes: (1) oral sessions, regular and invited, (2) poster sessions, (3) a student paper competition, (4) short courses, (5) software demonstrations, (6) an awards banquet, (7) vendor exhibits, and (8) social events. The ACES Symposium also includes plenary and panel sessions, where invited speakers deliver original essay-like reviews of topics of current interest to the computational electromagnetics community.

PAPER FORMATTING REQUIREMENTS

The recommended paper length, including text, figures, tables and references, is four (4) pages, with six (6) pages as a maximum. Submitted papers should be formatted for printing on 8.5x11-inch U.S. standard paper, with one (1) inch top, bottom, and side margins. On the first page, the title should be one and half (1.5) inches from top with authors, affiliations, and e-mail addresses beneath the title. Use single line spacing, with 11 or 12-point font size. The entire text should be fully justified (flush left and flush right). No typed page numbers. A sample paper can be found in the conference section on ACES web site at: ***http://aces.ee.olemiss.edu*****.** Each paper should be submitted in camera-ready format with good resolution and be clearly readable.

PAPER SUBMISSION PROCEDURE

No email, fax or hard-copy paper submission will be accepted. Photo-ready finished papers are required, in Adobe Acrobat format (*.PDF) and must be submitted through ACES web site using the “Upload” button in the left menu, followed by the selection of the “Conference” option, and then following the on-line submission instructions. Successful submission will be acknowledged automatically by email after completing all uploading procedure as specified on ACES web site. Notifications regarding paper submission, acceptance, and all other conference related issues will be directed to the corresponding author email supplied during the paper upload process.

SUBMISSION DEADLINE AND REGISTRATION REQUIREMENT

All papers must be uploaded to the ACES web site by the submission deadline of **November 14, 2008.** This is a firm deadline for all contributed and invited papers, including special session papers. A signed ACES copyright-transfer form must be mailed to the conference technical chair immediately following the submission as instructed in the acknowledgment of submission email message. Papers without an executed copyright form will not be considered for review and possible presentation at the conference. Upon the completion of the review process by the technical program committee, the acceptance notification along with the pre-registration information will be emailed to the corresponding author on or about **January 15, 2009.** Each presenting author is required to complete the paid pre-registration and the execution of any required paper corrections by the firm deadline of **January 31, 2009** for final acceptance for presentation and inclusion of accepted paper in the symposium proceedings.

BEST STUDENT PAPERS CONTEST

The best three (3) student papers presented at the 24th Annual Review will be announced at the symposium banquet. Members of the ACES Board of Directors will judge student papers submitted for this competition. The first, second, and third winners will be awarded cash prizes of **$300, $200**, and **$100**, respectively. Students who wish to participate in this competition should upload their papers directly to the designated **“student paper competition”** session.

For questions please contact one of the conference technical program co-chairs **Dr. Daniela Staiculescu, Prof. Manos Tentzeris, or Prof. Andrew Peterson,** or visit ACES on-line at: ***http://aces.ee.olemiss.edu***

Daniela Staiculescu, (404)-385-6402, *daniela.staiculescu@ece.gatech.edu*
Manos Tentzeris, (404)-385-0378, *etentze@ece.gatech.edu*
Andrew Peterson, (404)-894-4697, *peterson@ece.gatech.edu*

THE APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY

JOURNAL

Vol. 23 No. 2 June 2008

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THE APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY

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Applied Computational Electromagnetics Society

Technical Features

This issue sees the first of a two part feature by Fred Tesche which takes a look at a couple of classic shielding problems.

Electromagnetic Field Shielding of a Spherical Shell – Revisited

Part 1: A Complete Shell

F. M. Tesche
Holcombe Dept. of Electrical and Computer Engineering
College of Engineering & Science, 337 Fluor Daniel Building
Box 340915, Clemson, SC 29634-0915
Fred@Tesche.com

Abstract

This paper takes a fresh look at two classical EM shielding problems involving an integral imperfectly conducting spherical shell and a perfectly conducting hollow sphere with an aperture. Previous studies of the EM shielding provided by these objects have concentrated on evaluating the E- and H-fields at the center of the shield, where only one term of the spherical wave function expansion is needed. While the internal H-field in the shielded volume of the conducting shell is very close to being constant, the same is not true for the E-field, where there can be a significant variation in the E-field intensity from point to point within the interior.

For both of these canonical shielding problems, the method of analysis is described and then applied to determine cumulative probability distributions for the internal fields. In Part 1 of this paper, the frequency-dependent analysis for the case of the complete shell is discussed. To avoid certain numerical overflow problems in evaluating the spherical harmonic solution for lossy media, the use of scaled Hankel functions is described. Additionally, closed-form expressions for the wave expansion coefficients in the spherical coordinate system are derived.

In Part 2 of this paper, the treatment of the hollow sphere with an aperture is obtained using a quasi-static model that also permits the determination of the E-fields anywhere in and around the sphere.

This paper also appears as *Interaction Note 607*, June 5, 2008, Dr. Carl Baum, editor, at www.ece.unm.edu/summa/notes

1. Introduction

There is a continuing need to understand and describe the electromagnetic (EM) field environment inside a protective enclosure that is illuminated by an exterior source. There are several EM standards [1, 2 and 3] that provide measurement procedures to try to obtain shielding effectiveness parameters for enclosures and these standards are often used as requirements for the design and procurement of systems that are protected against external EM fields.

Most of the standards recognize the fact that the EM field within a real enclosure will vary with position and polarization, so that test procedures usually involve making several measurements of the internal field and determining a worst-case shielding estimate. However, due to time and budget constraints, it is unusual to have sufficient measurements to develop a robust statistical representation of the internal fields.

It is possible to use a computational model of an enclosure to determine the internal EM field and its variability. Such models can be of simple canonical shapes like a conducting slab, a cavity bounded by two slabs, a cylinder or a sphere [4, 5]. More complicated models of realistic enclosures having apertures and conducting penetrations are also possible using a finite-difference time domain (FDTD) procedure for solving Maxwell's equations in and around the enclosure [6].

The simplest, yet somewhat realistic, model for shielding is the sphere. Unlike the infinite cylinder or one or more slabs, the sphere has a finite volume, which is typical of a realistic enclosure. Moreover, the EM field in the vicinity of the sphere can be described by relatively simple mathematical functions that permit a numerical computation of the shielding.

Using the spherical wave functions defined by Stratton [7], Harrison and Papas [8] have developed expressions for the E- and H-field at the center of a thin spherical shield due to an incident plane wave excitation. Lindell [9] has examined Harrison's solution near the natural resonances of the sphere, and Shastry [10] has analyzed a hemisphere being excited by a point dipole source. Baum [11] has also examined this problem as a special case illustrating the use of the boundary connection supermatrix (BCS) of a sphere. While all of these investigators have used a modal expansion technique for the solution of the sphere shielding problem, Franceschetti [12] has employed an integral equation method. In each of these references, only the E-fields at the center of the sphere have been considered[1].

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[1] This may be due to two reasons. First, at the center only the $n = 1$ spherical harmonic is needed, so that evaluating an infinite series summation is not required. Second, it is well-known that the quasi-static magnetic field is constant within the sphere volume, and using the center as the B-field observation point is a good choice. Perhaps it was thought that this location would also be suitable for the E-field. However, as will be shown later, the E-field in the sphere varies significantly with position, and the E-field at the center is significantly lower than the average value of E within the sphere.

Real enclosures have openings, so perhaps a uniform spherical model is not the best one to use for understanding the behavior of the internal fields. References [13, 14, and 15] have described analysis procedures for treating a spherical shell with a circular aperture, but their emphasis is on the scattered EM field, not the internal field distribution. Sancer [16] has described a frequency dependent dual series solution for the internal field in a sphere with a hole, and has used this model to determine the quasi-static E and H-fields. Casey [17] has solved the same problem using a quasi-static dual series model. As in the previous references, only the E-fields at the center of the sphere have been calculated in these latter references. A more general frequency dependent solution for the internal fields in a sphere has been described in [18]. This solution involves a modal expansion for the E-fields and is based on the earlier work of [13]. The emphasis of this work, however, is in the resonance region of the sphere.

The work reported in this paper is a re-visitation of two classical canonical shielding problems: a thin spherical shell made of imperfectly conducting material, which is presented in Part 1, and a perfectly conducting hollow sphere with an aperture, which is discussed in Part 2.

In this Part 1, we describe the analysis of the penetrable sphere by using expansion of spherical vector wave functions in the three regions of the problem: inside and outside the sphere and in the wall material of the sphere. In performing this analysis, closed form expressions for the expansion coefficients are determined and tabulated, and a method for eliminating numerical overflow errors in evaluating the Hankel functions in the wave expansions is described. With a computer program developed to evaluate the E- and H-fields anywhere within the shielded volume of the shell, a Monte Carlo simulation has been performed to generate data suitable for describing the cumulative probability distributions (CPD) for the internal fields.

In Part 2, a quasi-static model useful for computing the internal E-field in a sphere with a hole is reviewed. Because the dual H-field problem can be solved from the E-field solution in this case, only the E-field shielding is discussed here. A Monte Carlo simulation is also performed for this shield, and the corresponding CPDs for the E-field are presented.

2. EM Shielding by a Spherical Shell

In this section, the classical solution for shielding of a spherical shell of imperfectly conducting material is reviewed, and the behavior of the internal and external E and H-fields examined. This solution is essentially the same as described by Harrison [8] and many others, although [8] only provides the expressions for the E-field expansion coefficients for the internal fields. In the development here, we will provide closed-form expressions for the EM field coefficients for all regions. In addition, in the present development we pay special attention to the machine computation of the spherical Hankel functions, which are needed in the solution for the E-fields. In particular, we describe a simple modification of the classical spherical wave expansion functions that permit an accurate evaluation of the E and H-fields inside and outside of the shell.

2.1 Problem Geometry

The geometry of the spherical shell illuminated by an incident plane wave propagating in the z-direction is shown in Figure 1. The incident E-field is taken to be in the *x*-direction, with the H-field being in the *y*-direction. The spherical shell is designated as region #1, and has outer and inner radii of *a* and *b*, respectively. The thickness of the shell is denoted by $\Delta = a - b$. The shell is assumed to have the constitutive parameters μ_1 and ε_1 and electrical conductivity σ_1. The material inside and outside the sphere is usually free space and is nonconductive. This material is designated as region #2, with parameters μ_2, ε_2 and $\sigma_2 = 0$. The spherical coordinate system is described by the usual (ρ, θ, ϕ) coordinates, as noted in the figure.

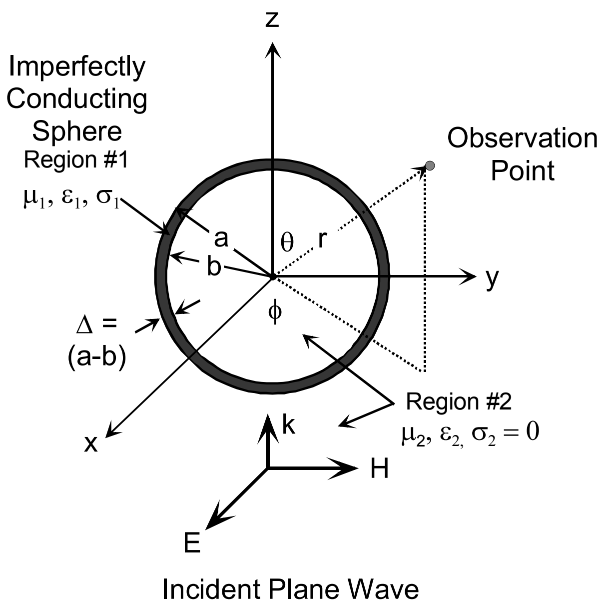

Figure 1. Illustration of a spherical shell illuminated by an incident plane wave.

2.2 Representation of Fields in Spherical Coordinates

In region #1, the wave propagation constant is

$$k_1 \approx \sqrt{\frac{\omega\mu_1\sigma_1}{2}}\left(1-j\right) \quad \text{for } \sigma_1 >> \omega\,\varepsilon_1 \tag{1a}$$

and in region #2

$$k_2 = \omega\sqrt{\mu_2\varepsilon_2}\ . \tag{1b}$$

For use later in this paper, the following ratios are defined:

$$\kappa = \frac{k_2}{k_1} \quad \text{and} \quad \Omega = \frac{\mu_2}{\mu_1} \tag{1c}$$

As developed by Stratton [7] (page 414), the EM field in a spherical coordinate system can be expressed as weighted sums of spherical wave vector functions $\overline{m}^{(i)}_{{}^{e}_{o}m,n}$ and $\overline{n}^{(i)}_{{}^{e}_{o}m,n}$, where indices $n = 0, 1, \cdots \infty$, and $m = 0, 1, \cdots n$. The symbols e and o denote solutions that are even or odd with respect to the x axis, and the index (i) denotes the type of radial function used in the expansion. These vector wave functions are expressed as

$$\overline{m}^{(i)}_{{}^{e}_{o}m,n} = \mp\left(-1\right)^m m\, z_n^{(i)}(kr)\frac{P_n^m(\cos\theta)}{\sin\theta}{}^{\sin}_{\cos}m\phi\,\hat{\theta} - \left(-1\right)^m z_n^{(i)}(kr)\frac{\partial P_n^m(\cos\theta)}{\partial\theta}{}^{\cos}_{\sin}m\phi\,\hat{\phi} \tag{2}$$

$$\begin{aligned}\overline{n}^{(i)}_{{}^{e}_{o}m,n} &= n(n+1)\left(-1\right)^m \frac{z_n^{(i)}(kr)}{kr}P_n^m(\cos\theta){}^{\cos}_{\sin}m\phi\,\hat{r} \\ &+\left(-1\right)^m \frac{1}{kr}\frac{\partial}{\partial(kr)}\left[kr\, z_n^{(i)}(kr)\right]\frac{\partial P_n^m(\cos\theta)}{\partial\theta}{}^{\cos}_{\sin}m\phi\,\hat{\theta} \\ &\mp\left(-1\right)^m \frac{m}{kr\sin\theta}\frac{\partial}{\partial(kr)}\left[kr\, z_n^{(i)}(kr)\right]P_n^m(\cos\theta){}^{\sin}_{\cos}m\phi\,\hat{\phi}\end{aligned} \tag{3}$$

where the radial function $z_n^{(i)}(kr)$ is

$$z_n^{(i)}(kr) = \begin{bmatrix} j_n(kr) & i=1 \\ y_n(kr) & i=2 \\ h_n^{(1)}(kr) & i=3 \\ h_n^{(2)}(kr) & i=4 \end{bmatrix}. \tag{4}$$

and k denotes the propagation constant for the specific medium in which the spherical waves are propagating.

The function $P_n^m(x)$ in Eqs.(2) and (3) are the associated Legendre polynomials[2], which according to [19, §8.66] , are defined from the Legendre polynomials $P_n(x)$ by

$$P_n^m(x) = (-1)^m (1-x^2)^{\frac{1}{2}m} \frac{d^m P_n(x)}{dx^m}. \tag{5}$$

From [8] the x-directed incident plane wave shown in Figure 1 may be expressed by the spherical wave functions as

$$\begin{aligned} E^i &= E_o e^{-jk_2 x} \hat{x} \\ &= E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[\overline{m}_{o,1,n}^{(1)} + j\overline{n}_{e,1,n}^{(1)} \right] \end{aligned} \tag{6a}$$

$$H^i = -\frac{k_2}{\omega\mu_2} E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[\overline{m}_{e,1,n}^{(1)} - j\overline{n}_{o,1,n}^{(1)} \right] \ , \tag{6b}$$

and the scattered (or "reflected") field for $r > a$ is

$$E^r = E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[a_n^r \, \overline{m}_{o,1,n}^{(4)} + j b_n^r \overline{n}_{e,1,n}^{(4)} \right] \ (r \geq a) \tag{7a}$$

$$H^r = -\frac{k_2}{\omega\mu_2} E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[b_n^r \, \overline{m}_{e,1,n}^{(4)} - j a_n^r \, \overline{n}_{o,1,n}^{(4)} \right] \ (r \geq a) \, . \tag{7b}$$

Note that the arguments of the radial functions in Eqs.(6) and (7) are (k_2a) and the leading factor for the H-field $k_2/\omega\mu_2$ is simply the characteristic wave impedance in medium 2.

Inside the material of the spherical shell, the EM fields are represented in a similar manner, as

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[2] It is unfortunate that there is an inconsistency in the definition of the associated Legendre polynomials in the literature. Some references, such as Abramowitz [19] include the $(-1)^m$ parameter in the definition, as shown in Eq.(5). However other authors, including Stratton, omit this factor, with the result that the definition of the vector wave functions of Eqs. (3) and (4) can vary from text to text. In this paper, we use Abramowitz's definition and have modified the wave functions of Stratton by adding the term $(-1)^m$ to Eqs. (3) and (4). Butler [20] has surveyed a number of widely used texts for their usage of this term with the following results. Those authors using the $(-1)^m$ term include Abramowitz & Stegun, R. Harrington, D. S. Jones, Magnus & Oberhettinger and S. Schelkunoff. Authors that exclude this term include J. Van Bladel, J. Stratton, A. Sommerfeld and W. Smythe.

$$E^s = E_o \left\{ \begin{array}{l} \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[p_n \overline{m}_{o,1,n}^{(4)} + j\, q_n\, \overline{n}_{e,1,n}^{(4)} \right] \\ + \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[d_n\, \overline{m}_{o,1,n}^{(3)} + j\, f_n\, \overline{n}_{e,1,n}^{(3)} \right] \end{array} \right\} \; (b < r < a) \qquad (8a)$$

$$H^s = -\frac{k_1}{\omega\mu_1} E_o \left\{ \begin{array}{l} \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[q_n\, \overline{m}_{e,1,n}^{(4)} - j p_n\, \overline{n}_{o,1,n}^{(4)} \right] \\ + \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[f_n\, \overline{m}_{e,1,n}^{(3)} - j d_n\, \overline{n}_{o,1,n}^{(3)} \right] \end{array} \right\} \; (b < r < a) \qquad (8b)$$

with the radial functions arguments being ($k_1 a$).

Inside the sphere void, the E-field representation is

$$E^c = E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[a_n^c\, \overline{m}_{o,1,n}^{(1)} + j b_n^c \overline{n}_{e,1,n}^{(1)} \right] \; (r \le b) \qquad (9a)$$

$$H^c = -\frac{k_2}{\omega\mu_2} E_o \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[b_n^c\, \overline{m}_{e,1,n}^{(1)} - j a_n^c\, \overline{n}_{o,1,n}^{(1)} \right] \; (r \le b)\,. \qquad (9b)$$

with the radial functions arguments ($k_2 a$).

The eight parameters a_n^r, b_n^r, p_n, q_n, d_n, f_n, a_n^c and b_n^c in Eqs.(7 – 9) are unknowns[3] that can be determined by the boundary conditions at the interfaces at $r = a$ and $r = b$ of the sphere. These boundary conditions are that the tangential components of E and H must be continuous through the interfaces, and are

$$\begin{array}{l} \left(E^i + E^r\right)_\theta = \left(E^s\right)_\theta \quad \text{and} \quad \left(E^i + E^r\right)_\phi = \left(E^s\right)_\phi \\ \left(H^i + H^r\right)_\theta = \left(H^s\right)_\theta \quad \text{and} \quad \left(H^i + H^r\right)_\phi = \left(H^s\right)_\phi \end{array} \; (\text{at } r = a) \qquad (10)$$

and with the same conditions at $r = b$.

In ref. [8], only the $n = 1$ case was considered, as the EM fields were to be calculated only at the center of the sphere. At that location, higher order terms of n in the E-field expansion vanish. For the more general case, however, other values of n must be considered. By applying the boundary conditions independently for each value of n, one can obtain a set of eight equations relating the coefficients $a_n^r, b_n^r \cdots b_n^c$. These equations are

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[3] These parameters are named in the same way as in ref. [8].

$$j_n(k_2a) + a_n^r h_n^{(2)}(k_2a) = p_n h_n^{(2)}(k_1a) + d_n h_n^{(1)}(k_1a) \tag{11a}$$

$$\left\{\left[k_2a\, j_n(k_2a)\right]' + b_n^r\left[k_2a\, h_n^{(2)}(k_2a)\right]'\right\} = \kappa\left[q_n\left[k_1a\, h_n^{(2)}(k_1a)\right]' + f_n\left[k_1a\, h_n^{(1)}(k_1a)\right]'\right] \tag{11b}$$

$$\frac{\kappa}{\Omega}\left[j_n(k_2a) + b_n^r h_n^{(2)}(k_2a)\right] = q_n h_n^{(2)}(k_1a) + f_n h_n^{(1)}(k_1a) \tag{11c}$$

$$\frac{1}{\Omega}\left\{\left[k_2a\, j_n(k_2a)\right]' + a_n^r\left[k_2a\, h_n^{(2)}(k_2a)\right]'\right\} = p_n\left[k_1a\, h_n^{(2)}(k_1a)\right]' + d_n\left[k_1a\, h_n^{(1)}(k_1a)\right]' \tag{11d}$$

$$p_n h_n^{(2)}(k_1b) + d_n h_n^{(1)}(k_1b) = a_n^c\, j_n(k_2b) \tag{11e}$$

$$\kappa\left\{q_n\left[k_1b\, h_n^{(2)}(k_1b)\right]' + f_n\left[k_1b\, h_n^{(1)}(k_1b)\right]'\right\} = b_n^c\left[k_2b\, j_n(k_2b)\right]' \tag{11f}$$

$$\frac{\Omega}{\kappa}\left[q_n h_n^{(2)}(k_1b) + f_n h_n^{(1)}(k_1b)\right] = b_n j_n(k_2b) \tag{11g}$$

$$\Omega\left\{p_n\left[k_1b\, h_n^{(2)}(k_1b)\right]' + d_n\left[k_1b\, h_n^{(1)}(k_1b)\right]'\right\} = a_n^c\left[k_2b\, j_n(k_2b)\right]' \tag{11h}$$

where the parameters κ and Ω have been defined in Eq.(1c).

2.3 Scaling of the Hankel Functions and Expansion Coefficients

In trying to use these equations for determining the expansion coefficients, there is a problem that arises in the evaluation of the wave functions in region #1 where $k = k_1$, due to the exponential variation of the Hankel functions $h_n^{(1)}(ka)$ and $h_n^{(1)}(kb)$. To see this, ref[19, §10.1.16] provides the following representations for the spherical Hankel functions

$$\begin{aligned} h_n^{(1)}(kr) &= j^{-n-1}(kr)^{-1} e^{jkr} \sum_{k=0}^{n} \frac{(n+k)!}{k!\Gamma(n-k+1)}(-2jkr)^{-k} \\ &\equiv e^{jkr}\hat{h}_n^{(1)}(kr) \end{aligned} \tag{12a}$$

$$\begin{aligned} h_n^{(2)}(kr) &= j^{n+1}(kr)^{-1} e^{-jkr} \sum_{k=0}^{n} \frac{(n+k)!}{k!\Gamma(n-k+1)}(2jkr)^{-k} \\ &\equiv e^{-jkr}\hat{h}_n^{(2)}(kr) \end{aligned} \tag{12b}$$

These relationships define $\hat{h}_n^{(1)}(kr)$ and $\hat{h}_n^{(2)}(kr)$, which are *scaled Hankel functions*[4]. These scaled functions maintain reasonable accuracy over a wide range of the complex parameter (kr) and are provided by many special function routines. Note that this is not an approximation to the Hankel functions, but rather, just a factorization of the functions.

As a consequence of Eq.(12a), we observe that in region #1 $h_n^{(1)}(kr) \sim e^{\sqrt{\frac{\omega\mu_1\sigma_1}{2}}r}$ and this function becomes unbounded as $\omega \to \infty$. The direct use of this function in a numerical calculation becomes impossible at high frequencies – even if its exponential growth may be ultimately cancelled somewhere in a complicated expression by the exponential decrease of functions like $h_n^{(2)}(kr) \sim e^{-\sqrt{\frac{\omega\mu_1\sigma_1}{2}}r}$.

To solve this problem, we express the boundary conditions and Hankel functions in region #1 using the scaled spherical Hankel functions and the appropriate scaling factors as

$$h_n^{(1)}(k_1a) = T_1\,\hat{h}_n^{(1)}(k_1a) \qquad h_n^{(2)}(k_1a) = \frac{1}{T_1}\hat{h}_n^{(2)}(k_1a) \tag{13}$$

$$h_n^{(1)}(k_1b) = \frac{T_1}{T_\Delta}\hat{h}_n^{(1)}(k_1b) \qquad h_n^{(2)}(k_1b) = \frac{T_\Delta}{T_1}\hat{h}_n^{(2)}(k_1b) \tag{14}$$

where $T_1 = e^{jk_1a}$ and $T_\Delta = e^{jk_1(a-b)} = e^{jk_1\Delta}$.

Using these scaled Hankel functions in region #1, the boundary conditions in Eqs.(11) can be written in a compact matrix form as

[4] In this paper, any parameter or function with the ^ symbol is designated as a scaled quantity.

$$
\begin{bmatrix}
-h_n^{(2)}(k_2a) & 0 & \frac{1}{T_1}\hat{h}_n^{(2)}(k_1a) & 0 & T_1\hat{h}_n^{(1)}(k_1a) & 0 & 0 & 0 \\
0 & -\left[k_2a\,h_n^{(2)}(k_2a)\right]' & 0 & \frac{\kappa}{T_1}\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]' & 0 & \kappa T_1\left[k_1a\,\hat{h}_n^{(1)}(k_1a)\right]' & 0 & 0 \\
0 & -\frac{\kappa}{\Omega}h_n^{(2)}(k_2a) & 0 & \frac{1}{T_1}\hat{h}_n^{(2)}(k_1a) & 0 & T_1\,\hat{h}_n^{(1)}(k_1a) & 0 & 0 \\
-\frac{1}{\Omega}\left[k_2a\,h_n^{(2)}(k_2a)\right]' & 0 & \frac{1}{T_1}\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]' & 0 & T_1\left[k_1a\,\hat{h}_n^{(1)}(k_1a)\right]' & 0 & 0 & 0 \\
0 & 0 & \frac{T_\Delta}{T_1}\hat{h}_n^{(2)}(k_1b) & 0 & \frac{T_1}{T_\Delta}\hat{h}_n^{(1)}(k_1b) & 0 & -j_n(k_2b) & 0 \\
0 & 0 & 0 & \frac{T_\Delta}{T_1}\kappa\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right] & 0 & \frac{T_1}{T_\Delta}\kappa\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' & 0 & -\left[k_2b\,j_n(k_2b)\right]' \\
0 & 0 & 0 & \frac{T_\Delta}{T_1}\frac{\Omega}{\kappa}\hat{h}_n^{(2)}(k_1b) & 0 & \frac{T_1}{T_\Delta}\frac{\Omega}{\kappa}\hat{h}_n^{(1)}(k_1b) & 0 & -j_n(k_2b) \\
0 & 0 & \frac{T_\Delta}{T_1}\Omega\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right]' & 0 & \frac{T_1}{T_\Delta}\Omega\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' & 0 & -\left[k_2b\,j_n(k_2b)\right]' & 0
\end{bmatrix}
\begin{bmatrix} a_n^r \\ b_n^r \\ p_n \\ q_n \\ d_n \\ f_n \\ a_n^c \\ b_n^c \end{bmatrix}
=
\begin{bmatrix} j_n(k_2a) \\ \left[k_2a\,j_n(k_2a)\right]' \\ \frac{\kappa}{\Omega}j_n(k_2a) \\ \frac{1}{\Omega}\left[k_2a\,j_n(k_2a)\right]' \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\tag{15}
$$

To observe the effects of using the scaled Hankel functions and to provide an alternative to a strict numerical inversion of Eq.(15), it is useful to develop closed-form expressions for the expansion coefficients. Reference [8] provides expressions for the coefficients a_1^c and b_1^c for the E-fields at the center of the sphere, and here we generalize their results for arbitrary n and for all regions. It should also be mentioned that Baum [11] in his Appendix A also provides expressions for the expansion coefficients, but not in stand-alone terms, but as ratios of confidents, relative to the coefficients of the incident plane wave.

Obtaining such a symbolic solution is tedious but it can be accomplished using a symbolic solver to invert Eq.(15) and obtain algebraic expressions for the coefficients. In doing this there are two terms that occur in the denominators of the various expressions for the coefficients. These are denoted as *Den1* and *Den2* and are

$$\begin{aligned} Den1_n = \frac{1}{T_\Delta}&\left[\left(\Omega\, j_n(k_2b)\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' - \left[k_2b\, j_n(k_2b)\right]'\hat{h}_n^{(1)}(k_1b)\right)\left(\hat{h}_n^{(2)}(k_1a)\left[k_2a\, h_n^{(2)}(k_2a)\right]' - \Omega\, h_n^{(2)}(k_2a)\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]'\right)\right] \\ +T_\Delta&\left[\left(\Omega\, j_n(k_2b)\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right]' - \left[k_2b\, j_n(k_2b)\right]'\hat{h}_n^{(2)}(k_1b)\right)\left(\Omega\, h_n^{(2)}(k_2a)\left[k_1a\,\hat{h}_n^{(1)}(k_1a)\right]' - \hat{h}_n^{(1)}(k_1a)\left[k_2a\, h_n^{(2)}(k_2a)\right]'\right)\right] \end{aligned} \tag{16a}$$

$$\begin{aligned} Den2_n = \frac{1}{T_\Delta}&\left[\left(\kappa^2 j_n(k_2b)\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' - \Omega\left[k_2b\, j_n(k_2b)\right]'\hat{h}_n^{(1)}(k_1b)\right)\left(\Omega\hat{h}_n^{(2)}(k_1a)\left[k_2a\, h_n^{(1)}(k_2a)\right]' - \kappa^2 h_n^{(2)}(k_2a)\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]'\right)\right] \\ +T_\Delta&\left[\left(\kappa^2 j_n(k_2b)\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right]' - \Omega\left[k_2b\, j_n(k_2b)\right]'\hat{h}_n^{(2)}(k_1b)\right)\left(\kappa^2 h_n^{(2)}(k_2a)\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]' - \Omega\hat{h}_n^{(1)}(k_1a)\left[k_2a\, h_n^{(2)}(k_2a)\right]'\right)\right] \end{aligned} \tag{16b}$$

It is important to note that the scaling function T_1 does not occur in these denominator functions as they have cancelled out in the products of terms like $\hat{h}_n^{(1)}(k_1b)\cdot\hat{h}_n^{(2)}(k_1a)$. There still is the scaling function $T_\Delta = e^{jk_1\Delta}$ present in these expressions, but for thin shells, this term is easily computed and it does not become so large as to cause numerical round-off problems.

The unscaled parameters a_n^r, b_n^r, p_n, q_n, d_n, f_n, a_n^c and b_n^c are given in closed form as follows:

$$\begin{aligned} a_n^r = -\frac{1}{Den1_n}\frac{1}{T_\Delta}&\left[\left(\hat{h}_n^{(2)}(k_1a)\left[k_2a\, j_n(k_2a)\right]' - \Omega\, j_n(k_2a)\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]'\right)\left(\Omega\, j_n(k_2b)\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' - \hat{h}_n^{(1)}(k_1b)\left[k_2b\, j_n(k_2b)\right]'\right)\right] \\ -\frac{1}{Den1_n}T_\Delta&\left[\left(\hat{h}_n^{(1)}(k_1a)\left[k_2a\, j_n(k_2a)\right]' - \Omega\, j_n(k_2a)\left[k_1a\,\hat{h}_n^{(1)}(k_1a)\right]'\right)\left(\hat{h}_n^{(2)}(k_1b)\left[k_2b\, j_n(k_2b)\right]' - \Omega\, j_n(k_2b)\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right]'\right)\right] \end{aligned} \tag{17a}$$

$$\begin{aligned} b_n^r = -\frac{1}{Den2_n}\frac{1}{T_\Delta}&\left[\left(\Omega\hat{h}_n^{(2)}(k_1a)\left[k_2a\, j_n(k_2a)\right]' - \kappa^2 j_n(k_2a)\left[k_1a\,\hat{h}_n^{(2)}(k_1a)\right]'\right)\left(\kappa^2 j_n(k_2b)\left[k_1b\,\hat{h}_n^{(1)}(k_1b)\right]' - \Omega\hat{h}_n^{(1)}(k_1b)\left[k_2b\, j_n(k_2b)\right]'\right)\right] \\ -\frac{1}{Den2_n}T_\Delta&\left[\left(\kappa^2 j_n(k_2a)\left[k_1a\,\hat{h}_n^{(1)}(k_1a)\right]' - \Omega\hat{h}_n^{(1)}(k_1a)\left[k_2a\, j_n(k_2a)\right]'\right)\left(\kappa^2 j_n(k_2b)\left[k_1b\,\hat{h}_n^{(2)}(k_1b)\right]' - \Omega\hat{h}_n^{(2)}(k_1b)\left[k_2b\, j_n(k_2b)\right]'\right)\right] \end{aligned} \tag{17b}$$

$$p_n = -\frac{1}{Den1_n}\frac{T_1}{T_\Delta}\left[\left(\frac{-j}{k_2 a}\right)\left(\hat{h}_n^{(1)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \Omega\, j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(1)}(k_1 b)\right]'\right)\right] \tag{17c}$$

$$q_n = -\frac{\kappa}{Den2_n}\frac{T_1}{T_\Delta}\left[\left(\frac{-j}{k_2 a}\right)\left(\Omega\,\hat{h}_n^{(1)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \kappa^2 j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(1)}(k_1 b)\right]'\right)\right] \tag{17d}$$

$$d_n = \frac{1}{Den1_n}\frac{T_\Delta}{T_1}\left[\left(\frac{-j}{k_2 a}\right)\left(\hat{h}_n^{(2)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \Omega\, j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(2)}(k_1 b)\right]'\right)\right] \tag{17e}$$

$$f_n = \frac{\kappa}{Den2_n}\frac{T_\Delta}{T_1}\left[\left(\frac{-j}{k_2 a}\right)\left(\Omega\,\hat{h}_n^{(2)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \kappa^2 j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(2)}(k_1 b)\right]'\right)\right] \tag{17f}$$

$$a_n^c = \frac{\Omega}{Den1_n}\left(\frac{-j}{k_2 a}\right)\left(\frac{2j}{k_1 b}\right) \tag{17g}$$

$$b_n^c = \frac{\Omega\kappa^2}{Den2_n}\left(\frac{-j}{k_2 a}\right)\left(\frac{2j}{k_1 b}\right) \tag{17h}$$

Equations (17c) through (17h) have been simplified somewhat through the use of appropriate Wronskian relationships between the radial functions. Reference [11] also discusses this simplification. Furthermore, if $\Omega = 1$, additional simplifications are possible.

Notice that in Eqs.(17a, b, g and f) for parameters a_n^r, b_n^r, a_n^c and b_n^c the scaling factors T_1 and $1/T_1$ have all canceled with each other, and these parameters do not occur in the solution. The evaluation of these parameters using the scaled Hankel functions poses no problem at all. However, if Eq.(16) were to be solved numerically, there would be serious overflow and underflow problems due to the presence of the scaling factors.

Furthermore, in Eqs.(17) we observe that the parameters p_n and q_n are proportional to T_1, and parameters d_n and f_n are proportional to $1/T_1$. These expressions show symbolically why the direct evaluation of even these closed-form coefficients is prone to error due to the very large or very small values of these proportionality constants. By removing the T_1 scaling parameter from Eqs.(17c) – (17f) as

$$\begin{aligned} p_n &= T_1 \hat{p}_n \qquad q_n = T_1 \hat{q}_n \\ d_n &= \frac{1}{T_1}\hat{d}_n \qquad f_n = \frac{1}{T_1}\hat{f}_n \end{aligned} . \tag{18}$$

we can define *scaled* expansion parameters $\hat{p}_n, \hat{q}_n, \hat{d}_n, \hat{f}_n$, which are

$$\hat{p}_n = -\frac{1}{Den1_n}\frac{1}{T_\Delta}\left[\left(\frac{-j}{k_2 a}\right)\left(\hat{h}_n^{(1)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \Omega\, j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(1)}(k_1 b)\right]'\right)\right] \quad (19a)$$

$$\hat{q}_n = -\frac{\kappa}{Den2_n}\frac{1}{T_\Delta}\left[\left(\frac{-j}{k_2 a}\right)\left(\Omega\, \hat{h}_n^{(1)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \kappa^2 j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(1)}(k_1 b)\right]'\right)\right] \quad (19b)$$

$$\hat{d}_n = \frac{1}{Den1_n} T_\Delta\left[\left(\frac{-j}{k_2 a}\right)\left(\hat{h}_n^{(2)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \Omega\, j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(2)}(k_1 b)\right]'\right)\right] \quad (19c)$$

$$\hat{f}_n = \frac{\kappa}{Den2_n} T_\Delta\left[\left(\frac{-j}{k_2 a}\right)\left(\Omega\, \hat{h}_n^{(2)}(k_1 b)\left[k_2 b\, j_n(k_2 b)\right]' - \kappa^2 j_n(k_2 b)\left[k_1 b\, \hat{h}_n^{(2)}(k_1 b)\right]'\right)\right] \quad (19d)$$

The use of these scaled parameters in evaluating the E- and H-fields is discussed in the next section.

It is worth pointing out that the evaluation of the required set of unscaled parameters a_n^r, b_n^r, a_n^c and b_n^c and scaled parameters $\hat{p}_n, \hat{q}_n, \hat{d}_n, \hat{f}_n$ can also be computed from a numerical inversion of Eq.(15). This may be done by setting the scaling parameter T_1 = 1 and using scaled Hankel functions $\hat{h}_n^{(1)}(k_1 a)$, $\hat{h}_n^{(2)}(k_1 a)$, $\hat{h}_n^{(1)}(k_1 b)$ and $\hat{h}_n^{(2)}(k_1 b)$ as indicated in Eq.(15) to obtain a numerically stable matrix equation that can be easily inverted. Although there is not much insight into the structure of the solution for these parameters in this numerical approach, the coding of this equation is certainly much simpler (and less error-prone) than developing code for the closed-form expressions.

2.4 Use of Scaled Parameters in Determining E- and H-fields

To use these scaled coefficients in the solution for the E-fields in the sphere, we observe that in Eq.(8) the p_n and q_n parameters are always multiplied by $h_n^{(2)}(k_1 r)$ and d_n and f_n occur together with $h_n^{(1)}(k_1 r)$. Thus, in Eq.(8) the product $p_n\, \vec{m}_{o,1,n}^{(4)}$ can be written as

$$p_n\, \vec{m}_{o,1,n}^{(4)} = T_1 \hat{p}_n\, e^{-jk_1 r}\, \hat{\vec{m}}_{o,1,n}^{(4)} \quad (20)$$

where the exponential scaling factor $e^{-jk_1 r}$ has been extracted from the Hankel function $h_n^{(2)}(k_1 r)$. The term $\hat{\vec{m}}_{o,1,n}^{(4)}$ denotes the spherical harmonic function *evaluated with the scaled Hankel function* $\hat{h}_n^{(2)}(k_1 r)$.

The scaling terms in Eq.(20) can be combined into a common factor $S(k_1 r)$ as

$$p_n\,\overline{m}^{(4)}_{o,1,n} = S\left(k_1 r\right)\hat{p}_n\,\hat{\overline{m}}^{(4)}_{o,1,n} \tag{21}$$

with

$$S\left(k_1 r\right) \equiv e^{jk_1(a-r)}\,. \tag{22}$$

Similarily, the other products of the parameters and wave functions can be written as

$$q_n\,\overline{m}^{(4)}_{e,1,n} = S\left(k_1 r\right)\hat{q}_n\,\hat{\overline{m}}^{(4)}_{e,1,n} \qquad p_n\,\overline{n}^{(4)}_{o,1,n} = S\left(k_1 r\right)\hat{p}_n\,\hat{\overline{n}}^{(4)}_{o,1,n} \qquad q_n\,\overline{n}^{(4)}_{e,1,n} = S\left(k_1 r\right)\hat{q}_n\,\hat{\overline{n}}^{(4)}_{e,1,n} \tag{23}$$

The other terms in the expression involving d_n and f_n are of the form

$$\begin{aligned} d_n\,\overline{m}^{(3)}_{o,1,n} &= \frac{1}{S\left(k_1 r\right)}\hat{d}_n\,\hat{\overline{m}}^{(3)}_{o,1,n} \qquad & f_n\,\overline{m}^{(3)}_{e,1,n} &= \frac{1}{S\left(k_1 r\right)}\hat{f}_n\,\hat{\overline{m}}^{(3)}_{e,1,n} \\ d_n\,\overline{n}^{(3)}_{o,1,n} &= \frac{1}{S\left(k_1 r\right)}\hat{d}_n\,\hat{\overline{n}}^{(3)}_{o,1,n} \qquad & f_n\,\overline{n}^{(3)}_{e,1,n} &= \frac{1}{S\left(k_1 r\right)}\hat{f}_n\,\hat{\overline{n}}^{(3)}_{e,1,n} \end{aligned} \tag{24}$$

Thus, in region #1 where $b < r < a$, the E and H-fields are expressed using a relationship similar to that of Eq.(8), but with the *scaled* expansion coefficients and Hankel functions *and* the scaling factor S:

$$E^s = E_o\left\{\begin{aligned} &\sum_{n=1}^{\infty}(-j)^n\frac{2n+1}{n(n+1)}S\left(k_1 r\right)\left[\hat{p}_n\,\hat{\overline{m}}^{(4)}_{o,1,n} + j\,\hat{q}_n\,\hat{\overline{n}}^{(4)}_{e,1,n}\right] \\ &+\sum_{n=1}^{\infty}(-j)^n\frac{2n+1}{n(n+1)}\frac{1}{S\left(k_1 r\right)}\left[\hat{d}_n\,\hat{\overline{m}}^{(3)}_{o,1,n} + j\,\hat{f}_n\,\hat{\overline{n}}^{(3)}_{e,1,n}\right]\end{aligned}\right\} \quad (b < r < a) \tag{25a}$$

$$H^s = -\frac{k_1}{\omega\mu_1}E_o\left\{\begin{aligned} &\sum_{n=1}^{\infty}(-j)^n\frac{2n+1}{n(n+1)}S\left(k_1 r\right)\left[\hat{q}_n\,\hat{\overline{m}}^{(4)}_{e,1,n} - j\hat{p}_n\,\hat{\overline{n}}^{(4)}_{o,1,n}\right] \\ &+\sum_{n=1}^{\infty}(-j)^n\frac{2n+1}{n(n+1)}\frac{1}{S\left(k_1 r\right)}\left[\hat{f}_n\,\hat{\overline{m}}^{(3)}_{e,1,n} - j\hat{d}_n\,\hat{\overline{n}}^{(3)}_{o,1,n}\right]\end{aligned}\right\} \quad (b < r < a) \tag{25b}$$

This scaling procedure permits the computation of the E-fields over a broad frequency range, which is impossible with the conventional wave expansion of Eq.(8). For the E-fields in the other regions where $r > a$ and $r < b$, the unscaled expressions in Eqs. (6), (7) and (9) can be used.

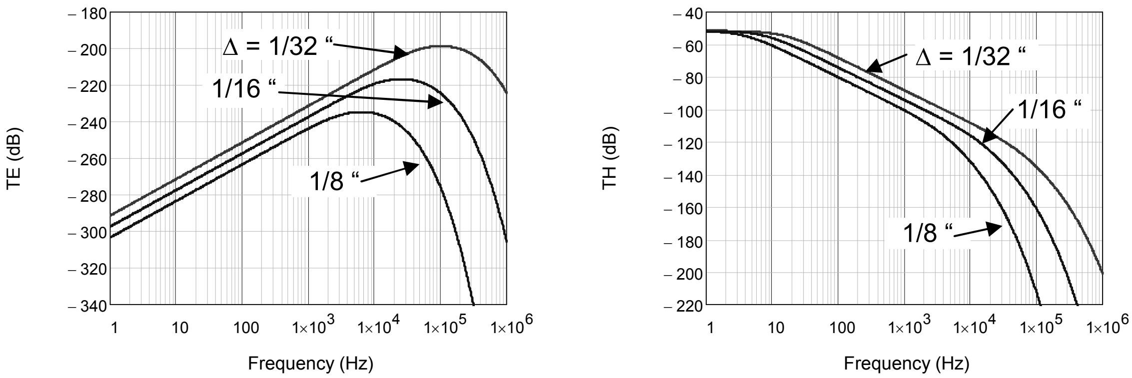
2.5 Numerical Results

A computer program was developed to evaluate Eqs. (6), (7), (9) and (25) using the closed form expressions for the expansion coefficients. As a check of this solution, it was verified that the various boundary conditions on the sphere were met, and that the overall behavior of the E-fields was correct.

As an additional check, the E-field and H-field transfer functions at the center of an aluminum shell (σ = 3.54 x 10^7 S/m) with radius a = 0.914 m (36 in) and thicknesses Δ = 0.794, 1.587 and 3.175 mm (corresponding to 1/32, 1/16 and 1/8 inches) were computed. This sphere is the same as that used in [8]. For these comparisons, transfer functions relating the total E and H-field magnitudes to the magnitude of the incident E-field are defined as

$$TE(r,\theta,\phi) = \frac{\left|\vec{E}(r,\theta,\phi)\right|}{E_o} \quad and \quad TH(r,\theta,\phi) = \frac{\left|\vec{H}(r,\theta,\phi)\right|}{E_o} \tag{26}$$

In Eq.(26), the transfer function TE is unitless and TH has units of Siemens, which is not ideal, but this is done to permit a direct comparison with the results of [8]. Figure 2 presents plots of the E-field and H-field transfer functions, expressed in dB, at the center of the aluminum sphere with different shell thicknesses, Δ. These plots are identical with those in Figures 2 and 8 of ref. [8], and this serves as a partial validation of the computational procedure. Note that usually the H-field transfer function is shown relative to the incident H-field, not the E-field, and at low frequencies, $H/H_0 \rightarrow 0$ dB. The low frequency limit in Figure 2a is –51.53 dB, which is exactly $1/Z_0$ expressed in dB.



a. E-field transfer function

b. H-field transfer function

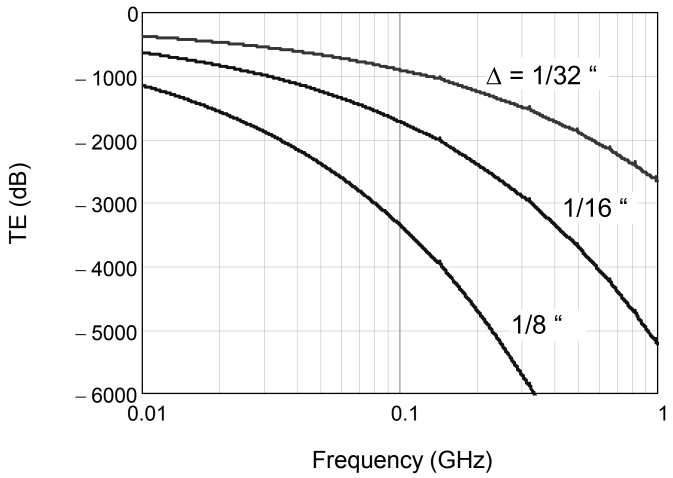
Figure 2. Plots of the total E-field and H-field transfer functions at the center of an aluminum sphere with radius *a* = 0.914 m for different shell thicknesses, Δ. (To be compared with Figures 2 and 8 of ref. [8].)

It is interesting to see that the upper frequency response of the transfer functions in Figure 2 is 1 MHz. Even for this relatively low frequency, the spherical wave function series is difficult to evaluate without scaling the Hankel functions. To illustrate the robustness of the present scaled solution at higher frequencies, Figure 3a presents a plot of the E-field transfer functions for the sphere for frequencies up to 1 GHz. The responses are reasonable in appearance, and if one carefully examines the transfer function for the thinnest shell, a hint of small peaks in the curves are seen at frequencies above about 200 MHz. Figure 3b plots the transfer function for this shell on a linear scale and these peaks are seen more clearly.

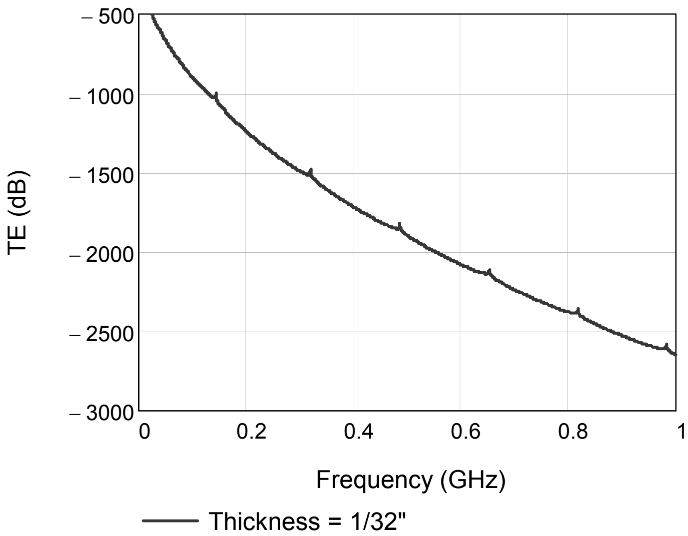
These peaks are due to the internal resonances in the shell. Since the shell material is highly conducting, we expect that these resonances will occur close to the classical internal resonances of a perfectly conducting sphere. According to Harrington [21, §6-2], such internal resonances occur at the roots of $J_n(k_2b) = 0$ for the TE modes, and at the roots of $[k_2b\ J_n(k_2b)]' = 0$ for the TM modes. Table 1. presents the roots for the first four TM modes, along with the resulting resonant frequencies for the sphere with a radius of about 0.914 m. We see that the agreement with the frequencies of the resonances in Figure 3b is very good. Of course, since the conductivity of the shell is so high, the internal E-field is extremely small – 1000 to 2000 dB down from the incident field.

Table 1. Interior TM resonances for a perfectly conducting shell.

No.	k_2b	Freq. (GHz)
1	2.744	0.143
2	6.117	0.320
3	9.317	0.487
4	12.486	0.653



a. TE for three different shell thicknesses.

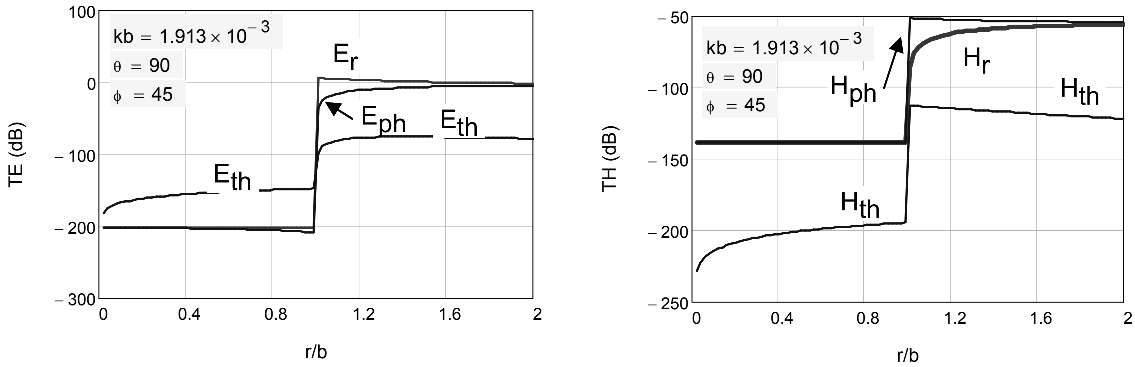


b. Linear plot of TE for a shell of thickness Δ = 1/32 in.

Figure 3. Plots of the total E-field transfer function at the center of the spherical shell for higher frequencies up to 1 GHz.

The primary motive for this study is to understand the behavior of the internal E- and H-fields within the shell. Using the same spherical shell as in the previous example, the transfer functions for the individual components of the E- and H-fields have been evaluated along the radial path in the direction defined by the angles $\theta = 90^{o}$ and $\phi = 45^{o}$. With reference to Figure 1, this path is in the *x-y* plane at z = 0 and at an angle of 45º to the *x* axis. Figure 4 shows these E-fields as a function of normalized radial distance *r/b* from the origin to *r/b* = 2 for a frequency of f = 100 kHz.

The important thing to observe from this plot is that for both the E- and H-fields inside the shell, there are observable spatial variations in the E-field components. For the H-field, the H_r and H_θ components are equal in magnitude (on this particular radial trajectory), but there is a definite variation of the H_ϕ component. For the E-field, the principal component is E_θ and its spatial variation is significant. Outside the sphere both the E- and H-fields approach the incident field at distances of $r/b \approx 2$.

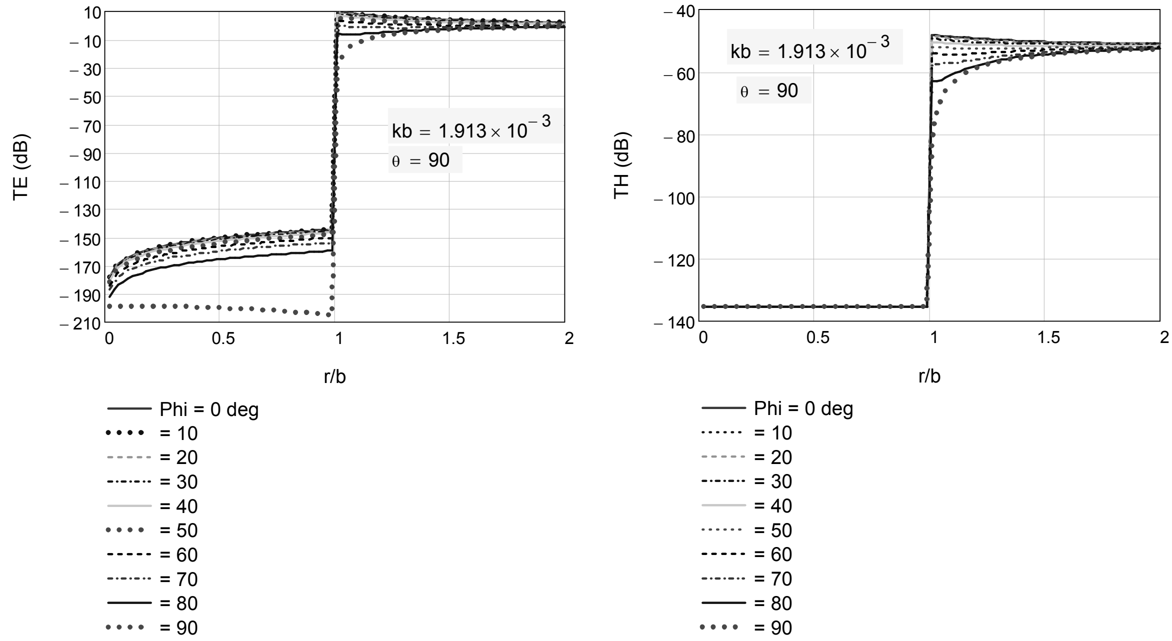


a. Electric field b. Magnetic field

Figure 4. E- and H-field transfer functions for the *r*, θ and ϕ field components for the spherical shell of inner radius *b* = 0.914 m and shell thickness Δ = 0.794 mm, at a frequency of 100 kHz. (These E-fields are shown as a function of radial distance on a path defined by the angles $\theta = 90^{o}$ and $\phi = 45^{o}$.)

Perhaps a more intuitive measure of the internal shell fields is the total field transfer functions given by Eq.(26). Figure 5 illustrates the behavior of the E-field transfer functions in the equatorial (z = 0) plane along different trajectories defined by the angle ϕ. Parameters are the same as in the previous example: b = 0.914 m, Δ = 0.794 mm, and f = 100 kHz.

In this figure, it is clear that the total internal H-field in the shell is constant for all practical purposes. However, there can be a significant variation of the total E-field inside the shell – about 60 dB, or a factor of 1000. Furthermore, we see that the value of TE for this shield reported in ref. [8] (at the center of the shell) is about – 198 dB. This is clearly not a representative measure of the shielding provided by this shell.



a. Electric field   b. Magnetic field

Figure 5. Plots of the total E- and H-field transfer functions in the equatorial (z = 0) plane along different trajectories defined by the angle ϕ. (Parameters are b = 0.914 m, Δ = 0.794 mm, and f = 100 kHz.)

Another way of visualizing the EM field distribution in and around the shell it to plot the total field transfer function as a contour plot. This is done in Figure 6 for TE and in Figure 7 for TH. In these figures we see that for all practical purposes, the H-field is uniform within the shell. However, this is not the case for the E-field transfer function, where the TE at the center is considerably smaller than that elsewhere in the shell.

The frequency dependence of the solutions for the E-and H-fields of the shell are shown in Figure 8 over a frequency range from 100 kHz to 10 MHz. As this is a range of relatively low frequencies for the ~ 1 meter sphere size, we do not expect much of a change in the shape of the E-fields, but only a change in the E-field amplitudes within the shell. This is confirmed by the data in these plots. Clearly, as the frequency increases, the internal field strength is reduced, due to the inductive shielding provided by the currents flowing in the shell [22].

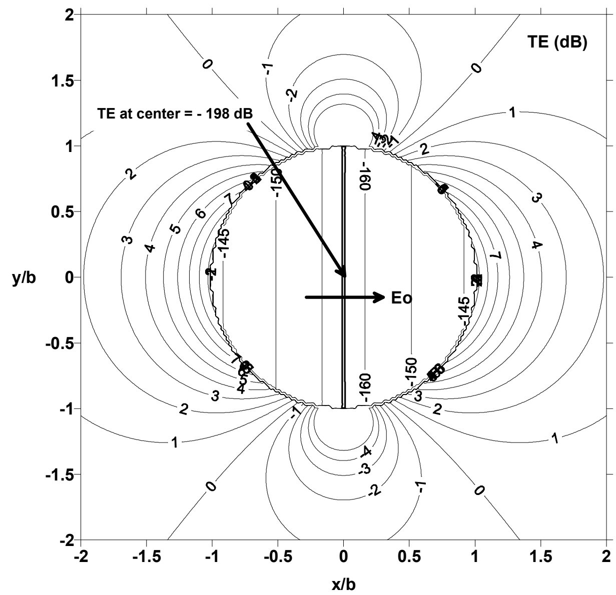


Figure 6. Contour plot of the total E-field transfer function (in dB)n the equatorial plane, inside and outside the aluminum shell, for *b* = 0.914 m, Δ = 0.794 mm, and *f* = 100 kHz.

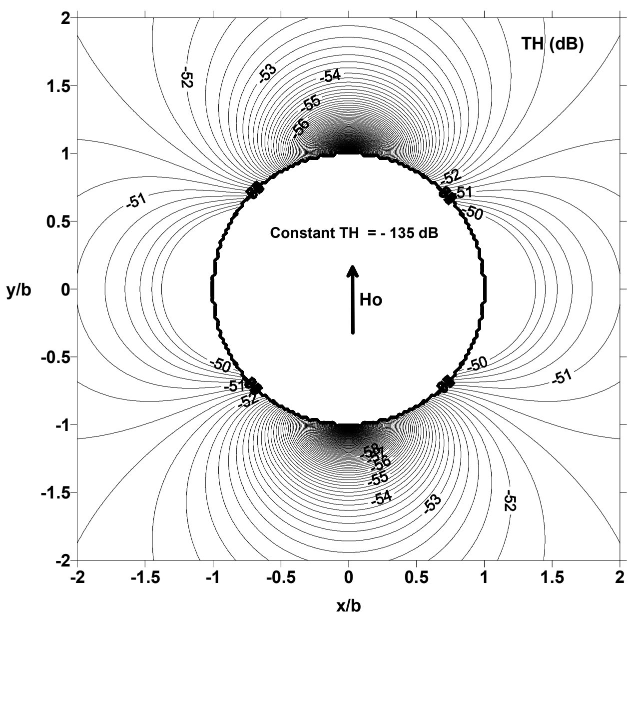
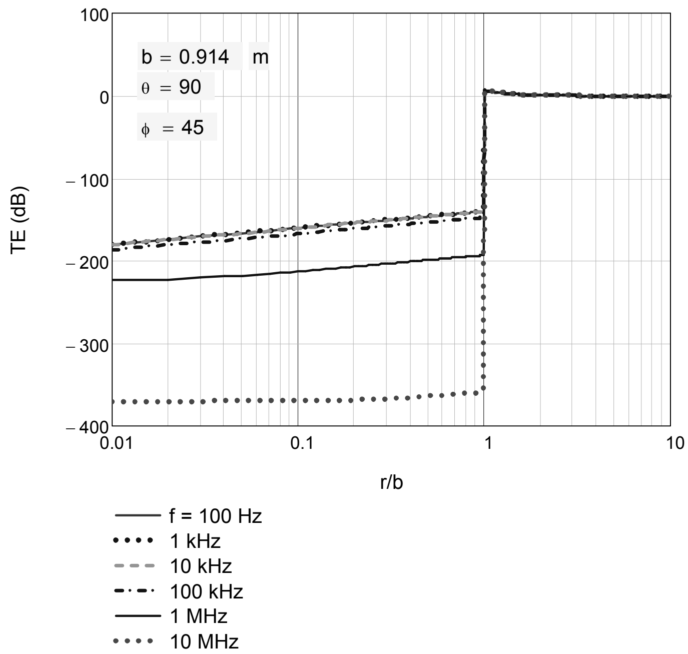
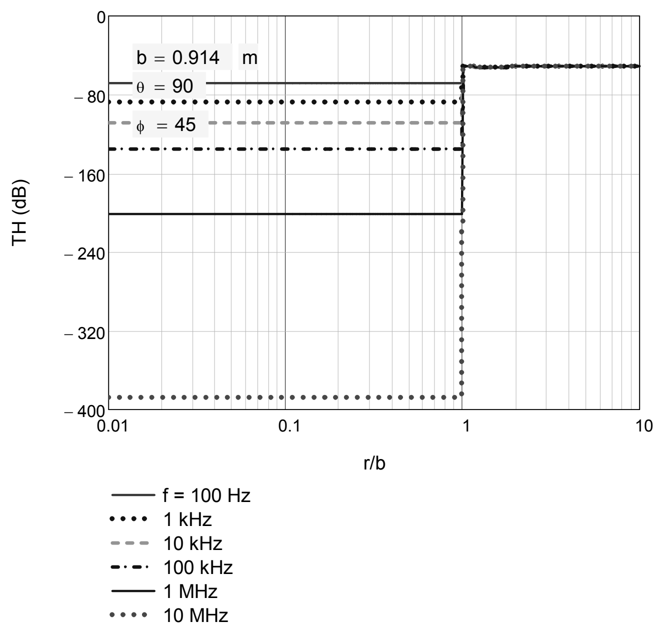


Figure 7. Contour plot of the total H-field transfer function (in dB) in the equatorial plane, inside and outside the aluminum shell, for *b* = 0.914 m, Δ = 0.794 mm, and *f* = 100 kHz.



a. E-field transfer function



b. H-field transfer function

Figure 8. Illustration of the frequency dependence of the E- and H-field transfer functions, along a radial path defined by the angles $\theta = 90^o$ and $\phi = 45^o$ for the aluminum shell with b = 0.914 m and Δ = 0.794 mm.

2.6 Statistical Description of the Internal Fields

To get a better quantitative description of the behavior of the EM fields within the spherical shell, Monte Carlo calculations were conducted for a wide range of frequencies on the aluminum shell (b = 0.914 m and Δ = 0.794 mm). In these simulations, the total E and H-fields at about 1000 randomly selected points within the shell were calculated and the response amplitudes were binned into histograms representing probability density functions. As an example, Figure 9 presents the histograms for the E-fields, computed at a frequency of 100 MHz. Clearly the H-field is a constant within the sphere, but the E-field has a wide range of values.

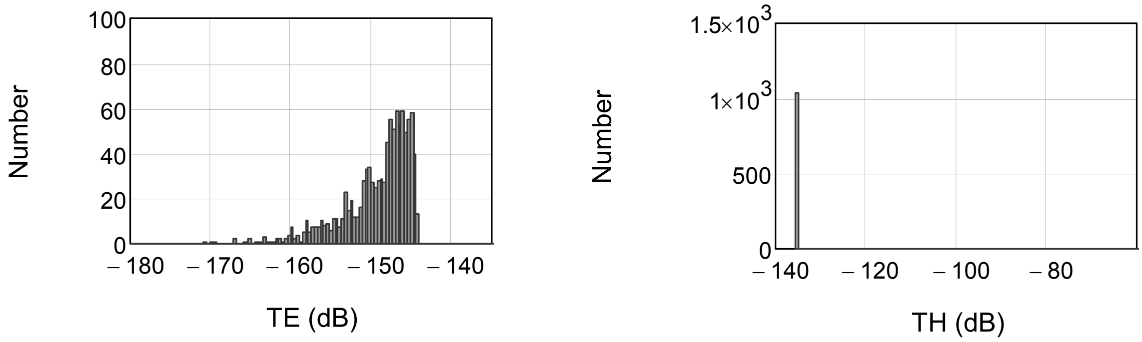
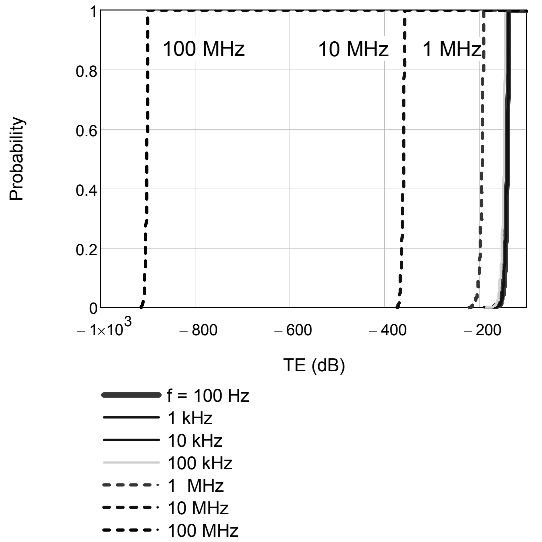


Figure 9. Example of the histogram functions for the internal E and H-fields for the aluminum sphere, at a frequency of 100 MHz.

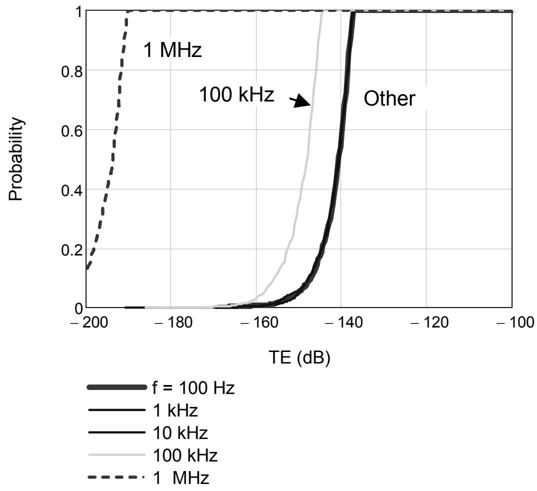
From the histogram distributions, cumulative probability distributions (CPDs) can be calculated. Such distributions for the E-field are shown in Figure 10. These distributions represent the probability of a randomly selected point in the shell having a TE *less than* the value specified on the x-axis.

As seen in this figure, at very low frequencies (from 100 Hz to 10 KHz), the E-field CPDs are virtual overlays. At higher frequencies, the shielding begins to improve and the average values of the shielding becomes larger, with slight changes in the shape of the distributions.

As expected, the H-field CPDs are much less interesting, due to the almost uniform nature of the internal H-field in the shell. Figure 11 presents these results, where there is a slight hint of a change in the slope of the CPD at high frequencies.



a. Complete frequencies range



b. Low frequency range

Figure 10. Cumulative probability distributions for the E-field within the aluminum shell (b = 0.914 m and Δ = 0.794 mm), shown for various frequencies.

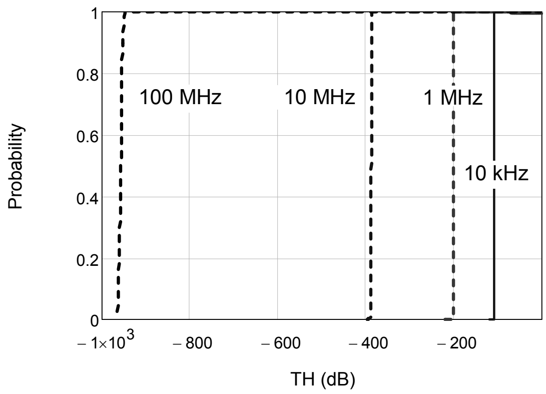


Figure 11. Cumulative probability distributions for the H-field within the aluminum shell, shown for various frequencies.

One way of summarizing the distributions of the internal field is by the mean value and standard deviation of the histograms. These quantities have been computed for the aluminum shell and are listed in Table 2. In addition to the data computed for the E-fields within the entire shell volume, the shielding values for the E-field and H-field at the center of the sphere from [8] are also listed.

From this summary, it is clear that the use of the H-field at the center of the shell as a representative sample of the shielding anywhere in the shell is a good measure. However, the same is not the case for the E-field at low frequencies, say below 1 MHz.

Table 2. Summary of the mean values and standard deviations of the distributions computed for the internal E- and H-fields of the aluminum shell.

Case	Frequency (Hz)	Avg. TE (dB)	TE Std. Dev. (dB)	TE (dB) from Ref.[8]	Avg. TH (dB)	TH Std. Dev. (dB)	TH (dB) from Ref.[8]
1	1.0E+02	-142	4.3	-251	-68	0.1	-68
2	1.0E+03	-142	4.2	-231	-88	0.1	-88
3	1.0E+04	-142	4.4	-211	-108	0.0	-108
4	1.0E+05	-149	4.4	-199	-135	0.0	-135
5	1.0E+06	-195	4.7	-224	-201	0.1	-201
6	1.0E+07	-360	3.1	-370	-388	0.4	-387
7	1.0E+08	-902	2.3	-900	-956	3.8	-958

3. Summary

This part of the paper has examined a simple canonical shielding problem with the goal of trying to gain a better understanding of the EM shielding provided by real shielding enclosures. The shield considered here was a spherical shell – one being made of finitely conducting material (aluminum) and having a finite wall thickness.

The reason for choosing this simple shape was that the calculation of the internal fields could be done mathematically through the use of spherical harmonics. This provides the possibility of evaluating the E- and H-fields anywhere inside or outside the sphere. In developing this analysis, closed form expressions for the expansion coefficients have been found, and these do not appear to be generally available in the literature. Moreover, a unique scaling technique was introduced that permits the accurate evaluation of the spherical Hankel function terms of the wave functions. This scaling is not an approximation to the Hankel functions as obtained by [11] and others, but is exact.

The benefit of this type of solution is that a Monte Carlo simulation can be used to develop probability distributions for the internal fields that show the variability of the field magnitudes. The difficulty, however, is that the solution is in the form of an infinite series of factors, which, at times, is difficult to sum. Moreover, there are numerical challenges in calculating the required Hankel functions of complex argument inside the lossy material due to numerical overflow and underflow.

This paper will conclude with Part 2, which deals with the quasi-static analysis of a spherical shell having an aperture.

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School of Engineering and Technology
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apd@dmu.ac.uk

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Giulio Antonini
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