High Frequency Electromagnetic Analysis - A Historical Perspective

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***Abstract* — The author has been involved in applied high frequency numerical electromagnetic analysis since the beginning of the field. Inspired by work on some of the first GaAs integrated circuits at GE Electronics Laboratory, Syracuse, NY, he learned electromagnetics with the intention of reducing and eliminating the multiple re-designs then required. This is the story, from the author's personal perspective of how electromagnetic analysis has developed and matured from the very beginning until today, when it is now a required part of the microwave design process.**

***Index Terms* — History, Method of Moments, Numerical electromagnetics.**

I. Introduction

"How did we get to where we are today?" is a central question in history. This paper provides an overview of my personal travels through time as they relate to this question with respect to applied numerical electromagnetics. It was not always clear that I would become a contributor to this field. In fact it was not always clear that I would even go to college…

II. Developing the Required Skill Set

My youth was spent on a farm, pitching hay and driving tractor. However, my father, originally an immigrant from Finland, had learned enough on his own to build and operate an amateur radio station prior to WWII. Although he did not operate radio during my youth, I was intensely interested in the maze of wires and equipment in the "radio room". The story of that journey from the farm house radio room to college, and ultimately to a Ph. D. in electromagnetics will perhaps be told another day.

Critical skills acquired during my down on the farm days include developing a strong intuitive feel for RF from building amateur radio equipment (we could not afford to purchase equipment). This includes finding creative solutions to problems using only what is available. According to Edison, "Invention requires creativity, and a pile of junk." I certainly had the pile of junk.

This lead me, not to college (funds were limited), but to the Air Force, where I trained as a technician for an auto-track radar. After that, I found a civilian job at NCR Ithaca as an electronics technician. Having saved enough for college, I then put myself through Cornell. As an undergraduate, I found a part time job (sometimes working for free) designing and building ionospheric radar. Such a thrill to work with an Eimac 4-1000Z and a 1 Ampère 10kV power supply! (I survived.)

Fig. 1. Sonnet started in 1983 with amateur radio antenna analysis software on the Apple][+ computer.

Next I worked for GE Valley Forge Space Division, and then GE Electronics Laboratory (E-lab), Syracuse., NY. I designed filters, amplifiers, and microwave measurement equipment. I also got my first taste of software, writing a circuit theory analysis program for the HP-1000E computer in FORTRAN-77. I carefully followed the new-fangled concept of "structured programming" that I had learned at Cornell. At E-lab, I ported the software to a VAX computer, also in FORTRAN-77. The port took three months. FORTRAN-77 was not a uniform standard.

At E-lab I helped design some of the first GaAs MMICs (Monolithic Microwave Integrated Circuits). My first design, a two stage C-band LNA, was successful, but only because I could make the circuit fairly large (a previous designer had failed, and we had only one try left). Most designs did not have that luxury and a high premium was placed on compactness. A design might work just fine with circuit theory, but fail with a tight layout. Most GaAs

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designs required multiple fabrications at tens of thousands of dollars and three to six months each.

Now there was no longer any need at E-lab for me to write software. But I really liked writing software. So I started my "keep the day job" company, Sonnet Software, in 1983. For my first project, I selected antenna analysis for the amateur radio market on the Apple][+, Fig. 1. Worked well, selling about 250 copies worldwide, but it was definitely still "keep the day job".

III. Finding a Solution

At this point, my skill set included a strong applied microwave design background, and the ability to write, market, and support software. As yet, however, no solution appeared for the GaAs problem. What was missing?

Inspired by interaction with Prof. Rolf Jansen, I started thinking that maybe there was a solution somewhere in electromagnetics. I did not know what or how, but I really had that feeling. And besides, one of the world's leading numerical EM researchers, Roger Harrington, Fig. 2, taught just a few minutes drive away at Syracuse University. So, after some negotiating, I was funded by E-Lab to pursue a Ph. D. under Prof. Harrington.

The solution gradually took shape, especially after I took Prof. Harrington's course on Method-of-Moments (MoM). I completed my dissertation [1] in 1986 on an EM analysis of shielded planar circuits. My technique divides a circuit into subsections and fills and then inverts a matrix. For N subsections, the matrix is N×N. I had the solution in hand. So now what?

IV. You Can't Get There From Here

Prof. Harrington once told me about some of his early MoM papers getting rejected because reviewers considered it useless. For example he was told that it had been proven that it was impossible for a computer to invert even a 100×100 matrix because the magnetic tape would wear out going back and forth…

Prof. Harrington had given me access to one of the first IBM-PCs, running at a blazing 4.77 MHz. And, for that time period, that was amazingly fast. For example, my first ham radio contact had been on 3.7 MHz. The PC used an 8088 Intel processor with an optional 8087 floating point co-processor. I converted the inner loop of my matrix solver to assembly language, hand coded and optimized for the co-processor. I could invert a 100×100 matrix in about one hour. Prof. Harrington was pleased.

In June 1986 Prof. Harrington organized a conference at Minnowbrook, an Adirondack "Great Camp" owned by Syracuse University. There were some very well known people there, and it was inspiring to give my first public

Fig. 2. Roger Harrington (fourth from left) and former students at his retirement party, Fall 1994.

presentation of my new technique to them. Afterwards, one prominent microwave designer came to me and commented that all this numerical EM stuff was Ivory Tower academic and not useful in real design.

He was right. One hundred subsections were not enough to do any more than a few simple discontinuities. Of course we could always get starry-eyed and suggest that maybe, some day, we could do 200×200 matrices. But direct matrix solve is an order N^3 process. So, double N and we need a computer eight times faster, nearly 40 MHz. Heck, that's VHF! Maybe five years? Maybe ten? How about maybe never.

V. Commericalization

Even with the limited problem size, I decided, perhaps foolishly, to pursue commercialization. That would not happen at E-lab, so I accepted a two year visiting professor position at Syracuse University. I also negotiated funding for two years from HP. I then set out to find a tenure track position and a company for commercialization.

I made serious attempts for a faculty position at both Syracuse and Cornell. Both attempts failed. Prof. Dalman (who had taught me microwaves) was my champion at Cornell. I was most grateful when I last met Prof. Dalman several years ago, he profusely apologized for Cornell not having hired me. He seemed to think if they had hired me, Cornell would still have a strong position in microwaves. Would have been nice to at least have tried.

I achieved total failure on the second goal as well. Just before Christmas 1987, HP told me they were no longer interested in funding my work. I approached several other companies. Likewise, no interest. So, I either had to drop the issue and get on with life, or do it myself.

VI. Quit the Day Job

I received my final pay check in June 1988. It was sink or swim. Funding from RCA David Sarnoff Labs made swimming easier. I worked out of my home for the first year. In 1989 I moved to office space, hired our first employee, and made our first commercial sale. Just before our first sale, EEsof beat us to market with an unshielded planar surface meshing tool, EMSim. Shortly after our initial product introduction, I found the reason HP lost interest in my work was because they had decided to market HFSS, a finite element tool developed by Ansoft. Around 1991, Compact Software introduced Microwave Explorer, based directly on my own published theory.

For planar structures, we were regularly beating all comers on technical merit. Then, in 1992, EEsof dropped EMSim and started marketing Sonnet. Now, we could concentrate on technical support and development, leaving sales and marketing to EEsof. That lasted one year. In 1993, EEsof was sold to HP. In difficult negotiations, going through Christmas, I vigorously pointed out that unshielded and shielded planar tools are complimentary. HP declined to agree. We finally agreed to a termination with HP. The financial settlement propelled us onto the Inc. 500 (the 500 fastest growing private US companies), the first and only microwave software company ever to do so. The settlement also enabled us to re-establish our marketing and sales organization.

Briefly summarizing important business developments from 1990 on: HP acquires EEsof (Sept. 1993). Ansoft acquires Compact Software (April 1997, Microwave Explorer is gone). HP acquires Alphabit (1997, original developers of Momentum, an unshielded surface meshing tool). HP and Ansoft part ways, each selling their own versions of HFSS (Jan. 1998). HP spins off Agilent (1999). Agilent sells their version of HFSS to Ansoft and exits the volume meshing EM market (July 2001). Agilent re-enters volume meshing market (May 2006). Over this period many startups enter the software market, with the most successful being CST selling a time domain volume meshing tool.

There were two major DARPA programs that had significant influence on the GaAs RFIC industry, MIMIC, and MAFET. While we did have some funding from the earlier MIMIC program, MAFET (1996 – 1999) had major influence on us. We developed user guided circuit subdivision (i.e, draw a line to split a circuit in two, then automatically analyze the two pieces and automatically connect them back together) and dielectric bricks, among other items. One major introduction that MAFET inspired was the first free version of any high frequency EM software, SonnetLite. With over 35,000 distinct registered users, SonnetLite is the most widely distributed high frequency EM software ever.

VII. Platform History

As mentioned above, the first computer used at Sonnet for EM analysis was the original IBM-PC with a 4.77 MHz clock. With hand-coded assembly language it inverted a 100×100 matrix in one hour. The computer ran DOS 3.1, had 640 kB of memory, and cost US$2 000. The software was written in Turbo Pascal (cost, US$50).

Next came an HP-300 UNIX workstation provided by HP in 1986 to facilitate my research. With 2 MB of RAM, it cost an estimated US$15 000 and inverted a 400×400 matrix in about an hour. We started programming in C as C is standardized across platforms and structured programming styles are easily realized.

The next major increase in speed was the SPARC-1 (about 1990) from Sun Microsystems. We acquired one with 8 MB of RAM in 1990 for US$10 000. Instead of being the size of a small washing machine (as with other workstations of the period), the SPARC-1 was the size of a pizza box, and it could turn a 1 000×1 000 matrix in about an hour. Suddenly, we are doing practical problems. In fact that same engineer who had said numerical EM was worthless, told me he had changed his mind because of what we could now do.

The introduction of Microsoft Windows 95, and the increased power of PCs, allowed us to return to the PC platform. Because we had written everything in C (and later, C++), porting to new platforms was easy. In 1999 we acquired a 450 MHz PC for US$3 000. With 256 MB of RAM, it inverted a 12 000×12 000 matrix in an hour.

Today, my two year old notebook computer inverts a double precision 20 000×20 000 matrix in under 25 minutes while I write this paper. Prototype multi-threaded code turns this matrix in 3.5 minutes on an 8 core 2.33 GHz machine. This corresponds to a 22 year processor improvement approaching 150 million times with respect to matrix solve. We have come a long way!

As for operating systems, several years ago Cadence standardized on LINUX. Today the major platforms for high frequency EM run either some version of Windows or LINUX. The various versions of UNIX are very much on the way out.

VIII. Numerical EM Technology

There are a wide variety of numerical EM techniques. My remarks are restricted primarily to that with which I am most familiar, planar surface meshing MoM.

First a comment on dimensionality. When I completed my Ph. D., we had 3-D fields and 2-D current. Taking a cue from fractal theory, I described my analysis as 2.5-D. I believe this was the first time fractional dimensionality had been cited in electromagnetics. Very soon after getting my degree, I had added the third dimension of current (for vias). Thus, now with 3-D current and 3-D fields, we describe it as 3-D planar, i.e., 3-D structures embedded in planar dielectric. However, the 2.5-D term is so attractive, it is still often used.

Back when HP was funding my work, it became apparent that the ports used in an EM analysis always had associated with them a discontinuity in the form of fringing fields. For my EM analysis software (a planar circuit inside a conducting shielding box), that discontinuity is a pure capacitance (plus a resistance if there is loss). It was relatively simple to develop a calibration algorithm (inspired by modern network analyzer calibration) to remove that discontinuity[2]. Fortunately, because we could use the perfectly conducting walls of the containing box as a perfect short circuit calibration standard, we could do perfect (to within numerical precision) calibration.

This concept of perfect calibration was extended several years ago when we found a way to do perfect calibration of ports interior to the circuit [3], including the new concept of ports with a floating ground. Perfect calibration, in turn, opens up new areas of microwave design.

To illustrate, in the early years of RFIC design, the EM analysis was used as a final validation after final layout. Later, designers would try tweaking the layout and repeating the EM analysis. This process was then automated in the form of optimization algorithms based directly on repeated EM analysis. These approaches have for the most part now been rendered obsolete.

Modern RFIC design optimization is effected by inserting perfectly calibrated tuning ports in various critical places in the design [4]. For example, insert a pair of ports into a length of transmission line. After EM analysis, a short adjustable length of circuit theory transmission line is connected to these tuning ports and the line length adjusted using circuit theory. Optimization now occurs with full circuit theory speed while nearly all of the circuit has been analyzed to EM accuracy. In addition, transistors, resistors, and capacitors can be removed from the layout and perfectly calibrated ports added. The appropriate models/S-parameters for the desired components are added and modified by means of circuit theory once the EM analysis is complete.

Even with the wide variety of EM analyses that are available, there remain a small but disturbing percentage of designers who feel that only one particular EM tool is the best. A typical exchange in an on-line forum might be, “Which EM analysis is best?” “XYZ is best!” There is no mention made of what kind of problem is to be solved or why XYZ has advantages for that problem. As a result work is being published today for which a quality EM tool has been applied to an inappropriate problem.

Another disturbing sight in published papers is the often reported good agreement between measured and calculated (we call it “GABMAC”). Bad agreement is rarely reported. For the last two decades, I have been politely suggesting that we as authors do not know what the reader’s requirements are and thus we can not judge “good”. Rather we should report that the difference between measured and calculated is X%, and then allow the reader for form her own conclusion. It might be my imagination, but it seems MTT authors have indeed been increasingly adopting this more objective style.

Finally, a word about interoperability. Tools from a variety of vendors are required for design success and thus interoperability is critical. Several microwave EDA framework companies have actively supported interoperability, even when that interoperability is with tools that have some degree of competitive aspect. These vendors should be commended.

IX. Conclusion

In the 25 years since I started my company, we have seen amazing changes. Back when it took a full hour to invert a 100×100 matrix it was simply unimaginable that someday we might invert a 20 000×20 000 matrix in 3.5 minutes on a desktop PC. With the astounding improvements in hardware, theory, and variety of numerical EM techniques, we now stand on the threshold of a new era in microwave design.

References

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