Predictions for the Future of Applied Microwave Electromagnetics

James C. Rautio
Sonnet Software, Inc.
1020 Seventh North #210
Liverpool, NY 13088
rautio@sonnetusa.com

The Beginning

The current era of electromagnetics can be said to have started in the later part of the 19th century when James Maxwell, drawing upon the work of Faraday, Gauss, Coulomb, and others, first wrote the equations which govern electromagnetic fields. The equations were later put into their modern vector form by Heavyside and Gibbs and came to be called Maxwell's equations. There followed a tremendous amount of theoretical work, however, application of Maxwell's equations was essentially limited to problems whose boundaries fall conveniently on constant surfaces in one or another coordinate system (rectangular waveguides, cylindrical resonators, etc.).

Then, about one century later, in the 1970's, electronic computing started to become widely available. The first impact of computers in our field was the development of linear circuit theory analysis software. Several tools were developed in the 1970's but wide commercial application was not seen until the 1980's. For this reason, I view the 1980's to have been "The Decade of Circuit Theory". In the beginning of the decade, most microwave design was done without the benefit of such software. By the end of the decade, use of such software was virtually universal.

It is interesting to note that circuit theory software is usually based on a nodal analysis using Kirchoff's Law and that Kirchoff's Law can be derived from Maxwell's Equations by setting the displacement current to zero. Thus, circuit theory is a special case of Maxwell's equations.

With computers starting to show promise, there was considerable theoretical work starting in the 1970's on numerical electromagnetics. Among the prominent researchers was my Ph. D. advisor, Prof. Roger Harrington. During the 70's and 80's, computing capability was limited and commercially viable numerical electromagnetic "codes" (as they were called at that time) did not exist. In fact, early numerical electromagnetic work met considerable opposition because of the limitations of computers of that time. Prof. Harrington described to me the comments of a reviewer of one of his early papers on the Method of Moments. As I recall, "The reviewer rejected the paper and the Method of Moments in general, saying it had all been done before. He also pointed out that it had been proven impossible for an electronic computer to invert even a 100 x 100 matrix because the magnetic tape would wear out going back and forth before the matrix inversion could be completed."

Of course, computing has changed since that time. However, just any computing power is not sufficient to allow the existence of commercially viable electromagnetic software, it had to be computing power on the engineer's desk top. That arrived in the early 1980's with the UNIX workstation and the IBM-PC.

In fact, it was an IBM-PC upon which I completed my dissertation research. It was an original: clock speed 4 MHz, 640 Kbytes of RAM (I splurged!), and two 5-1/4 inch floppy drives (again, I splurged!), no hard drive. By writing the matrix inversion loop in assembly language (everything else was in Turbo-Pascal), I could actually invert a 100 x 100 matrix in a bit over an hour. Prof. Harrington was pleased.

By the time I completed my research in 1986, the Decade of Circuit Theory was in full swing and I realized that I held in my hands the seeds of the 1990's, the "Decade of Electromagnetics".

Matrix Inversion - The Central Problem

From 1986 to 1989 I worked to transform the results of my research into something which might have a chance at commercial viability. In the meantime, I also tried to find some way to realize commercial viability with out having to actually start my own company. I approached one of my research sponsors (a commercial CAD vendor), but, as I was told later, they decided finite elements was superior to my approach, even for planar circuits. I approached my employer, but they had better things to do. So, with no other alternative, I decided to take my company (which I had started in 1983 as a conduit for my research funding) full time in 1988. In 1989, we incorporated, hired our first employee, and started shipping software. As it turned out, we had started shipping the first commercially viable microwave electromagnetic software in the industry.

In 1989, the largest problem we could handle in about one hour was a 400 x 400 matrix, thanks to an Apollo workstation with 4 Mbytes of RAM. Today, on a $5,000 to $10,000 computer (workstation or PC), we can invert a matrix of 4,000 x 4,000 in about one hour. This suggests that practical matrix inversion size increases by about one order of magnitude every ten years (or, one decade per decade). From this, I offer my first prediction for the future:

By the year 2010, a desktop computer in the $5,000 to $10,000 range will be able to invert a matrix of 40,000 x 40,000 in about one hour.

Does this mean that by the year 2020, we should be able to invert a 400,000 x 400,000 matrix on a low to mid range desktop computer? I do not think so. Gordon Moore has recently stated that he thinks Moore's Law (that integrated circuit complexity doubles every 18 months) will fail sometime in the future as integrated circuits confront fundamental physical limitations, specifically transistor size, heat dissipation, and electromigration. Thus, my second prediction:

The decade of 2010 - 2020 will see only about a factor of two increase in the size of matrix which can be inverted on a low to mid-range desktop computer in about one hour.

The above predictions are for a full, symmetric, real matrix solved by LU decomposition. While the various iterative matrix solution techniques have seen considerable research, none have yet had serious commercial impact. Our experience has been that most microwave designers need a reliable analysis error level of 1% or better. Our experience has also been that iterative solution techniques do not consistently achieve that level. While it is possible that additional research could provide a reliable, low error, iterative matrix solution technique, we think the following outcome is more likely:

Iterative matrix solutions will see commercially viable application in problems requiring solution of very large scale systems where error on the order of 5% to 10% is acceptable, for example, in EMI and signal integrity problems.

What's Wrong With Error?

At this point, I have made several references to error. You may be wondering just what is meant by "error". For microwave work, percent error can not be used, in general, in reference to S-parameters. The reason is that zero is an allowed, non-trivial correct value. This means that one could be forced to divide by zero in calculating percent error, for example, in calculating the percent error in the analysis of the reflection coefficient of a perfect 50 Ohm load. We have found it convenient to calculate percent error in reference to some underlying physical model of the structure being analyzed. Percent error referenced to an equivalent inductance, resistance, or transmission line impedance, etc., all work nicely as zero is not an allowed non-trivial value.

Admittedly, the above paragraph is a bit tutorial, but I feel compelled to provide it because there has been little active work in either the research or applied communities with regard to analysis error. For example, in nearly any other field of science or engineering, an error analysis can easily occupy fully half of the total research effort. In publications, measured data must be presented with error bars, there is simply no other choice.

In our field, error analysis is rarely presented. However, this situation is starting to change. In the 1997 MTT Symposium workshop WMA, George Matthaei presented a detailed error analysis of an electromagnetic analysis of a discontinuity which he uses in 1% bandwidth superconducting filters. By varying the cell size, he showed that the error varied in a predictable fashion (when cell size is reduced by half, the error is reduced by half). With this knowledge, he was able to model the discontinuity to better than the 0.1% error required for success on first fabrication. Without the error analysis, he would have achieved only about 1% error, which would then have destroyed any chance of success on first fabrication.

Reduction of error is the primary reason for using electromagnetic analysis. Because of this over-riding importance, and because of increasingly frequent work like that cited above, I offer the following predictions:

By 2010, quantitative evaluation of analysis error will become a widespread and serious research topic. Quantitative error models (i.e., error as a function of analysis parameters such as mesh size) will be commonly used by applied microwave designers. However, error bars on published measured data will still be rare.

One Last Prediction

Over the past few years I occasionally encounter someone who states, usually implicitly but sometimes explicitly, that their technique is superior to one or more other techniques. We call this "electromagnetic chauvinism". Most often, we see this attitude in commercial salesmen, whose intent is clear. However, we also occasionally see it in academic researchers as well. A classic example of this is when the early microwave finite element researchers and marketers positioned volume meshing finite elements as better than surface meshing techniques even for planar circuits. A present day example is FDTD researchers and marketers stating that FDTD is always better than TLM. Both positions are not only improper, they are also wrong.

Our position has always been that different electromagnetic techniques tend to be complimentary, not competitive. Each technique is best for a certain class of problems and works poorly outside that class. The fully equipped microwave designer of the next century will have finite elements, TLM, FDTD, numerical integration surface meshing, and, of course, our own FFT based surface meshing software. There is room for everyone in this field. No matter what technique you are using or researching, it will be useful. And this brings me to my final prediction, more based on human nature than on electromagnetics:

By the year 2010, there will be just as much electromagnetic chauvinism as there is today.

James C. Rautio (S'77-M'78-SM'91) received the B.S. in electrical engineering from Cornell University, Ithaca, NY, the M.S. in systems engineering from University of Pennsylvania, Philadelphia and the Ph.D. in electrical engineering from Syracuse University, Syracuse, NY, in 1978, 1982 and 1986, respectively.

From 1982 to 1986, he worked at General Electric, first at the Valley Forge Space Division and then at the Electronics Laboratory, Syracuse. He designed microwave circuits including filters for a Landsat receiver and various GaAs microwave integrated circuits. He also developed microwave and millimeter wave automated measurement equipment and wrote a large microwave circuit analysis program. From 1986 to 1988, he served as a visiting member of the faculty of Syracuse University and as an adjunct member at Cornell University, teaching microwave and computer courses as well as pursuing electromagnetics research. In 1983, he founded Sonnet Software with significant support from the David Sarnoff Research Center, Hewlett Packard, General Electric and Syracuse University. He went full time with the company in 1988. Sonnet Software develops and markets electromagnetic software to the microwave design community.

Dr. Rautio is Tau Beta Pi, ARFTG, AP and MTT. He has served as chairman of the Syracuse MTT/AP chapter and as a member of the 1987 MTT Symposium Steering Committee.