PCs for AP and Other EM Reflections

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This column is the second part of two the first appearing in December, 1999–that integrate a description of the evolution of computational electromagnetics (CEM) since the 1960s with my own personal experience in the field.

Introduction to the Method of Moments at MBAssociates, San Ramon, CA, 1968-1971

My introduction to the Method of Moments came upon joining MBAssociates, of San Ramon, California, where I worked from 1968-1971. A forerunner of *NEC*, called *BRACT*, was under development there, with primary programming being handled by Gerry Burke. Within a year of my arrival at MBA, Andy Poggio also joined us.

The basic thrust of the research being done at MBA was initially the development of computational models for the analysis and design of penetration aids: decoys that would accompany reentry vehicles to confuse enemy radars. *BRACT* was based on the thin-wire electric-field integral equation (EFIE), and used a three-term current basis (constant, sine, and cosine) and point matching, being adapted from Mei's approach [1]. My early contributions to *BRACT* included adding adaptive quadrature, and introducing the closed-form expressions for five of the six field terms needed to fill the impedance matrix. Also, it was finally appreciated that while *BRACT* was originally devised for modeling scattering, a simple change in the right-hand side made it suitable, as well, for antenna applications. Subsequently, antenna modeling became the primary thrust of the MBA work.

Computing resources during part of this period at MBA were rather limited, consisting of batch processing done on a CDC-3800 computer located in Sunnyvale, California, about 40 miles away. Card decks and output were delivered by an MBA employee or handled via courier. In 1969 or so, a Tymeshare connection was made, which enabled job entry to be achieved via a teletype, with output eventually provided at MBA from a high-speed chain printer, a big improvement. A typical "large" problem at this time involved a wire-grid model of an OH-6 military helicopter, which incorporated 194 unknowns for the basic structure, and possibly 15 more, depending on the specific antenna being used! This wire-grid OH-6 helicopter, shown in Figure 1, was one of the earlier such models employed, but Richmond [2] was probably the first to report using wire grids as approximation for solid surfaces.

An interim step between *BRACT* and *NEC* was *AMMP* (Antenna Mathematical Modeling Program), developed from US Army-sponsored work that began in 1971. Other sponsors were interested in modeling interface effects, for which an initial Sommerfeld treatment was developed in 1970. The Sommerfeld-based model was initially limited to horizontal and vertical wires, using only five (!) segments, due to the cost of evaluating the Sommerfeld fields. An approach we termed the "Reflection Coefficient Approximation" (RCA) was also developed, to avoid the expense of Sommerfeld-integral evaluation [3-4].

The RCA extended the rigorous model for a PEC half space to a lossy ground, by approximating the interface-reflected fields using the PEC image and Fresnel plane-wave reflection coefficients. A hint for this development was provided by Dr. Mogens Andreason, of TCI, after a talk he gave in Palo Alto at an IEEE evening meeting. One other significant MBA modeling code was developed in 1970 by Gerry Burke, a time-domain EFIE, which was later given the name *TWTD* (Thin Wire Time Domain) at Lawrence Livermore National Laboratory [5]. Also while at MBA, Andy Poggio and I wrote a chapter on time- and frequency-domain integral equations for a book edited by Raj Mittra [6]. One of the topics treated in this chapter was the derivation of an integral equation for a penetrable object.

CEM at Lawrence Livermore National Laboratory, 1971-1985

On joining LLNL in 1971, I was permitted surprisingly, in retrospect–by MBA to take copies of *BRACT* and *TWTD*. A special attraction of the move to LLNL was the suite of computers avail-

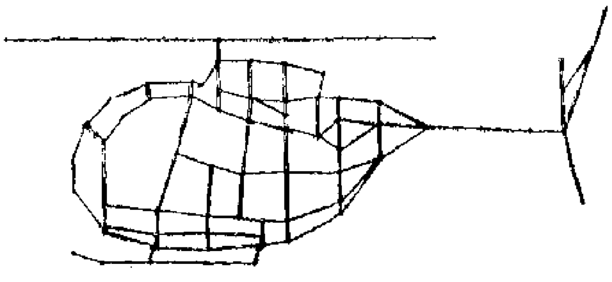

Figure 1. A wire-grid model of an OH-6A helicopter, having a total of 194 segments.

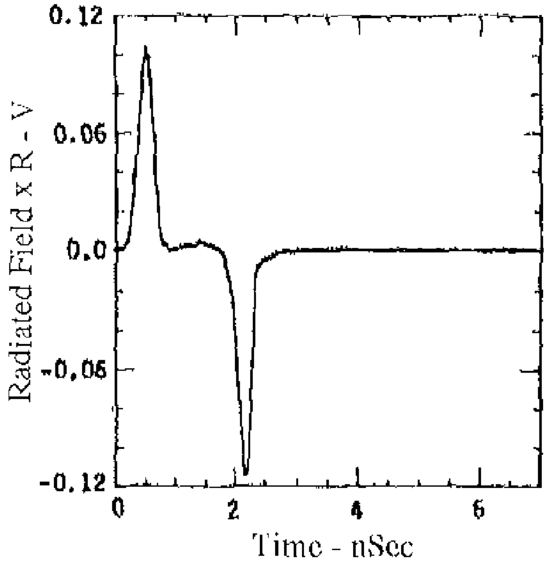

Figure 2a. The time-dependent broadside radiated field of an impulsively excited straight wire having an ideal diode on each of its 60 segments. The radiation field is dominated by that coming from the source region (the positive pulse), and that caused by reverse charge motion being stopped (the negative pulse) by the diodes.

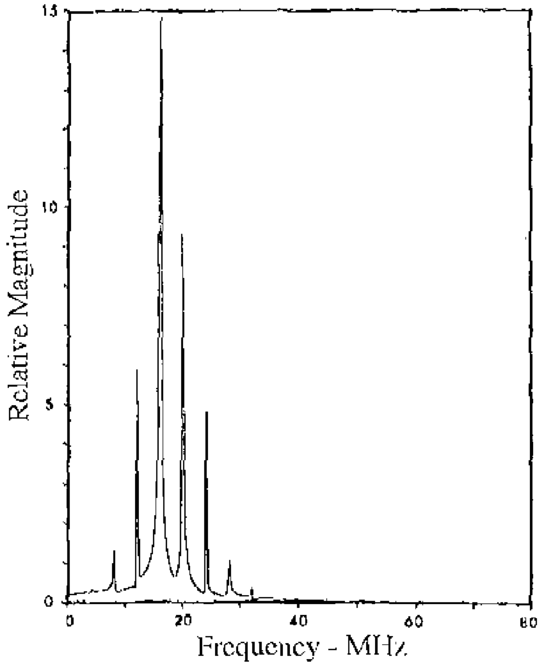

Figure 2b. The frequency spectrum of the field scattered from a straight wire illuminated from broadside by a 16 MHz plane wave, and the center resistance of which is square-wave modulated at 4 MHz to produce upper and lower sidebands at 4 MHz intervals.

able there, including CDC-6600 computers, which were soon followed by CDC-7600s, as well as the latest generations of CRAYs, on a regular basis. There was also an extensive terminal network at LLNL, so that programs could be developed and executed nearly everywhere within the Laboratory. In addition, there were extensive support services and peripherals available, including a state-of-art storage system called photo-store, which had an unimaginable, for the time, 10^{12} bits capacity. Physical storage was provided by an array of slide-like films, or chips, about half the size of a playing card, on which data was stored using optical techniques. Each of the chips held about 4.7 million bits, 32 chips being held in small plastic boxes called cells, with 6,750 cells available for on-line access. [Thanks to Fred Deadrick of LLNL for finding some of this long-forgotten information about photo-store.]

It was also convenient to produce various kinds of output from computer runs, e.g., making movies of transient phenomena generated using *TWTD*. Although full-color movies of EM fields have come to be a standard sort of presentation aid, especially with the wide-spread use of FDTD models, even the simpler kinds of visualization that were available in the early 1970s could reveal physical behavior that might not otherwise be easily seen in the CEM results. A selection of such *TWTD* results is still available, in a sequence of movie strips that can still be obtained from the IEEE (e.g., *IEEE AP-S Magazine*, October 1999, p. 119). *TWTD* was subsequently extensively modified at LLNL, by Jerry Landt, to include non-linear impedance loading, time-varying loading, and near-field computations. Examples of the former two applications are shown in Figure 2 [7].

My first CEM project at LLNL was modeling of US Coast Guard Loran-C antennas, during which rather extensive modification of *BRACT* was begun, in a version that we called *WAMP* (Wire Antenna Modeling Program). One of the first changes was the addition of a ground-screen capability [8]. This was easy to incorporate in the Reflection Coefficient Approximation (RCA) formulation, following some previous work by Jim Wait [9], and seemed to provide realistic results, at least when compared with scale-model and full-scale measurements. Adding a layered ground and a buried ground screen were also straightforward, following a similar procedure, to model the influence of subsurface salt water at a variable depth beneath the sectionalized-Loran-transmitting (SLT) antenna, as shown in Figure 3. Although experimental data

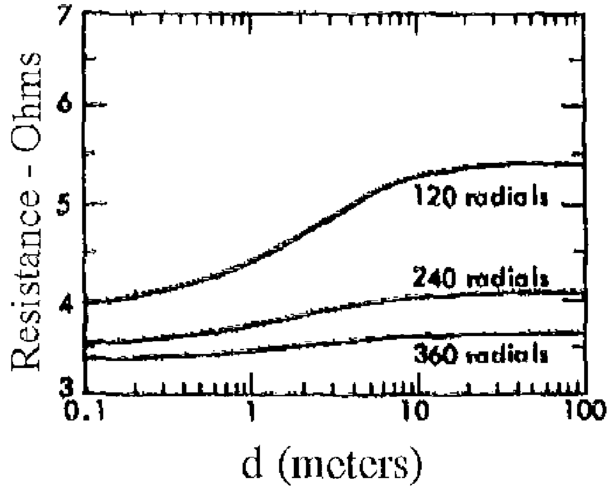

Figure 3. The variation in the input resistance of the SLT antenna, as a function of the depth to subsurface salt water, with the number of wires in a radial ground screen as a parameter.

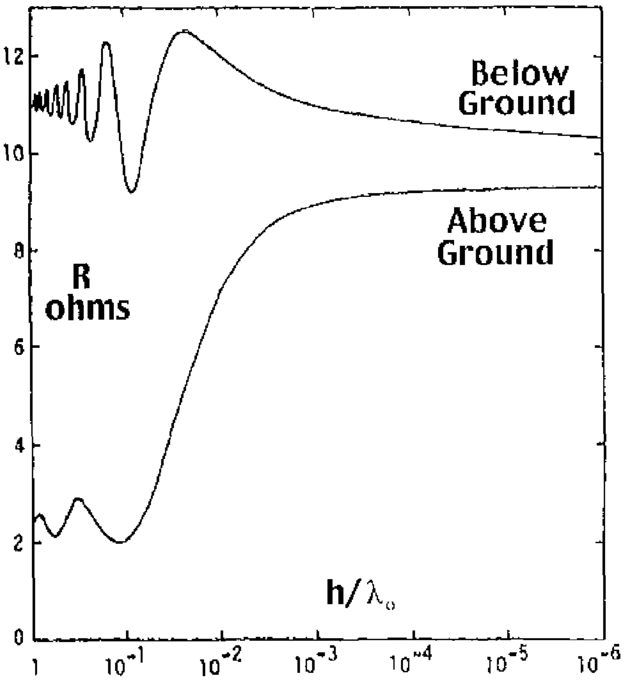

Figure 4a. The resistance of a horizontal dipole 0. 1 wavelength long and 10^{-8} wavelengths in radius, as a function of the distance from a dielectric half space of relative permittivity 16.

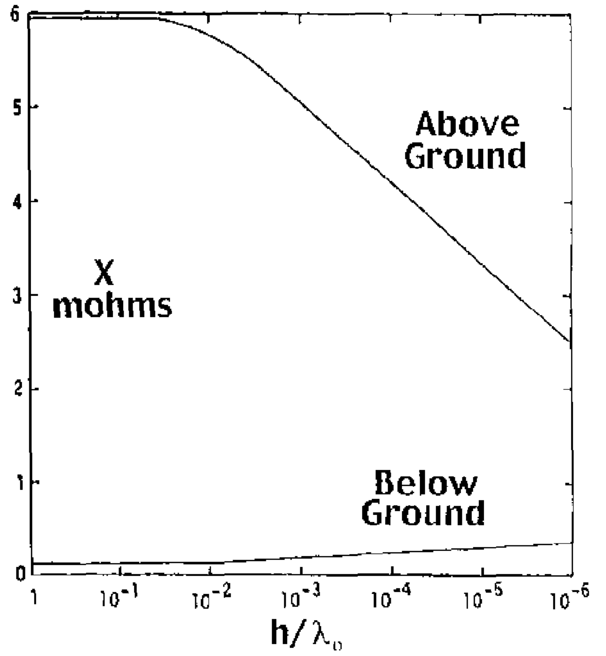

Figure 4b. The reactance of the horizontal dipole of Figure 4a. Although the thin-wire approximation used here requires that the dipole be kept several radii away from the interface, it appears as though the reactance curves, if extrapolated, would intersect at a height (or depth) of about the wire radius.

were not available to confirm these results, the resistance variation was similar to changes seen in SLT antennas located near shorelines.

A growing variety was EM-related work began in my new Group, Electromagnetic Waves and Applications, about that time, which was later summarized in the AP-S *Newsletter* [10]. Some of this work had an experimental focus, for example, through-ground propagation experiments begun by Jeff Lytle [11]. One goal of Jeff's experiments was to develop EM "images" of the ground between two vertical bore holes, by using a succession of transmitter and receiver locations. The data were processed using increasingly sophisticated tomographic techniques, and the procedure became known as geotomography. An initial application of geotomography was to search for the coal-gas interface when coal was being burned underground for in-situ gasification. Another was to locate tunnels in certain areas.

The initial interface model, based on the RCA, was subsequently much improved by incorporating general expressions for the rigorous Sommerfeld field integrals into *WAMP*. Even on the LLNL computers, these integrals could require excessive computer time. A substantial speed improvement was realized by interpolating between accurately computed Sommerfeld fields stored in a two-dimensional mesh [12, 13]. Interpolation worked well for the one-sided problem, i.e., where the source and observation points were on the same side of the interface, an example of which is shown in Figure 4. However, it was much less attractive for the situation where they were on opposite sides of the interface, since a three-dimensional field mesh was then needed.

An alternative to three-dimensional interpolation, as a logical extension of the two-sided problem, was then developed, using model-based parameter estimation (MBPE). Rather than using standard interpolation formulas, MBPE instead employs "basis" functions that represent various asymptotic forms of the Sommerfeld fields. The amplitudes of the various bases were obtained by fitting their sum to Sommerfeld-field values over the physical space of interest. This approach provided accuracy comparable to using only the Sommerfeld fields, with a time reduction of as much as a 1,000 [14]. This initial MBPE approach to the Sommerfeld problem eventually led to development and application of the same idea to the sampling of frequency spectra and radiation patterns, as described elsewhere [15].

One application for both *BRACT* and *TWTD* was the modeling of a variety of objects exposed to an EMP waveform. In support of this work, a ground-plane time-domain range was developed about 1973, largely following the design of one located at Sperry Research Lab in Sudbury, Massachusetts, designed by Gerry Ross and his team [16]. Also in connection with the LLNL EMP activity, a Computer Code Newsletter was initiated in 1975, with several hundred code copies delivered to recipients around the world, over about a four-year period [17].

It's interesting to recall just what was considered a really "big" EM problem in the mid-1970s. For ease in visualizing how big a problem might be considered practically solvable, I had begun using a one-hour solution time as a measure of computer speed. In this time period, for a frequency-domain integral-equation model with a matrix that was solved using LU decomposition, the one-hour problem size was about 300 wavelengths of wire, or 30 square wavelengths for a surface, using a CDC-7600 computer. This assumes a sampling rate of 10 times/wavelength and 100 times/square wavelength, respectively. Now, problems of this size

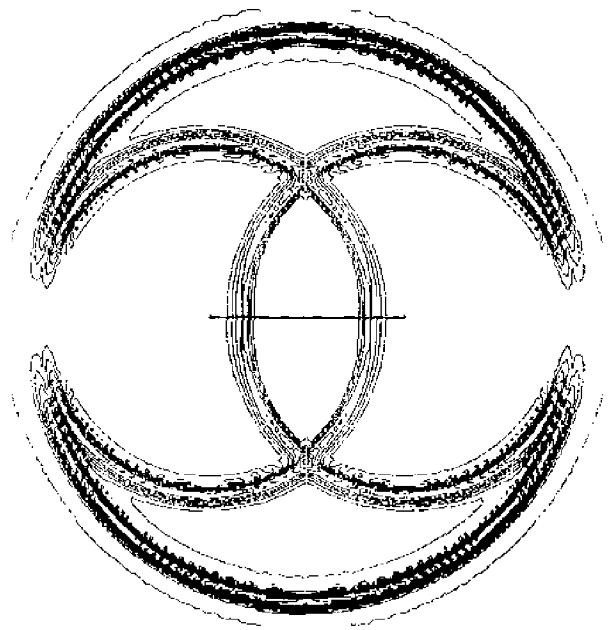

Figure 5. Contours of constant near electric fields, multiplied by the radial distance, as a function of space (or time) around an impulsively excited wire, obtained from *TWTD*. The outermost "bubble" of field is due to radiation from the source region as charge is set into motion, while the smaller bubbles, centered at the wire ends, are due to outward-propagating Q/I pulses that have just been reflected.

can be solved in times of 10s of minutes or less on PCs. On mainframe computers, the one-hour-time problem size ranges from 10s to 100s of thousands of unknowns, depending on the nature of the formulation and solution procedure. Time-domain differential-equation models FDTD, for example have employed 100s of millions to 10^9 unknowns. While CEMers have made substantial improvements in model formulation and development, the credit for much of this increase in problem size must also be given to improvements in computer hardware. Since the advent of the UNIVAC-1, in 1953 or so, the speed of computer throughput has increased by about a factor of 10 every five years, with a commensurate increase in storage.

Scientific Visualization and Electromagnetics

As mentioned above, *TWTD* was used in the early 1970s to make movies, as it was soon obvious that the amount of data provided by a time-domain model could be overwhelming, besides which being able to examine transient phenomena dynamically was extremely rewarding. Not too long after beginning our movie making at LLNL, Chalmers Butler, who was then at the University of Mississippi, and I collaborated on a proposal to the National Science Foundation to develop visualization "products," with an emphasis on computer movies for the teaching of electromagnetics. We solicited the involvement of 30 or so professors from schools around the country to ensure that the output of this project would be actually used. Unfortunately, the NSF elected not to fund it. Many years later, the CAEME [originally, Computer Applications in ElectroMagnetic Education, and now the Center of Excellence for Multimedia Education and Technology; see their home page at http://www.caeme.elen.utah.edu/] project came into being through the endeavors of Irene Peden and Magdy Iskander, as a means of using computer-visualization and interactive capabilities for EM instruction. CAEME has become a real success story, and has broadened to the more general focus of engineering education, for which Magdy Iskander deserves our hearty congratulations.

My own interest in visual EM (VEM) continued over the years. Aside from the value of VEM to computer modeling [18], I continued to feel that visualization can be a powerful tool for teaching an abstract topic like electromagnetics. Eventually, I obtained funding while still at LLNL for a two-summer program (1985-86), held in collaboration with Associated Western Universities. This involved having college teachers come to LLNL for a few weeks or month to make computer movies for use in their own courses. I actually participated as one of the college visitors in the summer of 1986. The output of this program was published in 1988 as a three-volume report by LLNL [19], which is provided in connection with the *TWTD* movies mentioned above. A frame from one of the movie-strips that shows the near electric field around an impulsively excited dipole is presented in Figure 5.

After joining the faculty of the Electrical and Computer Engineering Department at Kansas University, in 1985, one of the courses I organized was on computer graphics in engineering applications. The goal of this course was for the two-person student teams to develop a computer movie for use in one of their courses, in collaboration with one of their professors, using a new laboratory being organized for that purpose. I was both amazed and gratified by how much effort the students who participated were willing to devote to this activity, and the quality of the projects that they produced. The results of the LLNL and KU projects are described in a series of papers and articles [20-22].

The Arrival of Hand-Held Calculators and the First PCs

The first HP-35 hand-held calculator came to market about 1975. Just as I had about decided to part with the $395.00 price of the calculator, it was announced that Commodore would be demonstrating a self-contained computer called the PET (Personal Electronic Transactor) at LLNL. After seeing the demonstration, I decided to instead buy a PET, which I obtained in early 1976. Two models of the PET were offered, one having 4 kB of memory, and the other 8 kB, priced at $600.00 and $800.00, respectively. I bought the latter. The PET had a Motorola 68000 processor, and cassette-magnetic-tape I/O, but no printer was available, initially. It came with *BASIC* and an operating system in ROM, and fairly elaborate graphics, for the time. I squeezed Prony's Method into the PET with about five bytes of memory to spare, when doing a 10-pole waveform.

My next PC was an Apple II+, acquired in 1980. The Apple was used to run *MININEC* [23, 24], as well as *TWTD*, which had been transferred to the Commodore and Apple by Jerry Landt. Even given the slow speed and limited memories of these early micros, they could do interesting problems using such codes. A talk at the 1983 URSI meeting, describing some of these applications [25], led to an invitation by Dan Schaubert, then the AP-S *Newsletter* Editor, to write a feature article on this topic, from which this column originated.

I got my first Macintosh in 1985, and have upgraded several times since, but also acquired a PC clone a few years ago. Although I did a great deal of programming in my days at the University of Michigan, I had not personally made use of models like *NEC* and *TWTD* until rather recently. I first used a Macintosh version of *TWTD* in 1987, and began using *NEC* on a Mac about 1995, after I retired. The motivation for beginning to run these codes myself was that I no longer had much contact with others who might be willing to run problems in which I was interested. This experience has been enlightening, especially in seeing for myself just how much can be learned about electromagnetic physics from looking at some rather simple, but fundamental, problems.

Some Other AP-S/IEEE Activities

In 1985, I was asked by Y. T. Lo to join the AP-S Education Committee, of which I became Chairman shortly after. Two issues were on the committee's agenda: one was the development of videos on topics of interest to the Society that would be made available to members, and the other was the possibility that AP-S should offer short courses to attendees at our yearly meetings. To get started on the latter, Bud Adams, also a committee member, and I prepared a brief questionnaire to distribute to participants at the 1985 meeting, held at the University of British Columbia in Vancouver. Based on the very encouraging response received, we organized a "test run" of the short-course idea for the 1986 meeting in Philadelphia. Bud and I together gave a half-day short course on the Moment Method, and Yahya Rahmat-Samii gave another on reflector antennas, both held on Friday of that week.

The large attendance at this first short-course experiment led us to expand our offerings at the 1987 meeting, at Virginia Tech, to four, of which two were video-taped: "Pattern Synthesis for Antenna Arrays," by Robert S. Elliott, and "Adaptive Processing Antenna Systems," by William F. Gabriel, which are also available from the IEEE [see the "AP-S Video Courses" box elsewhere in this issue, usually near the Short Courses listings]. These initial two short-course ventures were successful enough that short courses have become a standard component of the AP-S yearly meetings ever since.

Although short courses provide one way to develop the videos mentioned above, they are not normally able to be given in a setting designed for such productions. Thus, we also sought other means for developing videos. Subsequently, some others were made in TV studios, and these can also be found in the "AP-S Video Courses" listing.

The validation of CEM software and results had been a long-standing interest of mine. This led, with some prodding and participation by Leo Felsen, to organizing a special session on this topic at the 1988 Syracuse meeting, followed by two subsequent workshops at the 1989 and 1990 AP-S meetings, in San Jose and Dallas. The goals for the workshops were several, including the development of databases for results from computation and measurement that would be easily accessible, and the devising of quantitative ways for standardized comparison of results from different sources. [See PCs for AP, October, 1987; October, 1989; February, 1990; August, 1990.] Unfortunately, although there was general agreement with the idea of collecting data for validation purposes, and with the principle of encouraging quantitative comparisons of different results, implementation of these goals was not found to be easy. Although some progress has been made in making authors more aware of the value of stating data comparisons quantitatively, the perception remains that this is difficult to do and is probably not worth the effort.

The Applied Computational Electromagnetics Society also became involved in this problem of software validation. A special issue of the *ACES Journal* on "Electromagnetics Computer Code Validation" was published in 1989. Several benchmark problems, intended for validation purposes, were later published in a special issue of the *ACES Journal* titled "The ACES Collection of Canonical Problems, Set 1," in the Spring of 1990. Still another issue of the *ACES Journal*, in 1993 (volume 8, number 2), contained a special section on TEAM (Testing Electromagnetic Analysis Methods) Benchmark Problem Solutions. Incidentally, TEAM is still active, according to the following information received from Hal Sabbagh: "TEAM is a series of workshops intended for the comparison of solution methods and codes for electromagnetic field computation. The workshop started in 1985, and is organized in rounds. In each round, lasting about two years, there are a number of regional workshops, ending in a final workshop that is normally held in conjunction with the COMPUMAG conference. The last workshop that I am aware of was the sixth round, and was held at Okayama, Japan, but I suspect that they are already into the eighth round. The problems are industrially oriented, and scan the entire frequency range. The solutions tend to favor finite elements, but not exclusively. There are several that incorporate boundary elements with finite elements."

Concluding Comments

Over the years, my own interests in CEM have remained focused on a few areas. One, discussed above, is visualization. Another is the information-related aspects of computer modeling, which provided a motivation for the model-based work in which I've been involved. A third somewhat-related topic is the possible role of statistics in problem formulation, solution, and application. Finally–for reasons that I can't fully recall anymore–there is the problem of where and why does radiation originate from in a body?

From a personal perspective, I feel very fortunate regarding my working career. Most of the time I have had positions where I looked forward to going back to work on Monday morning, and otherwise didn't want to miss a day. Also, not being particularly analytically inclined, the arrival of the digital computer happened at just the right time for me. I was, in addition, fortunate over most of my career that financial support was usually not a limiting factor in doing the things I wanted to do. Finally, there were generally interesting problems on which to work, supportive sponsors, and creative, congenial, and collaborative colleagues. Overall, I'm grateful to be able to say that work was challenging, worthwhile, and fun.

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