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# Research in Electromagnetic Scattering

Final report for Contract # F49620-98-C-0011 submitted to the  
Air Force Office of Scientific Research

by

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## Abstract

This document constitutes a final report for our research in electromagnetic scattering during the years 1998–2000. The technical research accomplishments during each year divide conveniently into the areas of time-domain electromagnetics, high-frequency diffraction, and surface integral equations. In the year 2000, work also was initiated in the area of analyzing arrays of small elements using a source scattering-matrix description of coupled radiators. As principal investigator, Arthur D. Yaghjian carried out the major portion of the research, and coordinated his efforts with those of R.A. Shore of the Air Force Research Laboratory, T.B. Hansen of Schlumberger-Doll, R.A. Albanese of Brooks AFB, R.W. Ziolkowski of the University of Arizona, V. Oliner of MATIS, S.W. Lee of SAIC, and A.J. Devaney of A.J. Devaney Associates.

## 1 Technical Summary of Accomplishments

Our research accomplishments in electromagnetic scattering during each of the years 1998, 1999, and 2000 divide conveniently into three main areas:

- Time-Domain Electromagnetics
- High-Frequency Diffraction
- Surface Integral Equations.

In addition, we initiated a promising new area of research in 2000 by developing a general method for rigorously analyzing linear arrays of electrically small coupled radiators. This final report documents the progress made in these areas of electromagnetic research on a year by year basis.

## 1.1 Research in the Year 1998

In 1998 our research efforts were concentrated in the three main areas: time-domain electromagnetics, high-frequency diffraction, and surface integral equations. As a "Research Scientist Emeritus" at AFRL/SNH, Hanscom AFB, Dr. Yaghjian consulted in 1998 with a number of Hanscom engineers and scientists: principally, with Dr. Robert Shore (as mentioned below), and, for example, with Dr. Edward Altshuler on his work with designing small resonant wire antennas using genetic algorithms. He also collaborated with Dr. Thorkild B. Hansen in finishing their book on the "Plane-Wave Theory of Time-Domain Fields." Yaghjian and Devaney also consulted on numerous topics in electromagnetics throughout the year.

### Time-Domain Electromagnetics

In the area of time-domain electromagnetics, Yaghjian and Hansen continued to develop the "plane-wave theory of time-domain fields" and completed the manuscript of the book under this title to meet the September 1998 submission deadline of the IEEE Press. As part of this effort, Yaghjian proved the intriguing result that the output of an arbitrary receiving antenna satisfies the time-domain homogeneous wave equation as the receiving antenna translates without rotation in the fields of a transmitting antenna. He used this result, which he had obtained previously in the frequency domain, to derive the probe-corrected time-domain plane-wave transmission formula for determining time-domain far fields from near-field measurements. This near-field time-domain work was presented as an invited paper at the International EUROEM Conference in June 1998. Also, Yaghjian applied the method he discovered in 1997, for determining the minimum possible source region, to a number of different far-field patterns. This minimum source region work was presented at the Triennial International Symposium on EM Theory in May 1998. The work of Yaghjian and Hansen in formulating time-domain near-field measurement techniques has formed the basis of a new program begun in 1998 at the Technical University of Denmark for implementing these techniques.

### High-Frequency Diffraction

In the area of high-frequency diffraction, Yaghjian and Shore applied the shadow-boundary incremental length diffraction coefficients (ILDC's), which they derived, to elliptic cylinders. They found that the agreement was excellent between the scattered fields predicted by the ILDC's and the method of moments (MOM) solution to the dual-surface integral equations, especially with the ILDC's that they recently modified to improve the accuracy for more rapidly varying radii of curvature. This ILDC work was presented in part at the Triennial International Symposium on Electromagnetic Theory in May 1998. Plans were made with Dr. V. Oliner of MATIS and Dr. S.W. Lee of SAIC to incorporate these shadow-boundary ILDC's during the years 1999 to 2001 into the production high-frequency computer codes

they continue to develop for the Air Force.

### **Surface Integral Equations**

In the area of surface integral equations, the preconditioner that Yaghjian discovered in 1997, for reducing and stabilizing the number of iterations required by the iterative solution to the 2-D electric-field integral equation (EFIE), was applied by Professor Weng Chew et al. in two papers presented at the IEEE APS/URSI meeting in Atlanta GA, June 1998. In the first paper, "Use of Preconditioners to Ease Disparate Grid Size Problem," they applied the preconditioner to 3-D problems and concluded that "the near-field preconditioner [Yaghjian's] is the best since it takes the least amount of time and its slope is only slightly greater than  $N^2$ ." In the second paper, "Approximate Inverse Preconditioner for Near Resonant Scattering Problems," they were able to reduce the CPU time (required to apply the preconditioner) to  $O(N)$  per iteration for 2-D problems solved by the FMM method and its modifications. The challenge remains to reduce the CPU preconditioner time to  $O(N)$  per iteration for 3-D problems solved by these state-of-the-art computational methods.

## **1.2 Research in the Year 1999**

In 1999 milestones were reached in the areas of time-domain electromagnetics and high-frequency diffraction. A minor effort with surface integral equations produced lesser, though noteworthy accomplishments in this area as well. As a "Research Scientist Emeritus" at AFRL/SNH, Hanscom AFB, Dr. Yaghjian consulted in 1999 with a number of Hanscom engineers and scientists, principally, with Dr. Robert Shore (as mentioned below). He continued to consult with Dr. Edward Altshuler in his work designing small resonant wire antennas. He also consulted with Professor Richard Ziolkowski of the University of Arizona and Dr. Richard Albanese of Brooks AFB on the computation of the motion of charges with particle-in-cell computer codes. Yaghjian and Devaney also consulted on numerous topics in electromagnetics and applied mathematics throughout the year.

### **Time-Domain Electromagnetics**

In the area of time-domain electromagnetics, Yaghjian and Hansen added the final revisions to the manuscript of their book, "Plane-Wave Theory of Time-domain Fields," published by IEEE Press in June 1999. The chapter of this book that develops probe-corrected near-field scanning in the time domain was presented as an invited paper at the 26th URSI General Assembly (Toronto, Ontario, Canada, August 1999). Antenna measurement laboratories at the Technical University of Denmark and at the Delft University of Technology continue to use their formulation of time-domain near-field scanning. Also, in the area of time-domain electromagnetics, Yaghjian began a basic investigation into deriving unambiguous expressions for the classical time-dependent forces on electric and magnetic dipoles

in polarized material. The derivation of well-defined general expressions for these dipolar forces has remained a challenging, fundamental problem in electromagnetics for over a century. Yaghjian has made significant progress toward solving this problem during 1999 and presented his preliminary findings in a paper invited to the special session on electromagnetic theory at the 1999 IEEE Int'l Symposium on Antennas and Propagation (Orlando, FL, July 1999). He continues to research this fundamental problem in electromagnetics.

Finally, in the area of time-domain electromagnetics, Yaghjian consulted with Richard Ziolkowski on the computation of the motion of charges with particle-in-cell (PIC) computer codes. Yaghjian was able to show theoretically three important results. First, the effect of including the self force on charges entered into a PIC code would be negligible for the design of high power microwave tubes. Second, the two-step algorithm for computing forces and fields of moving charges, utilized in the existing PIC codes, is necessary to avoid having to solve a prohibitively difficult nonlinear differential equation (which Yaghjian derived, nonetheless). Third, existing PIC codes should be capable of accurately computing trajectories of individual charges accelerating between charged plates. This latter result was confirmed by Ziolkowski using the TwoQuik PIC code developed at Sandia National Laboratory.

### **High-Frequency Diffraction**

In the area of high-frequency diffraction, Shore and Yaghjian, in just a few months of work with obliquely incident fields scattered from perfectly conducting spheroids, were able to demonstrate conclusively the importance and effectiveness of the shadow-boundary incremental length diffraction coefficients (ILDC's) for enhancing the accuracy of the computed physical optics (PO) fields. These shadow-boundary ILDC's, which Yaghjian derived a couple of years ago, are implemented by simply integrating a closed-form expression along shadow-boundary lines, and thus do not add significantly to the PO computer time. With one parameter (the local radius of curvature normal to the shadow boundary), they account for the significant part of the contribution to the fields from all the creeping waves that emanate from the shadow boundary. Shore and Yaghjian showed that the ILDC computed fields were as accurate as, or more accurate than, the uniform theory of diffraction (UTD) solution, which requires a time-consuming surface integration throughout the shadow region. Shadow-boundary ILDC's are now ready for incorporation into production PO computer codes. We look forward to assisting in this effort in the future, and completing the documentation of our ILDC work.

### **Surface Integral Equations**

The area of surface integral equations took a backseat in 1999 to the areas of time-domain electromagnetics and high-frequency diffraction. Nevertheless, in preparing a paper on low-frequency scattering invited to an IEEE/URSI Special Session in Orlando, FL, Yaghjian was able to prove uniqueness of solution to a new, more accurate low-frequency integral equation

solution for scattering from perfectly conducting cylinders of arbitrary cross section. Also, within the area of surface integral equations, Shore and Yaghjian applied the dual-surface magnetic-field integral equation (MFIE) for bodies of revolution to compute the “exact” solution for scattering from the spheroids used in our shadow-boundary ILDC calculations reported in the previous paragraph. Shore also ran the body of revolution dual-surface electric-field integral equation (EFIE) code, which uses triangular basis and testing functions, and found that it produced erroneous results for multi-wavelength spheroids illuminated by obliquely incident plane waves. Since the EFIE, but not the MFIE, applies to open (as well as closed) conductors, we plan to try to determine the cause of the failure of the triangular-function method-of-moments solution to the EFIE for large bodies of revolution. It should then be possible to remedy this failure and produce a more robust procedure for solving the dual-surface EFIE (and EFIE’s in general).

### **1.3 Research in the Year 2000**

In 2000 we completed the tasks that we proposed in our three main areas of research (time-domain electromagnetics, high-frequency scattering, and surface integral equations) and we initiated a promising new area of research by developing a general method for rigorously analyzing linear arrays of electrically small coupled radiators. Following is a summary of our progress in these areas of research in 2000 as well as our plans for 2001. Further review of our past work and future objectives can be found in the follow-on research proposal submitted at the end of 2000 to AFOSR by A.J. Devaney Associates, Inc. As a “Research Scientist Emeritus” at AFRL/SNH, Hanscom AFB, Dr. Yaghjian continued to consult in 2000 with a number of Hanscom engineers and scientists, principally with Dr. Robert Shore (as mentioned above) and with Dr. Edward Altshuler in designing small resonant wire antennas and small superdirective arrays (see FY-2000 Annual Task Report submitted by Altshuler). As indicated in the previous paragraph, Yaghjian and Professor A.J. Devaney also consulted throughout the year on various topics in electromagnetics and applied mathematics.

#### **Time-Domain Electromagnetics**

In the area of time-domain electromagnetics, Yaghjian continued the fundamental work of deriving unambiguous expressions for the time-dependent forces on electrically and magnetically polarized materials. By clearly defining polarization densities in continuous media, and then carefully distinguishing between cavity defined and mathematically defined electromagnetic fields through the rigorous differentiation of singular vector and scalar potentials, he was able to prove that a continuous model of polarization densities produces the same form of the macroscopic Maxwell equations irrespectively of whether the constituent dipole moments of the polarization are generated by electric or magnetic charge-current. These results, which were presented as an invited paper at EUROEM 2000, are a prerequisite for deriving unambiguous expressions for electromagnetic forces in a polarized continuum. Al-

though the possibility of a successful resolution of this century-old fundamental problem in classical electromagnetic theory would invite Yaghjian's full attention in 2001, additional commitments and interests require his time be divided among three other areas of research.

### **High-Frequency Diffraction**

In the area of high-frequency diffraction, Shore and Yaghjian began the process of documenting and implementing their newly derived and tested shadow boundary incremental length diffraction coefficients (ILDC's) by writing three papers and presenting three talks (two invited) on the subject in 2000, and by outlining with S.W. Lee the detailed tasks required to incorporate shadow boundary ILDC's into production computer codes, namely the Xpatch code now owned by SAIC. We anticipate that some of our time in 2001 will be needed in the continued effort to implement ILDC's into production computer codes.

### **Surface Integral Equations**

In the area of surface integral equations, Shore and Yaghjian completed the difficult task of deriving, programming, testing, and documenting a robust numerical procedure for accurately solving for the scattering from open and closed bodies of revolution using the dual-surface electric-field integral equation (DSEFIE). Although the dual-surface electric- and magnetic-field integral equations were derived previously by Yaghjian, only the DSMFIE had been successfully programmed. (The computation speed of solution for surface integral equations far surpasses that of any other numerical solution to the exact Maxwell equations.) The addition of a reliable DSEFIE program allows one to efficiently and confidently determine estimates of error by comparing the numerical solutions obtained independently from the DSEFIE and either the DSMFIE (when applicable) or the combined field integral equation. As part of our numerical analysis and experimentation, we found that the highly singular kernel of the DSEFIE required a sophisticated method of numerical solution to obtain a reasonably accurate solution and it precluded a simple pulse-basis point-matching solution. To reduce both the programming effort and solution time through the use of pulse basis functions and point matching, we propose for 2001 to recast the EFIE and DSEFIE into a form whose kernel has no greater singularity than the free-space Green's function. Preliminary work indicates that such a reduction is possible.

### **Scattering-Matrix Analysis of Small-Element Arrays**

Initiating a new area of research in 2000, Yaghjian and Devaney mathematically combined the basic principles of linearity, reciprocity, and power conservation with a spherical-wave source scattering matrix description of electroacoustic transducers. This scattering-matrix analysis simply and clearly revealed the existence and properties of traveling waves supported by both finite and infinite linear arrays of small electroacoustic transducers as well as the complete radiating and scattering characteristics of the arrays. We hope to continue this

promising area of research in 2001 by extending the scattering-matrix analysis to arrays of electromagnetic radiators (antennas/scatterers), including the arrays of small antenna elements used in the design of electromagnetic bandpass filters.

## 2 Principal Publications

### 2.1 Books and Book Chapters

1. T.B. Hansen and A.D. Yaghjian, *Plane-Wave Theory of Time-Domain Fields: Near-Field Scanning Applications*, New York: IEEE Press, June 1999.
2. A.D. Yaghjian and T.B. Hansen, "Wave equations and transmission formulas for the output of a receiving antenna," in *Ultra-Wideband, Short-Pulse Electromagnetics 4*, New York: Plenum Press, 1999 (Invited).

### 2.2 Published Articles

1. A.D. Yaghjian, "Review of dual-surface integral equations," *Digest of National Radio Science Meeting (Boulder, CO)*, p. 235, January 1998 (Invited paper).
2. R.A. Shore and A.D. Yaghjian, "A comparison of two incremental length diffraction coefficients for convex perfectly electrically conducting cylinders," *Proceedings of the International Symposium on Electromagnetic Theory (Thessaloniki, Greece)*, vol. 1, pp. 4-6, May 1998.
3. A.D. Yaghjian, "Confined, classical, causal pulses produced by finite-energy sources in a bounded volume," *Digest of National Radio Science Meeting (Boulder, CO)*, p. 121, January 1999.
4. A.D. Yaghjian, "Review of low-frequency scattering from two-dimensional perfect conductors," *USNC/URSI Digest (Orlando, FL)*, p. 163, July 1999 (Invited).
5. A.D. Yaghjian, "Electromagnetic forces on point dipoles," *Digest of IEEE Int'l Symposium on Antennas and Propagation (Orlando, FL)*, pp. 2868-2871, July 1999 (Invited).
6. A.D. Yaghjian and T.B. Hansen, "Formulation of probe-corrected planar near-field measurement of pulsed antennas," *Digest of the 26th URSI General Assembly (Toronto, Ontario, Canada)*, p. 110, August 1999 (Invited).
7. A.D. Yaghjian, T.B. Hansen and A.J. Devaney, "Determination of the minimum convex source region from the electromagnetic far-field pattern," *Radio Science*, pp. 417-425, March-April 2000 (Invited).
8. A.D. Yaghjian and R.A. Shore, "Comments on incremental diffraction coefficients for plane conformal strips with application to bistatic scattering from the disk," *Journal of Electromagnetic Waves and Applications*, pp. 881-883, July 2000.

9. R.A. Shore and A.D. Yaghjian, "Shadow boundary incremental length diffraction coefficients applied to scattering from 3-D bodies," *IEEE Transactions on Antennas and Propagation*, February 2001.
10. A.D. Yaghjian, "Incremental length diffraction coefficients for arbitrary cylindrical scatterers," *IEEE Transactions on Antennas and Propagation*, accepted December 2000, to appear August 2001.
11. A.D. Yaghjian, "A scattering-matrix analysis of linear periodic arrays," *IEEE Transactions on Antennas and Propagation*, submitted May 2000.
12. A.D. Yaghjian, "Direct derivation of dispersion relations" *Journal of Mathematical Physics*, submitted February 2001.

### 2.3 Reports

1. R.W. Ziolkowski and A.D. Yaghjian, *Upgrading the Field-Particle Physics and Numerics of PIC codes for HPM Tube Design*, Final Report for STTR AF98T010, October, 1999.
2. R.A. Shore and A.D. Yaghjian, *Dual Surface Electric Field Integral Equation*, AFRL In-House Report, submitted September 2000.