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In the main area of Frequency-Domain Electromagnetics, we made significant accomplishments in the sub-areas of Scattering-Matrix Analysis of Periodic Arrays, Bandwidth and Quality Factor of Antennas, Supergain Arrays, and Surface Integral Equations. Yaghjian also continued to consult with John Moore of SAIC on his further testing of the source-based ILDC's implemented in recent years into the widely used high-frequency computer code Xpatch. A joint paper with Shore and Moore on the subject was presented at the 2005 Washington DC IEEE AP-S Symposium.

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Research in Electromagnetic Scattering

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by
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Abstract

This document constitutes a final report for our research in electromagnetic scattering during the two-year period between 15 March 2004 and 15 March 2006. The technical research accomplishments during these two years divide conveniently into two main areas: first, FREQUENCY-DOMAIN ELECTROMAGNETICS with the four sub-areas of Scattering-Matrix Analysis of Periodic Arrays, Bandwidth and Quality Factor of Antennas, Supergain Arrays, and Surface Integral Equations; second, TIME-DOMAIN ELECTROMAGNETICS with the two sub-areas of Classical Equations of Motion of Charged Particles and Fundamental Electromagnetic Theory. Significant consultations were also made in the areas of incremental length diffraction coefficients, the development of the Air Force cylindrical near-field scanning facility for measuring bistatic RCS, and the Hanscom effort to create a low-loss negative index of refraction metamaterial at GHz frequencies. As principal investigator, Arthur D. Yaghjian carried out the major portion of the research and coordinated his efforts with those of R.A. Shore, E.E. Altshuler, S.R. Best, U.H.W. Lammers, R.A. Marr, and J.S. Derov of the Air Force Research Laboratory, as well as with J.T. Moore of SAIC, T.B. Hansen of Witten Technologies, T.H. O'Donnell of ARCON, and A.J. Devaney of A.J. Devaney Associates.

1 Summary of Technical Research Accomplishments

Our research accomplishments in electromagnetic scattering during the two years between 15 March 2004 and 15 March 2006 divide conveniently into two main areas with six sub-areas:

Frequency-Domain Electromagnetics

Scattering-Matrix Analysis of Periodic Arrays

Bandwidth and Quality Factor of Antennas

Supergain Arrays

Surface Integral Equations

Time-Domain Electromagnetics

Classical Equation of Motion of Charged Particles

Fundamental Electromagnetic Theory.

In addition, we continued consulting in the implementation of incremental length diffraction coefficients (ILDC's) in conjunction with SAIC, in the development of a cylindrical near-field scanning facility for measuring bistatic RCS at Hanscom AFB, and in the efforts at Hanscom to design and fabricate a low-loss negative index of refraction metamaterial at GHz frequencies.

1.1 Frequency-Domain Electromagnetics

In the main area of Frequency-Domain Electromagnetics, we made significant accomplishments in the sub-areas of Scattering-Matrix Analysis of Periodic Arrays, Bandwidth and Quality Factor of Antennas, Supergain Arrays, and Surface Integral Equations.

Yaghjian also continued to consult with John Moore of SAIC on his further testing of the source-based ILDC's implemented in recent years into the widely used high-frequency computer code Xpatch. A joint paper with Shore and Moore on the subject was presented at the 2005 Washington DC IEEE AP-S Symposium.

Scattering-Matrix Analysis of Periodic Arrays

During the first year, Yaghjian and Shore of AFRL-Hanscom applied their scattering-matrix analysis to array elements that couple both electric and magnetic dipole fields, and combined this analysis with the exact Mie solution to determine a transcendental equation for the propagation constants and stopbands of traveling waves on linear arrays of magnetodielectric spheres that could be used to create "double negative" (DNG) material if the same results for linear arrays hold for 2-D and 3-D arrays. As a first step toward solving the 2-D and 3-D electromagnetic dipolar array problem, they extended their results for linear arrays of acoustic monopoles to 2-D and 3-D arrays. The dipolar sphere work was presented at the 2004 ISAP and subsequently invited for publication in a special issue of the IEICE Transactions. The manuscript for this publication was prepared and submitted. On the topic of DNG materials, Yaghjian gave an invited talk on the fundamentals of DNG media in a special session devoted to this topic at the 2004 Triennial Electromagnetic Theory Symposium in Pisa, Italy.

During the second year, Shore and Yaghjian were able to derive transcendendal equations for the propagation constants of traveling waves on 2-D and 3-D arrays of electromagnetic dipole scatterers that approached the simplicity of the transcendendal equations they had previously derived for 1-D arrays. Within a few minutes of desktop computer time, these transcendental equations enable them to obtain, for example, the k–β diagrams for 1-D, 2-D, and 3-D arrays of both nanospheres (glass as well as silver and gold) that have been proposed for use as optical waveguides and magnetodielectric spheres that have potential use as double negative (DNG) metamaterials. These DNG results have presently become the focus of the Hanscom-AFRL composite materials program under the direction of Dr. John Derov. In fact, it was Yaghjian who suggested that small inexpensive magnetodielectric cubes could be substituted for the spheres, which are prohibitively expensive to machine in the numbers required for 3D arrays.

Bandwidth and Quality Factor of Antennas

As another major research topic in frequency-domain electromagnetics, Yaghjian and Best completed their work on determining universal exact definitions and useful approximate formulas for the bandwidth and quality factor (Q) of antennas. Specifically, during the first year they determined a simple method for removing the dependence of the defined Q on the point to which the far field of the antenna is referenced, they proved the need for frequency derivatives of the constitutive parameters in the "internal energy" used to define the Q of a general antenna, they generalized their expressions for Q to be applicable to material with negative constitutive parameters, they further tested their theoretical results both analytically and numerically by applying them to more complicated antennas, and they submitted a write-up of this considerable body of work to the IEEE AP-S Transactions, where it was accepted for publication. Also, Best and Yaghjian prepared and submitted two other shorter manuscripts (one on the Foster reactance theorem for antennas and one on the lower bounds on Q for lossy antennas) both of which were accepted for journal publication in the IEEE Antennas and Wireless Propagation Letters. Both Best and Yaghjian have received a number of invitations to speak on the subject of the bandwidth and Q of antennas.

During the second year of research, the editors of the IEEE AP-S Transactions requested that the companion papers submitted by Yaghjian and Best on the "Impedance, Bandwidth, and Q of Antennas" be combined into a single (27 page) paper. In making the necessary revisions, Yaghjian decided to generalize their definition of quality factor (Q) to antennas containing the most general linear, spatially nondispersive material characterized by the constitutive tensors $\mu(\boldsymbol{r},\omega)$, $\epsilon(\boldsymbol{r},\omega)$, $\tau(\boldsymbol{r},\omega)$, and $\nu(\boldsymbol{r},\omega)$. As a strong confirmation of the validity of their definition of Q, he proved that the internal electromagnetic energy associated with their defined Q is always positive in lossless manifestations of this most general linear material, regardless of the values (positive or negative) of the constitutive parameters or their variation in space ($\boldsymbol{r}$) and frequency (ω).

Supergain Arrays

Since the publication of their paper in FY-2005 on "A Monopole Superdirective Array," O'Donnell, Best, Altshuler, and Yaghjian have been working to design an electrically small resonant antenna with a high enough radiation resistance that two of these antennas could be placed a tenth of a wavelength apart to create superdirectivity without losing their gain to a reduced efficiency. As part of that effort, Yaghjian suggested replacing the sensitive input network (needed to feed each of the two antennas with the proper current magnitude and phase to obtain superdirectivity) with an ordinary voltage source feeding one antenna while shorting the second antenna so that it resonates as a parasitic element. By merely adjusting the frequency and separation distance of this parasitic two-element array, O'Donnell was able to show that nearly as much superdirectivity was obtainable with this simple parasitic arrangement as with the more complicated controlled feeding of the two elements separately. The possibility of such a simple two-element superdirective antenna stirred an enthusiastic effort within AFRL/SNHA to build and test a prototype of this antenna in the near future.

Surface Integral Equations

Yaghjian and Shore also refined their derivation and numerical solution to the low-singularity electric-field integral equation (LEFIE) and submitted the work to the Journal of EM Waves and Applications, where it was accepted for publication. They also prepared and submitted a recently published manuscript to the IEEE AP-S Transactions on "Dual-Surface Integral Equations in Electromagnetic Scattering." Although these equations had seen considerable development and use at Hanscom AFB, they had not seen the light of archival journal publication.

1.2 Time-Domain Electromagnetics

In the main area of Time-Domain Electromagnetics, significant achievements were made in the sub-areas of Classical Equation of Motion of Charged Particles and Fundamental Electromagnetic Theory.

Classical Equation of Motion of Charged Particles

During the first year, Yaghjian continued to prepare the second edition of his book on the classical equation of motion of charged particles. Despite the considerable time he spent on frequency-domain electromagnetic projects at Hanscom, he managed to derive a revised classical equation of motion that eliminates both pre-deceleration as well as pre-acceleration, to verify the range of validity of the revised equation of motion by applying it to a number of convincing examples, and to begin entering these revisions into the Latex macro for the second edition of the book.

The second year of research saw the completion of the manuscript for the second edition of the Springer book, "Relativistic Dynamics of a Charged Sphere," which appeared in early 2006. As part of that completion, Yaghjian was able to derive both the necessary and sufficient conditions for the Landau-Lifshitz approximate solution for synchrotron motion to be an accurate solution to the Lorentz-Abraham-Dirac renormalized equation of motion of a charged particle. As Rohrlich says in the Foreword to the second edition, "It is remarkable how these results call for empirical tests yet to be performed at the necessarily extreme conditions and with sufficiently high accuracy." Probably the most remarkable implication of the second edition of the book was realized shortly before the final manuscript was submitted. Namely, that any causal Lorentz-Dirac renormalized equation of motion must have a high-energy limitation. In the words of Chapter 8 of the second edition, "the generalization of Newton's second law of motion to classical point charges with renormalized mass is incompatible with the Maxwell-Lorentz equations and conservation of energy if the magnitude of the externally applied force becomes too large." In other words, the "high-energy catastrophe" that limits the scope of present-day quantum physics and prevents the successful unification of the gravitational, electromagnetic, weak, and strong forces arises in accepted classical physics as well. As far as we are aware, this is the first time such a result for classical physics has been proven.

Basic Electromagnetic Theory

A second surprising development that occurred in time-domain electromagnetics was a fundamental theorem that Yaghjian recently discovered on the positive semidefiniteness of the internal energy of lossless media. This theorem allows a definitive interpretation of Poynting's theorem in the time domain for lossless media. Although this theorem was required in the time domain, it was applied to quasi time-harmonic fields to provide theoretical rational for our frequency-domain definitions of antenna quality factor.

2 Principal Publications

2.1 Published Articles

1. A.D. Yaghjian, "Fundamentals of linear, homogeneous, isotropic, lossless media with negative permeability and permittivity," *Proc. of URSI EMTS*, vol. 1, pp. 87–89, May 2004 (Invited).

2. S.R. Best and A.D. Yaghjian, "The Foster reactance theorem and quality factor for antennas," *IEEE Trans. Antennas Wireless Propagation*, pp. 306–309, December 2004.

3. S.R. Best and A.D. Yaghjian, "The lower bounds on Q for lossy electric and magnetic dipole antennas," *IEEE Trans. Antennas Wireless Propagation*, vol. 3, pp. 314–316, December 2004.

4. R.A. Shore and A.D. Yaghjian, "A low-order singularity electric-field integral equation solvable with pulse basis functions and point matching," *Journal of EM Waves and Applications*, vol PIER 52, pp. 129–151, January 2005.

5. A.D. Yaghjian and S.R. Best, "Impedance, bandwidth, and Q of antennas," *IEEE Trans. Antennas Propagat.*, vol. 53, pp. 1298–1324, April 2005.

6. R.A. Shore and A.D. Yaghjian, "Traveling electromagnetic waves on linear periodic arrays of lossless spheres," *Electronics Letters*, vol. 41, pp. 578–580, May 2005.

7. R.A. Shore and A.D. Yaghjian, "Dual-surface integral equations in electromagnetic scattering," *IEEE Trans. Antennas Propagat.*, vol. 53, pp. 1706–1709, May 2005.

8. R.A. Shore and A.D. Yaghjian, "Traveling electromagnetic waves on linear periodic arrays of lossless penetrable spheres," *Trans. IEICE*, vol. E88-B, pp. 2346–2352, June 2005 (Invited).

9. J.T. Moore, A.D. Yaghjian, and R.A. Shore, "Shadow boundary and truncated wedge ILDCs in Xpatch," *Proc. APS Symp.*, vol. 1, pp. 10–13, July 2005.

10. R.A. Shore and A.D. Yaghjian. "Determination of k–β diagrams for arrays of penetrable spheres," *Proc. APS Symp.*, vol. 2B, pp. 308–311, July 2005 (Invited).

11. E.E. Altshuler, T.H. O'Donnell, A.D. Yaghjian, and S.R. Best, "A monopole superdirective array," *IEEE Trans. Antennas Propagat.*, vol. 53, pp. 2653–2661, August 2005.

12. R.A. Shore and A.D. Yaghjian, "Scattering-matrix analysis of 1D, 2D, and 3D arrays of acoustic monopoles and electromagnetic dipoles," *Proc. URSI General Assembly*, Session B02, 4 pages, October 2005.

2.2 Reports

1. R.A. Shore and A.D. Yaghjian, *A Low-Order Singularity Electric-Field Integral Equation Solvable with Pulse Basis Functions and Point Matching*, AFRL Technical Report, Hanscom AFB, June 2004.

2. R.A. Shore and A.D. Yaghjian, *Traveling Waves on Linear Periodic Arrays of Small Lossless Penetrable Spheres*, AFRL Technical Report, Hanscom AFB, July 2004.

2.3 Presentations

1. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *University of Massachusetts at Amherst*, April 2004 (Invited).

2. R.A. Shore and A.D. Yaghjian, "Traveling waves on linear periodic arrays of small lossless penetrable spheres," *Int'l Symp. on Antennas and Propagation (Sendai, Japan)*, August 2004 (Invited).

3. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *University of Illinois at Champaign-Urbana*, September 2004 (Invited).

4. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *IEEE APS Washington DC Chapter*, 26th October 2004 (Invited).

5. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *IEEE APS Baltimore MD Chapter*, 27th October 2004 (Invited).

6. R.A. Shore and A.D. Yaghjian, "Traveling electromagnetic waves on linear metallic nanosphere arrays," *ANTEM Symp.* (Saint Malo, France), June 2005.

7. A.D. Yaghjian, T.H. O'Donnell, E.E. Altshuler, and S.R. Best, "An electrically small superdirective array," *URSI/APS Symp.* (Washington DC), July 2005 (Invited).

8. A.D. Yaghjian, "Impedance, bandwidth, and Q of antennas," *IEEE APS Los Angeles CA Chapter*, July 2005 (Invited).

In closing, the research of the principal investigator and his collaborators continues to be recognized through awards, numerous citations, invitations to present and submit papers, requests to review papers and chair sessions, and through an invitation for Yaghjian to serve as an "IEEE Distinguished Lecturer" for the Antennas and Propagation Society during the years 2003–2005.