

UNCLASSIFIED

Defense Technical Information Center
Compilation Part Notice

ADP015062

TITLE: Electromagnetic Scattering by a System of Dielectric Spheres
Coated With a Dielectric Shell

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Applied Computational Electromagnetics Society Journal. Volume
18, Number 4, November 2003. Special Issue on ACES 2003 Conference.
Part 1

To order the complete compilation report, use: ADA423296

The component part is provided here to allow users access to individually authored sections
of proceedings, annals, symposia, etc. However, the component should be considered within
the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP015050 thru ADP015064

UNCLASSIFIED

Electromagnetic Scattering by a System of Dielectric Spheres Coated With a Dielectric Shell

A-K. Hamid
Department of Electrical and
Computer Engineering
University of Sharjah
P.O. Box 27272, Sharjah, U.A.E
email: akhamid@Sharjah.ac.ae

M. I. Hussein
Department of Electrical Engineering
United Arab Emirates University
P.O. Box 17555, Al-Ain, United Arab
Emirates
email: MIHussein@uaeu.ac.ae

M. Hamid
Department of Electrical Engineering
University of South Alabama
Mobile, AL 36688, U.S.A
email: mhamid@usouthal.edu

Abstract

Analytical solution is derived to the problem of scattering of electromagnetic plane wave by an array of dielectric spheres each coated with a dielectric shell. The incident, scattered and transmitted electric and magnetic fields are expressed in terms of the vector spherical wave functions. The vector spherical translation addition theorem is applied to impose the boundary conditions on the surface of various layers. Numerical results are computed and presented graphically for the radar cross sections of several configurations of spheres system with multi dielectric layers.

1. Introduction

Many authors have studied the scattering of electromagnetic plane wave by a dielectric sphere coated with a dielectric shell. Aden and Kerker [1] obtained analytical expressions to the scattering of electromagnetic plane wave by a dielectric sphere coated with a concentric spherical shell of different dielectric materials, while Scharfman [2] presented numerical results for the special case of a small electrical radius ($ka < 1$) dielectric coated conducting sphere. It was found in those early studies that the presence of dielectric coatings leads to substantial increase in the backscattering cross section for an appropriate choice of the dielectric constant and thickness of the coating relative to that of uncoated sphere. Further, Wait has extended the solution to the case of scattering by a radially inhomogeneous sphere [3], while a numerical solution using the method of moments obtained by Medgyesi-Mitschang and Putnam for the case of dielectric-coated concentric sphere [4]. More recently, an exact solution of electromagnetic plane wave scattering by an eccentric multilayered sphere was developed by Lim and Lee [5]. Numerous papers on the scattering from systems of spheres of various natures in close proximity have been treated by numerous researchers [6-11].

Up to now, there has been no analytical or numerical solution to the problem of scattering of electromagnetic plane wave by an array of conducting spheres each coated

with a dielectric layer. In this paper, we extend the solution of scattering by two dielectric spheres covered with a dielectric shell [9] to the case of scattering by a system of dielectric spheres each covered with a dielectric shell. The solution to this problem has many practical applications since, for example, it may be used to study the scattering by complex objects simulated by a collection of spheres [12], and it may also be used to check the accuracy of numerical solutions.

From the design point of view, the backscattering cross section of an array of N dielectric coated spheres can be controlled to exploit multiple resonances by optimizing the multivariables of the system. These include the size and location of each sphere, number of dielectric layers coating each sphere as well as the thickness and relative dielectric constant of each layer as already done for conducting cylinders [13].

2. Formulation of the Problem

Consider a linear array of N dielectric spheres each coated with a dielectric shell and having different radii and unequal spacing with centers lying along the z axis, as shown in Fig. 1. Electromagnetic plane wave of unit electric field intensity, whose propagation vector $\vec{K}$ lies in the x - z plane and makes an angle α with the z -axis, is assumed to be incident on the spheres. Its incident electric and magnetic fields are

$$\vec{E}_i = e^{j\vec{k} \cdot \vec{r}} \hat{y} \quad (1)$$

$$\vec{H}_i = -\frac{1}{\eta} e^{j\vec{k} \cdot \vec{r}} (\cos \alpha \hat{x} - \sin \alpha \hat{z}) \quad (2)$$

with k being the wave number, $\hat{x}$, $\hat{y}$, and $\hat{z}$ are the unit vectors along the x , y and z axes, respectively, and η is the surrounding medium intrinsic impedance. The incident electric and magnetic fields may be expanded in terms of spherical vector wave functions around the center of the p^{th} sphere as

$$\bar{E}_i(r_p, \theta_p, \phi_p) = \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [P_p(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + Q_p(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p)] \quad (3)$$

$$\eta \bar{H}_i(r_p, \theta_p, \phi_p) = j \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [P_p(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + Q_p(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p)] \quad (4)$$

where $\bar{M}_{mn}^{(1)}$ and $\bar{N}_{mn}^{(1)}$ are the spherical vector wave functions of the first kind representing incoming waves associated with the spherical Bessel function, while $P_p(m, n)$ and $Q_p(m, n)$ are the incident field expansion coefficients defined in [7-8,14]. The field in the region II can be also expressed in terms of the vector spherical wave functions of the first and third kinds. Hence the electric and magnetic fields may be written as

$$\bar{E}_{II}(r_p, \theta_p, \phi_p) = \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A'_{Ep}(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A''_{Ep}(m, n) \bar{N}_{mn}^{(3)}(r_p, \theta_p, \phi_p) + A'_{Mp}(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A''_{Mp}(m, n) \bar{M}_{mn}^{(3)}(r_p, \theta_p, \phi_p)] \quad (5)$$

$$\eta \bar{H}_{II}(r_p, \theta_p, \phi_p) = j \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A'_{Ep}(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A''_{Ep}(m, n) \bar{M}_{mn}^{(3)}(r_p, \theta_p, \phi_p) + A'_{Mp}(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A''_{Mp}(m, n) \bar{N}_{mn}^{(3)}(r_p, \theta_p, \phi_p)] \quad (6)$$

where $A'_{pE}(m, n)$, $A'_{pM}(m, n)$, $A''_{pE}(m, n)$, and $A''_{pM}(m, n)$ are the field expansion coefficients, while $\bar{M}_{mn}^{(3)}$ and $\bar{N}_{mn}^{(3)}$ are the vector spherical wave functions of the third kind representing outgoing waves associated with the spherical Hankel function. The subscripts E and M denote transverse magnetic (TM) and transverse electric waves (TE), respectively. The field in region I of the p th sphere may be written in terms of the vector wave functions of the first kind, i.e.,

$$\bar{E}_I(r_p, \theta_p, \phi_p) = \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A_{EP}(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A_{MP}(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p)] \quad (7)$$

$$\bar{H}_I(r_p, \theta_p, \phi_p) = \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A_{EP}(m, n) \bar{M}_{mn}^{(1)}(r_p, \theta_p, \phi_p) + A_{MP}(m, n) \bar{N}_{mn}^{(1)}(r_p, \theta_p, \phi_p)] \quad (8)$$

where A_{EP} and A_{MP} are the unknown transmitted coefficients. Finally, the scattered electric and magnetic fields from the p th sphere are expanded as

$$\bar{E}^s(r_p, \theta_p, \phi_p) = \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A_{Ep}(m, n) \bar{N}_{mn}^{(3)}(r_p, \theta_p, \phi_p) + A_{Mp}(m, n) \bar{M}_{mn}^{(3)}(r_p, \theta_p, \phi_p)] \quad (9)$$

$$\eta \bar{H}^s(r_p, \theta_p, \phi_p) = j \sum_{n=1}^{\infty} \sum_{m=-n}^{m=n} [A_{Ep}(m, n) \bar{M}_{mn}^{(3)}(r_p, \theta_p, \phi_p) + A_{Mp}(m, n) \bar{N}_{mn}^{(3)}(r_p, \theta_p, \phi_p)] \quad (10)$$

where $A_{Ep}(m, n)$, $A_{Mp}(m, n)$ are the unknown scattered field coefficients. To express the scattered fields from the q th sphere in the coordinate system of the p th sphere, we apply the spherical vector translation addition theorem for translation along the z -axis [15], i.e.,

$$\bar{M}_{mn}^{(3)}(r_q, \theta_q, \phi_q) = \sum_{v=1}^{\infty} [A_{mn}^{mv}(d_{pq}) \bar{M}_{mv}^{(1)}(r_p, \theta_p, \phi_p) + B_{mn}^{mv}(d_{pq}) \bar{N}_{mv}^{(1)}(r_p, \theta_p, \phi_p)] \quad (11)$$

$$\bar{N}_{mn}^{(3)}(r_q, \theta_q, \phi_q) = \sum_{v=1}^{\infty} [A_{mn}^{mv}(d_{pq}) \bar{N}_{mv}^{(1)}(r_p, \theta_p, \phi_p) + B_{mn}^{mv}(d_{pq}) \bar{M}_{mv}^{(1)}(r_p, \theta_p, \phi_p)] \quad (12)$$

where $A_{mn}^{mv}(d_{pq})$ and $B_{mn}^{mv}(d_{pq})$ are the translation coefficients of the spherical vector translation addition theorem. To determine the unknown scattered field coefficients, we apply the boundary conditions on the various interfaces, i.e.,

$$\bar{r}_p \times \left[\bar{E}_i(b_p, \theta_p, \phi_p) + \sum_{p=1}^N \bar{E}^s(b_p, \theta_p, \phi_p) \right] = \bar{r}_p \times \bar{E}_{II}(b_p, \theta_p, \phi_p) \quad (13)$$

$$\bar{r}_p \times \left[\bar{H}_i(b_p, \theta_p, \phi_p) + \sum_{p=1}^N \bar{H}^s(b_p, \theta_p, \phi_p) \right] = \bar{r}_p \times \bar{H}_{II}(b_p, \theta_p, \phi_p) \quad (14)$$

$$\bar{r}_p \times \bar{E}_{II}(a_p, \theta_p, \phi_p) = \bar{r}_p \times \bar{E}_I(a_p, \theta_p, \phi_p) \quad (15)$$

$$\bar{r}_p \times \bar{H}_{II}(a_p, \theta_p, \phi_p) = \bar{r}_p \times \bar{H}_I(a_p, \theta_p, \phi_p) \quad (16)$$

Substituting the appropriate field expansion expressions in equations (13) to (16), and applying the orthogonality properties of spherical vector wave functions and eliminating the transmission coefficients we obtain

$$A_{EP}(m, n) = v_n(\rho_p) P_p(m, n) + \sum_{q=1}^N \sum_{\substack{q \neq p \\ q \neq p}}^{\infty} [A_{mn}^{mv}(d_{pq}) A_{EP}(m, v) + B_{mn}^{mv}(d_{pq}) A_{MP}(m, v)] \quad (17)$$

$$A_{MP}(m, n) = u_n(\rho_p) Q_p(m, n) + \sum_{q=1}^N \sum_{\substack{q \neq p \\ q \neq p}}^{\infty} [A_{mn}^{mv}(d_{pq}) A_{MP}(m, v) + B_{mn}^{mv}(d_{pq}) A_{EP}(m, v)] \quad (18)$$

where $v_n(\rho_p)$ and $u_n(\rho_p)$ are the electric and magnetic scattered field coefficients for a single dielectric sphere coated with a dielectric layer [1,9]. Equations (17) and (18) may be written in matrix form for the purpose of computing the scattered field coefficients, i.e.

$$\bar{A} = \bar{L} + T \bar{A} \quad (19)$$

where $\bar{A}$ and $\bar{L}$ are column matrices for the unknown scattered and incident field coefficients, respectively, and T is a square matrix which contains the translation addition coefficients.

Once the scattered field is computed from equation (19), the normalized bistatic cross section can be obtained as in [16].

3. Numerical Results

In order to check the validity of our computer program, several numerical tests were conducted and the results compared favorably with previously published results [7-8,11]. These tests included the limiting cases of (i) an array of dielectric spheres obtained by setting $kb \approx ka$, $\epsilon_{lr} = 1$ or $\epsilon_{lr} = \epsilon_{lr}$ (ii) an array of conducting spheres each coated with a single dielectric layer obtained by setting $\epsilon_{lr} = \infty$ and (iii) an array of conducting spheres obtained by setting $\epsilon_{lr} = \infty$ and $kb \approx ka$ or $\epsilon_{lr} = 1$.

In this paper, we presented numerical results for different sphere arrays to show the dependence of the radar cross section on various parameters characterizing the geometry, material properties, and incidence angles. Fig. 2 shows the normalized bistatic cross section versus the scattering angle θ for a system of three identical spheres in the E and H-planes. The electrical radii of the outer and inner spheres are $ka=2.0$ and $kb=2.5$, respectively, while the electrical separation between successive spheres is $kd=7.0$, and the relative dielectric permittivity of the inner dielectric layer is 3.0 and the outer is air. The purpose of this comparison is to check the accuracy of the computer code for the dielectric sphere case [8] as a special case of the dielectric spheres except the relative dielectric permittivity of the dielectric layer is set equal to unity. The parameters of Fig. 3 are similar to Fig. 2 except that the dielectric layer has a value of 2. We can see that the number of resonances in E plane is increased. Figs. 4 and 5 have the same parameters as in Fig. 3 except that the number of spheres is increased to five and eight, respectively. We can see that the number of resonances also increases with the number of spheres. Fig. 6 shows the normalized backscattering cross section versus the electrical distance (kd), which ranges from 8 (touching) to 15.5 for end fire incidence and the number of spheres is five. The electrical radii of outer and inner spheres are $ka=4.0$ and $kb=3.0$, respectively, while the relative dielectric permittivity of the inner dielectric layer is 3.0 and for the outer layer is 2. Fig. 7 is similar to Fig. 6 except the number of spheres is increased to 8. We can see that the location of the maximum peaks did not change by increasing the number of spheres for both cases. Furthermore, the magnitude of the normalized backscattering cross section at the maximum peaks increased with increasing number of spheres.

In Figs. 8 and 9 we have plotted the normalized backscattering cross as a function of the angle of incidence α , which ranges from 0 to 90 degrees for a system of three and eight spheres. The electrical radii of the outer and inner spheres are $ka=1.5$ and $kb=1.0$, respectively, while the relative permittivity of the inner dielectric layer is 4 while

for the outer layer is 3 and the electrical separation between the centers of the spheres is 3.0 (touching).

4. CONCLUSIONS

We have obtained an analytic solution of the problem of scattering by an array of dielectric spheres each coated with a dielectric shell. The boundary conditions are satisfied at various interfaces with the help of the vector translation addition theorem. The system of equations was written in matrix form while the scattered field coefficients were obtained by matrix inversion. Numerical results were presented for different numbers of spheres, angles of incidence, electrical separation, and relative dielectric constant. For the general case of spheres orientation, the reader may find more details in [8].

ACKNOWLEDGMENT

The first author wishes to acknowledge the support provided by University of Sharjah. The second author wishes to acknowledge the support of the United Arab Emirates University, while the third author wishes to acknowledge the financial support of the University of South Alabama and the National Science Foundation.

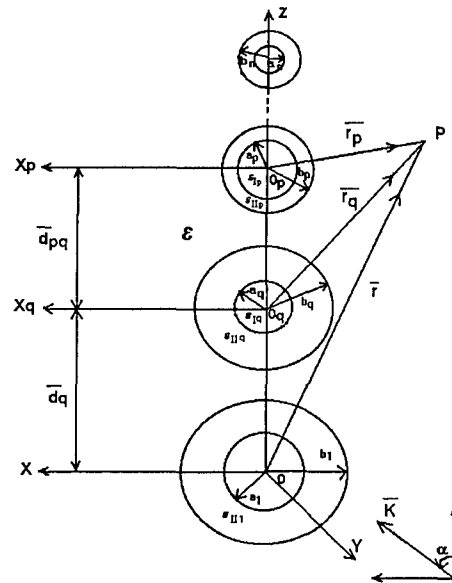


Fig. 1: Geometry of the scattering problem.

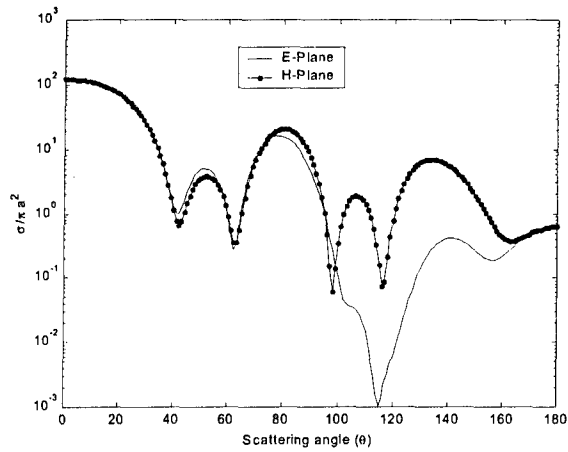


Fig. 2: Normalized bistatic cross section patterns for three identical dielectric spheres each covered with dielectric layer with $ka=2.0$, $kb=2.5$, $kd=7.0$, $\alpha=0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=1.0$. In the E-plane ($\phi=\pi/2$) and H-plane ($\phi=0$).

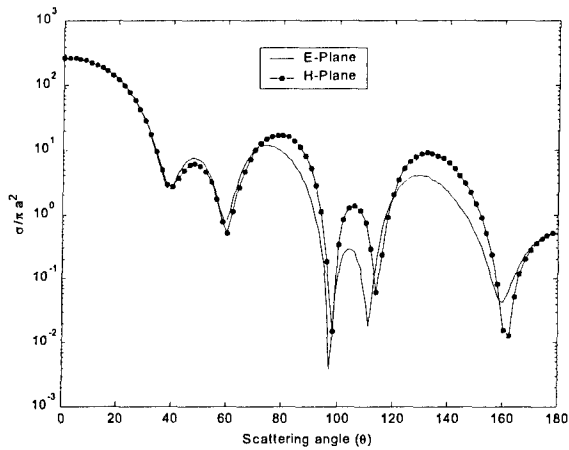


Fig. 3: Normalized bistatic cross section patterns for three identical dielectric spheres each covered with dielectric layer with $ka=2.0$, $kb=2.5$, $kd=7.0$, $\alpha=0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=2.0$.

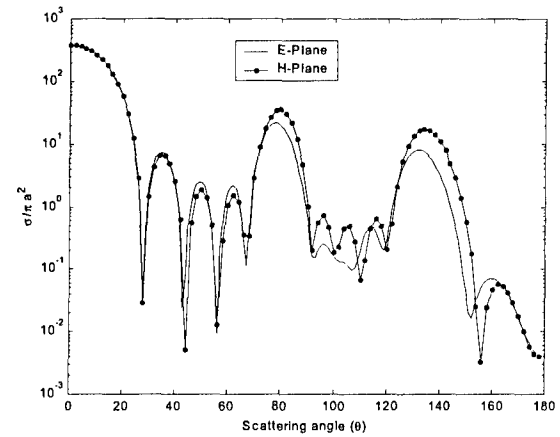


Fig. 4: Normalized bistatic cross section patterns for five identical dielectric spheres each covered with a dielectric layer with $ka=2.0$, $kb=2.5$, $kd=7.0$, $\alpha=0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=2$.

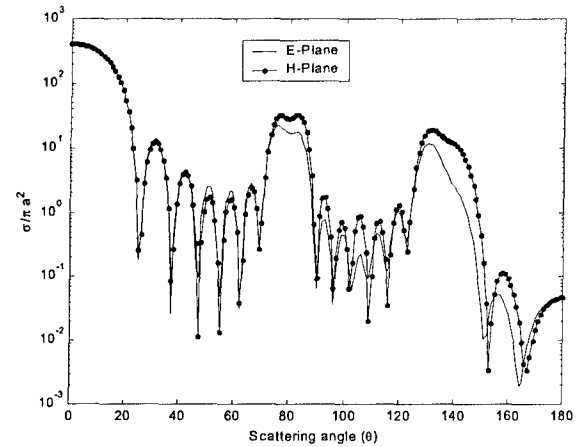


Fig. 5: Normalized bistatic cross-section patterns for eight identical dielectric spheres each covered with a dielectric layer with $ka=2.0$, $kb=2.5$, $kd=7.0$, $\alpha=0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=2.0$.

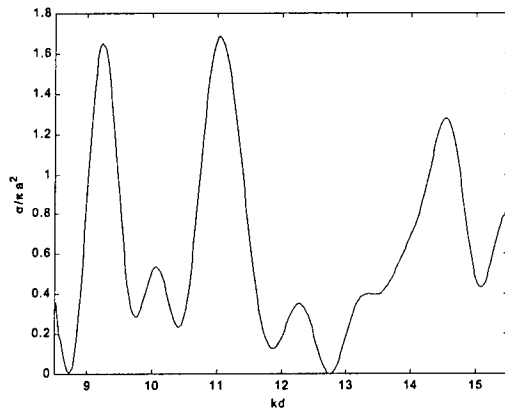


Fig. 6: Normalized backscattering cross section versus electrical separation (kd) for end-fire incidence and a linear array of five identical dielectric spheres each covered with a dielectric layer with: $ka=4.0$, $kb=3.0$, $\alpha = 0.0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=2.0$.

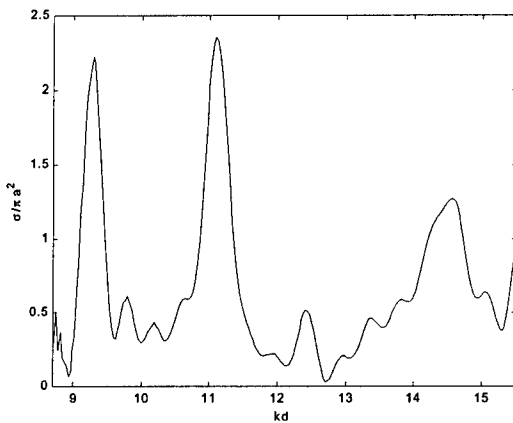


Fig. 7: Normalized backscattering cross section versus electrical separation (kd) for end-fire incidence and a linear array of eight identical dielectric spheres each covered with a dielectric layer with: $ka=4.0$, $kb=3.0$, $\alpha = 0.0$, $\epsilon_{lr}=3.0$, and $\epsilon_{llr}=2.0$.

REFERENCES

1. Aden, A.L., and Kerker, M., "Scattering of electromagnetic waves from two concentric spheres", J. Appl. Phys., 22, pp. 1242-1246, 1951.
2. Scharfman, H., "Scattering from dielectric coated spheres in the region of the first resonance", J. Appl. Phys., 25, pp. 1352-1356, 1954.
3. Wait, J.R., "Electromagnetic scattering from a radially inhomogeneous spheres," Appl. Sci. Res., vol. 10, p. 441, 1963.

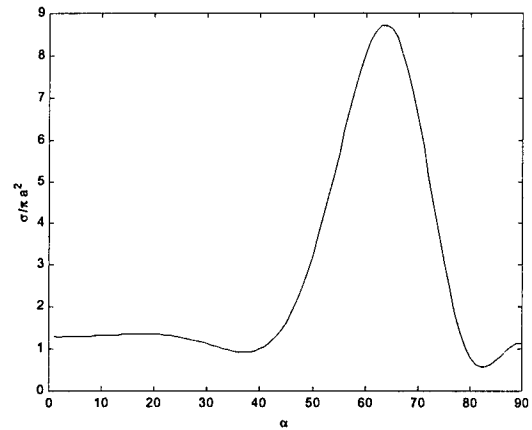


Fig. 8: Normalized backscattering cross section versus aspect angle α for a linear array of three identical dielectric spheres each covered with a dielectric layer with $ka=1.5$, $kb=1.0$, $kd=3.0$, $\epsilon_{lr}=4.0$, and $\epsilon_{llr}=3.0$.

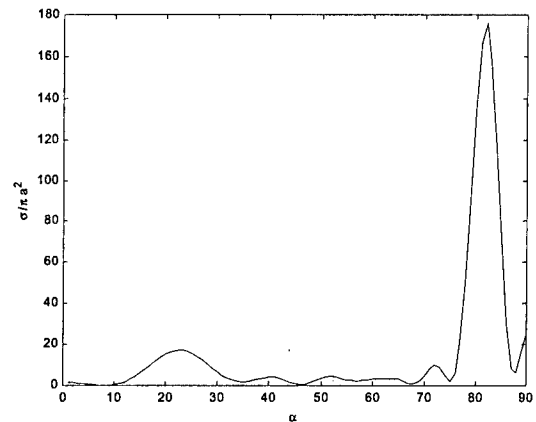


Fig. 9: Normalized backscattering cross section versus aspect angle α for a linear array of eight identical dielectric spheres each covered with a dielectric layer with $ka=1.5$, $kb=1.0$, $kd=3.0$, $\epsilon_{lr}=4.0$, and $\epsilon_{llr}=3.0$.

4. Medgyesi-Mitschang, L.N, and Putnam, J.M., "Electromagnetic scattering from axially inhomogeneous bodies of revolution," IEEE Trans. Antennas Propag., vol. AP-32, no. 8, pp. 797-806, 1984.
5. Kyutae, L., and Lee, S.L., "Analysis of Electromagnetic scattering from an eccentric multilayered sphere," IEEE Trans. Antennas Propag., vol. AP-43, no. 11, pp. 1325-1328, 1995.
6. Bruning, J. H., and Lo, Y., 1971, "Multiple scattering of EM waves by spheres: Parts I

- and II", IEEE Trans., AP-19, pp. 378-400, 1971.
7. Hamid, A-K., Ciric I.R., and Hamid, M., "Multiple scattering by a linear array of conducting spheres", Can. J. Phys., vol. 68, pp. 1157-1165, 1990.
 8. Hamid, A-K., Ciric I.R., and Hamid, M., "Iterative Solution of The Scattering by an Arbitrary Configuration of Conducting or Dielectric Spheres", IEE Proc., Part H, vol. 148, pp. 565-572, 1991.
 9. Hamid, A-K., Ciric I.R., and Hamid, M., "Analytic Solutions of The Scattering by Two Multilayered Dielectric Spheres", Can. J. Phys., vol. 70, pp. 696-705, 1992.
 10. Comberg, U., and Wriedt, T., "Comparison of scattering calculations for aggregated particles based on different models," J. of Quantitative Spectroscopy and Radiative Transfer, vol. 63, pp. 149-162, 1999.
 11. A-K. Hamid, M.I. Hussein, and M. Hamid, "Radar Cross Section of a System of Conducting Spheres Each Coated with a Dielectric Layer," J. of Electromagnetic Waves and Applications, vol. 17, pp. 431-445, 2003.
 12. Hamid, A-K., "Modeling the Scattering from a Dielectric Spheroid by System of Dielectric Spheres", J. of Electromagnetic Waves and Applications, vol.10, no.5, pp. 723-729, 1996.
 13. Hamid, M., and Rao, T.C.K., "Scattering by a multilayered dielectric-coated conducting cylinder", International J. of Electronics, vol. 38, pp. 667-673, 1975.
 14. Stratton, J.A., "Electromagnetic Theory", (McGraw Hill, New York), 1941.
 15. Cruzan, O.R., "Translational addition theorems for spherical wave functions", Quart. Appl. Math., 20, pp. 33-40. 1962.
 16. Hamid, A-K., Hussein, M.I., and Hamid, M., "Bistatic Cross Section of an Array of Dielectric Spheres Each Covered with a Dielectric Shell," the 19th Annual Review of Progress in Applied Computational Electromagnetics, Naval Postgraduate School, Monterey, California, U.S.A., pp. 77-81, March 2003.

A.-K. Hamid was born in Tulkarm, West Bank, on Sept. 9, 1963. He received the B.Sc. degree in Electrical Engineering from West Virginia Tech, West Virginia, U.S.A. in 1985. He received the M.Sc. and Ph.D. degrees from the university of Manitoba, Winnipeg, Manitoba, Canada in 1988 and 1991, respectively, both in Electrical Engineering. From 1991-1993, he was with Quantic Laboratories Inc., Winnipeg, Manitoba, Canada, developing two and three dimensional electromagnetic field solvers using boundary integral method. From 1994-

2000 he was with the faculty of electrical engineering at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Since Sept. 2000 he has been an associate Prof. in the electrical/electronics and computer engineering department at the University of Sharjah, Sharjah, United Arab Emirates. His research interest includes EM wave scattering from two and three dimensional bodies, propagation along waveguides with discontinuities, FDTD simulation of cellular phones, and inverse scattering using Neural Networks.

Mousa I. Hussein received the B.Sc. degree in electrical engineering from West Virginia Tech, USA, 1985, M.Sc. and Ph.D. degrees from University of Manitoba, Winnipeg, MB, Canada, in 1992 and 1995, respectively, both in electrical engineering. From 1995 to 1997, he was with research and development group at Integrated Engineering Software Inc., Winnipeg, Canada, working on developing EM specialized software based on the Boundary Element method. In 1997 he joined the faculty of engineering at Amman University, Amman, Jordan, as an Assistant Professor. Currently Dr. Hussein is an Associate Professor with the Electrical Engineering Dept. at the United Arab Emirates University. Dr. Hussein research interests include computational electromagnetics, electromagnetic scattering, antenna analysis and design, EMI and signal integrity. microstrip antennas, phased arrays, slot and open ended waveguide antennas.

Michael Hamid Graduated from McGill University in Montreal with a B.Eng. degree in 1960, a M.Eng. degree in 1962 and from the University of Toronto with a Ph.D. degree in 1966, all in Electrical Engineering. He joined the University of Manitoba in 1965 where he became a Professor of Electrical Engineering and head of the Antenna Laboratory. He was a visiting Professor at the Naval Postgraduate School as well as the universities of California Davis and Central Florida and is presently a Professor of Electrical Engineering at the University of South Alabama. He is a past president of the International Microwave Power Institute, a Fellow of IEE and IEEE and published 307 referred articles and 25 patents.