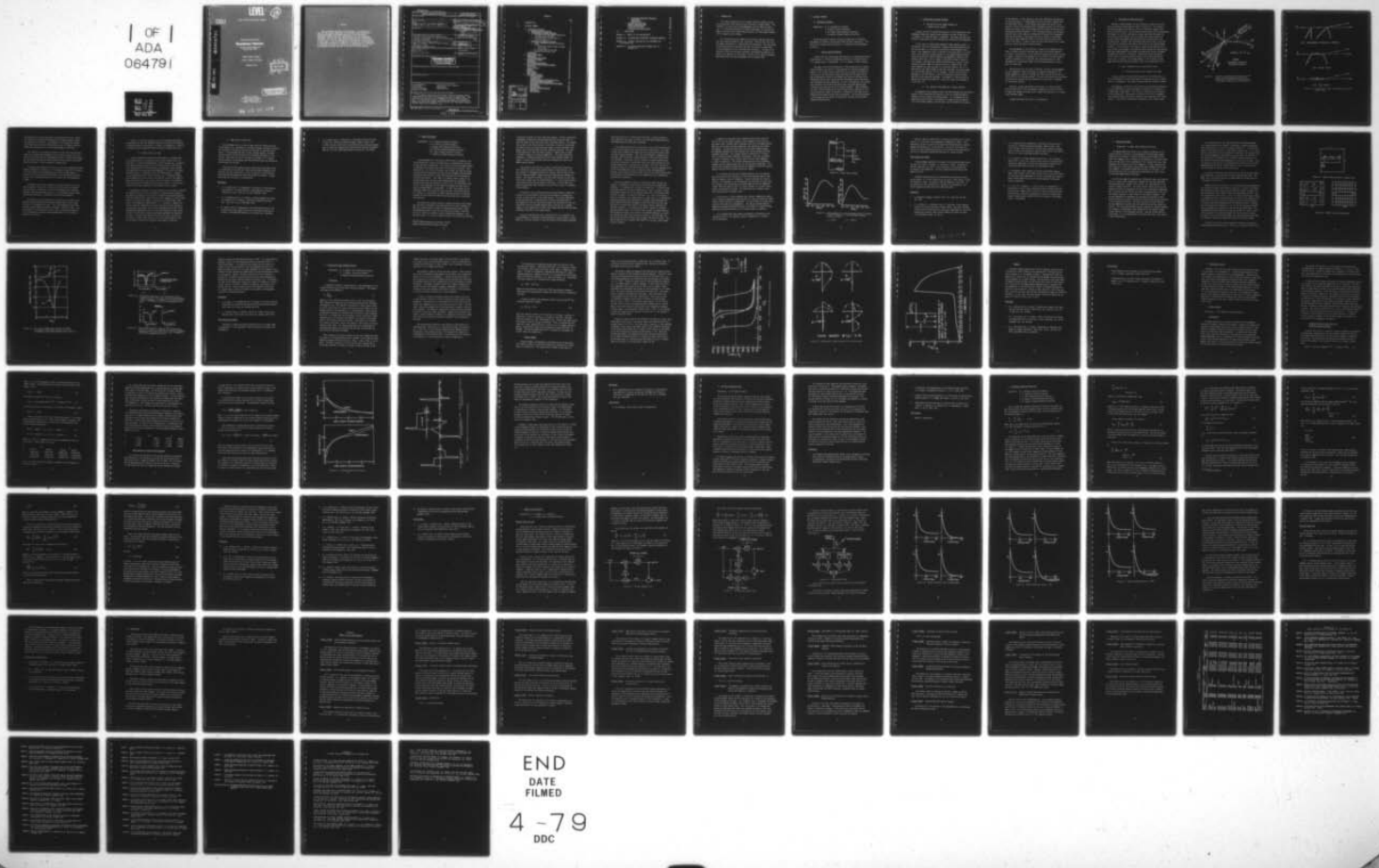
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report presents the first annual review of research at Ohio State sponsored by the Joint Services Electronics Program (JSEP). The research is in the area of electromagnetics and the specific topics are: (1) Diffraction Studies; (2) Hybrid Techniques; (3) Surface Cell Model; (4) Electrically Small Antenna Studies; (5) Time Domain Studies; and (6) Adaptive Array Studies.

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I. INTRODUCTION

This report presents the first annual review of research at Ohio State sponsored by the Joint Services Electronics Program (JSEP). The research is in the area of electromagnetics and the specific topics are: (1) Diffraction Studies; (2) Hybrid Techniques; (3) Surface Cell Model; (4) Electrically Small Antenna Studies; (5) Time Domain Studies; and (6) Adaptive Array Studies.

The following sections summarize the research that has been done and the research planned for the second year. Each section also lists the papers submitted or in preparation for publication. The conclusions section discusses the work under the JSEP in relation to other work in electromagnetics at the ElectroScience Laboratory. Listings of all research at the ElectroScience Laboratory and sponsoring agencies are given in the Appendicies along with a listing of all reports and papers published during the period September 1977 to October 1978.

II. RESEARCH SUMMARY

A. *Diffraction Studies*

Researchers: R. G. Kouyoumjian, Professor
R. Tiberio, Visiting Professor
P. H. Pathak, Senior Research Associate
J. Jirapunth, Graduate Research Associate

During the present contract the work accomplished in extending the Geometrical Theory of Diffraction (GTD) has been substantial. This involves the research and writing which is detailed in the paragraphs to follow.

1. Surface wave diffraction

A paper entitled "Surface-Wave Diffraction by a Truncated Dielectric Slab Recessed in a Perfectly-Conducting Surface," has been written by P. H. Pathak and R. G. Kouyoumjian. It is to appear in Radio Science.

The paper treats the diffraction of a TM_0 surface wave by a terminated dielectric slab which is flush mounted in a perfectly-conducting surface. The incident surface wave gives rise to waves reflected and diffracted by the termination; these reflected and diffracted fields may be expressed in terms of the geometrical theory of diffraction by introducing surface wave reflection and diffraction coefficients which are associated with the termination. In this investigation, the surface wave reflection and diffraction coefficients have been deduced from a formally exact solution to this canonical problem. These parameters are used in the GTD analysis of the radiation from an aperture or slot array covered by a sheet of dielectric. Antennas of this type are employed on high-speed aircraft and on spacecraft. The results presented in this paper are also useful in testing the validity of the surface impedance approximation.

2. Diffraction at convex surfaces

a. Diffraction at the shadow boundary of a smooth convex surface

A paper entitled "A Uniform GTD Analysis of the Scattering of Electromagnetic Waves by a Smooth Convex Surface" has been written by P. H. Pathak, W. D. Burnside and R. J. Marhefka. This paper has been submitted for publication to IEEE Transactions on Antennas and Propagation.

In this paper an approximate asymptotic high frequency result is obtained for the field scattered by a smooth, perfectly-conducting convex surface when it is excited by an arbitrary electromagnetic wavefront. This asymptotic result is uniform in the sense that it is valid within the transition regions adjacent to the shadow boundaries where the pure ray optical solution based on the geometrical theory of diffraction (GTD) fails, and it reduces to the GTD solution in terms of the incident, reflected, and surface diffracted rays, exterior to the transition regions where the latter solution is indeed valid. This result employs the same ray paths as in the GTD solution, and it is expressed in the simple format of the GTD: therefore, it may be viewed as a uniform GTD solution for this problem. In that this solution is developed in the GTD format, it can be conveniently and efficiently applied to many practical problems. For example, it could be used to analyze the scattering effects of the mast on a ship, the fuselage of an aircraft, etc.

b. The radiation from apertures in convex surfaces

An asymptotic high frequency result has been obtained for the electromagnetic field radiated by an aperture or slot in a smooth perfectly-conducting convex surface of arbitrary shape. It is assumed that the tangential electric field in the aperture is known so that an equivalent infinitesimal magnetic current source can be defined at each point

in the aperture. In this analysis, the field radiated by the aperture is then associated in a simple manner with the rays which emanate from the equivalent source. In the shadow region where the source is not directly visible, the radiated field is produced by means of diffraction around the surface, and is associated with the surface diffracted rays introduced by Keller; whereas, in the illuminated region, the radiation from the source (this does not include the diffracted field components which may be present if the convex surface is closed) is associated with the incident geometrical optics ray path direct from the source to the field point. A similar result has also been obtained for a monopole on a convex surface of arbitrary shape.

The development of this solution is based on the asymptotic solutions of simpler canonical problems where the infinitesimal magnetic or electric current source is on a perfectly-conducting circular cylinder or sphere. Presently, the accuracy of this solution is being carefully tested by employing it to calculate the radiation patterns of slots and monopoles on spheroidal shapes for which measured data are available for comparison.

The motivation for this work is twofold. Firstly, the development of this asymptotic result constitutes an important extension of the uniform geometrical theory of diffraction (GTD) solution which was obtained earlier for the same problem[1]. The earlier solution was restricted to surface rays without torsion, whereas this restriction is removed in the present solution.

Secondly, a major application of this work is in the radiation pattern prediction of slot and monopole antennas on elliptic cylinder or spheroidal geometries which serve to model aircraft, missile, or spacecraft fuselage shapes.

A paper describing this work is in preparation.

3. Extensions of edge diffraction

Consider a high-frequency EM field obliquely incident on the perfectly-conducting curved wedge as shown in Figure A-1. ES indicates the planes tangent to the convex surfaces of the curved wedge at the point of diffraction Q_E. The diffraction coefficients given by Kouyoumjian and Pathak[2] are valid in the exterior region away from the planes ES; in particular, they remain valid at and near the shadow boundary SB and the reflection boundary RB, where the earlier expressions given by Keller fail. However, the diffraction from surface rays S_r excited at Q_E must be included in the region near ES and in the region between ES and S_r. Thus a natural first step to improve the present GTD solution for the curved wedge is to determine these surface ray contributions. Additional improvements can be made by extending the present treatment of wedge diffraction to include the illumination by non ray-optical fields, such as transition region fields or the fields from sources very close to the edge. The accomplishments in the research on the edge diffraction of transition region fields will be described first.

a. Edge illumination by non ray-optical fields

i. Transition region fields incident on an edge

A paper entitled "A Uniform GTD Solution for the Diffraction by Strips Illuminated at Grazing Incidence" has been written by R. Tiberio and R. G. Kouyoumjian. This paper has been submitted to Radio Science.

An asymptotic solution for the diffraction by perfectly-conducting strips illuminated at grazing incidence, as depicted in Figure A-2c, is described in this paper. The solution is obtained by an extension of the uniform GTD[2]. Expressions are given for the field throughout the transition region for plane, cylindrical and spherical wave illumination. In the case of plane wave illumination a very simple closed

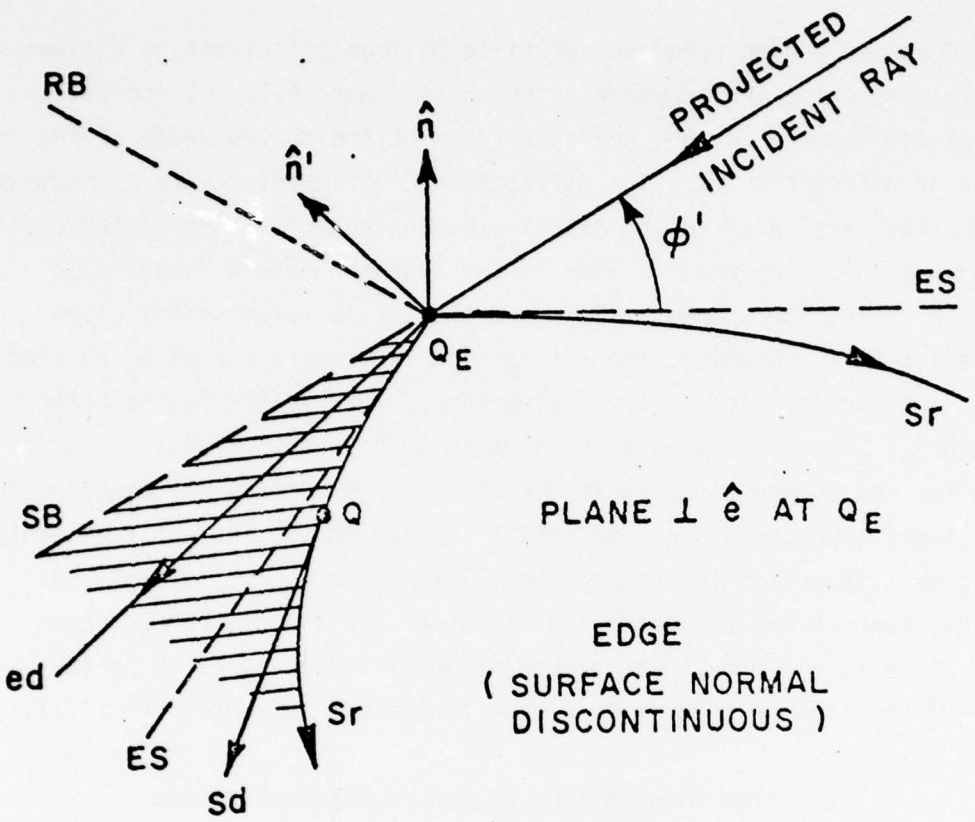
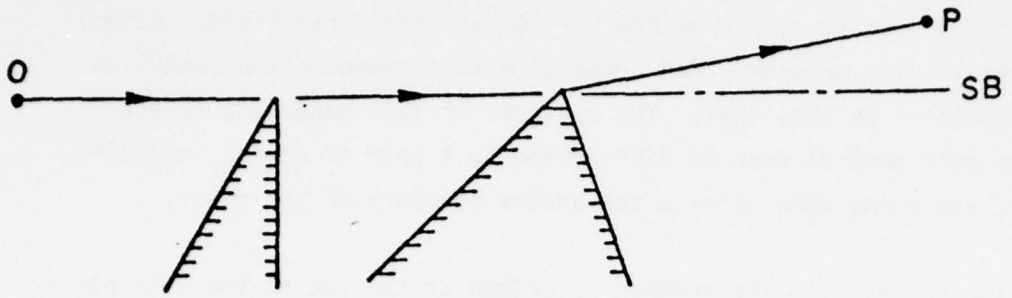
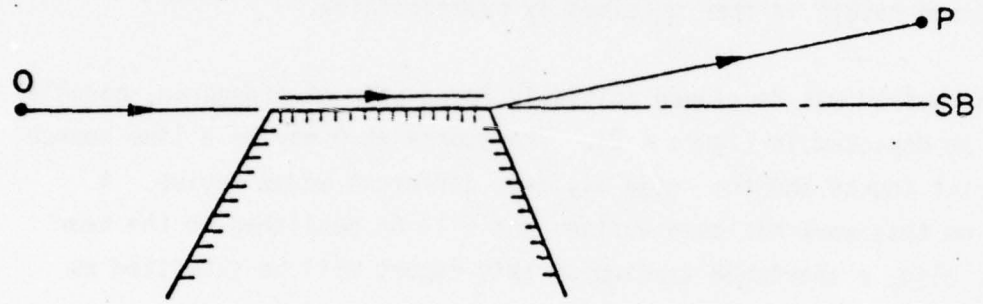


Figure A-1. Incident, reflected and diffracted rays and their associated shadow and reflection boundaries projected onto the plane normal to the edge at the point of diffraction Q_E.



(a) STAGGERED PARALLEL WEDGES



(b) THICK EDGE



(c) THE STRIP

Figure A-2. Diffraction at edges illuminated by transition region fields.

form expression is also provided for the scattered far field. Numerical results are presented and compared with a moment method solution. The agreement is excellent. The contents of this paper are related to the more general case of diffraction by a pair of nearby, parallel edges, where one edge lies on the shadow boundary of the other.

The solution to the problem described at the end of the last paragraph can be obtained by decomposing the transition region field incident on the second edge into inhomogeneous plane, cylindrical and spherical waves whose diffraction can be handled by the ordinary uniform GTD. The desired result is then obtained by superposition.

The method was developed initially for a pair of staggered, parallel wedges as depicted in Figure A-2a. The source at O may be a line source or a point source and the wedge may have different wedge angles. A report on this work has been written and will be published in the near future; also, a shortened version of this report will be submitted as a paper.

The method also has been applied to grazing incidence on a thick edge as shown in Figure A-2b. Both the TE and TM cases are treated and expressions are obtained for the field throughout the transition regions. When the observation point P is on the shadow boundary these expressions simplify to a closed form for both polarizations.

Calculations of the scattered field are found to be within a few percent of those obtained by the moment method, when the thick edge is part of a rectangular cylinder. This close agreement occurs even when the surface exposed to grazing incidence is only 0.2λ wide. Similar results are also obtained for the case of a perfectly-conducting strip illuminated at grazing incidence, mentioned in the first paragraph of this section.

A paper[3] on the work described in the two preceding paragraphs was presented at the 1978 USNC/URSI Meeting at College Park, Maryland. A written version of this paper is currently in preparation. The work is being partially supported by NOSC Contract No. N00123-76-C-1371.

ii) Source close to an edge

In the conventional form of the uniform GTD it is assumed that the incident field is a ray-optical field, which implies that it is polarized in a direction perpendicular to the incident ray. In general this requires that the source of the incident field be sufficiently far from the point of diffraction that the component of the incident field parallel to its ray path (the component in the radial direction from the source) is negligible at the diffracting point. However, in some applications this is not the case, e.g., a monopole antenna may be mounted at or very close to the edge of a ship or the edges of wings and stabilizers. This case is also of interest in the development of the hybrid GTD/moment method solution, where it is desired to calculate the input impedance to wire antennas close to edges.

An asymptotic solution for the diffraction of the fields of electric and magnetic dipoles close to the edge of a wedge has been obtained. The analysis proceeds as done earlier in developing improved wedge diffraction coefficients[4], except that the radial component of the incident field is included, which makes it necessary to include higher order terms in the asymptotic approximation. It is planned to compare this solution with the eigenfunction solution for the fields of dipoles at or very close to an edge. In turn the eigenfunction solution can be approximated asymptotically for its far and intermediate range fields, so that it can be used to check and perhaps supplement the preceding solution. From the local behavior of edge diffraction, one expects to be able to extend these solutions to curved wedge geometries and to use them to calculate the radiation from complex structures.

b. Edge-excited surface rays

Curved wedges occur as a part of many practical antenna and scattering shapes, e.g., the edge of a reflector antenna, the base of conical and cylindrical structures, and the trailing edge of wings and stabilizers. A curved wedge may have a plane surface; however, the edge-excited surface rays do not have to be introduced separately at this surface. They occur as part of the space ray system. At a concave surface forming a curved wedge, multiply-reflected waves and whispering gallery modes are excited.

In the case of the convex surface, outside the region where there is a confluence of the edge and curved surface shadow boundaries, the excitation of the surface rays S_r at Q_E in Figure A-1 has been determined from the GTD parameters which are presently available. A paper describing this research is in preparation.

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3. R. Tiberio and R. G. Kouyoumjian, "A Uniform GTD Analysis of the Diffraction by Thick Edges and Strips Illuminated at Grazing Incidence," 1978 USNC/URSI Meeting at the University of Maryland.

4. P. H. Pathak and R. G. Kouyoumjian, "The Dyadic Diffraction Coefficient for a Perfectly-Conducting Wedge," Report 2183-4, June 5, 1970, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Contract AF 19(628)-5929 for Air Force Cambridge Research Laboratories. (AD 707827)

B. Hybrid Techniques

Researchers: W. D. Burnside, Research Scientist
G. A. Thiele, Associate Professor
C. Chuang, Senior Research Associate
*E. Eckelman, Graduate Research Associate
**A. Fenn, Graduate Research Associate
L. Henderson, Graduate Research Associate

The development of a diffraction coefficient for a magnetic line source mounted on a planar structure which is terminated by a curved surface has been accomplished. The solution utilizes the moment method to determine the currents which exist on the entire structure. Even though this is an infinite structure, the currents far from the plate/curved surface discontinuity are found using the moment method whereby one defines the currents in terms of known functions with unknown excitation coefficients. This leads to a compact linear system of equations which can be solved using standard numerical techniques. It has been shown that the solution is stable (i.e., the diffraction coefficient is not dependent on the number of unknowns provided that at least a minimum number is considered). In fact, the currents on the structure, which are a much more sensitive test, also remain stable. As a result, it is felt that our hybrid approach provides an accurate solution for the diffraction coefficient associated with a plate-cylinder junction.

Even though the currents provide a complete solution to this problem, the fields scattered by the structure are not easily obtained in that the scattered field is given by integrating the current times the appropriate Green's function over the entire surface. Since the surface is infinite in extent, a direct integration procedure is far too inefficient. As a result a major portion of our effort has involved

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*Now at Andrew Corporation, Chicago, Illinois.
**Now at Martin-Marietta, Denver, Colorado.

solving this problem in a more resourceful manner. The most significant refinements to date have involved describing the surface currents in terms of known current forms plus small correction factors. For example, the current on the planar portion is described in terms of the current that would exist on an equivalent half plane, a small diffraction component, and a few pulse type currents around the junction. The scattering pattern for the half plane currents is simply given in terms of Fresnel integrals as shown by Sommerfeld[1]. The small diffraction component is integrated analytically which gives another Fresnel integral. Finally, the few pulse terms are integrated as done in any moment method problem.

The current on the circular cylinder is described in terms of a Fock current plus pulse terms placed adjacent to the junction. The Fock current is integrated analytically giving a Pekeris function solution as shown by Pathak[2], whereas the pulse functions are treated as before. This approach provides a very efficient solution for the scattered fields except near the shadow boundary, i.e., the direction pointing outward from the source toward the junction. In this region one needs to apply some other technique since the Fock current is truncated at the junction.

A solution to this problem has been obtained through a proper combination of Fock and Pekeris functions which appears to produce the correct scattered fields in the shadow region. The proper combination of the two functions is determined by satisfying two conditions: 1) the summation of the two terms should ensure the continuity of the scattered field across the shadow boundary going from the lit to shadow regions; 2) the combination of terms should blend smoothly with the known scattered field deep in the shadow region.

Using this approach the total scattered field for a magnetic line source mounted on a perfectly conducting planar structure which is terminated by a circular cylinder is very efficiently and accurately obtained.

One should note that a diffraction coefficient is simply related to the scattered field; thus, in effect, the diffraction coefficient has been determined using the above procedure.

This diffraction coefficient solution is very significant because it will provide numerically a new diffraction coefficient. This coefficient can be added to the wedge and curved surface diffraction coefficients already available. Thus, the electromagnetic community will be better able to simulate large structures in that more coefficients are available. Previously, one was limited to curved structures and flat plate simulations in which the plates and curved surfaces did not attach tangentially as treated here. Further, since this solution is written in terms of a diffraction coefficient, it can be extended easily to the three-dimensional case as shown by Pathak and Kouyoumjian[3]. Finally, this solution provides insight into how one might develop other new diffraction coefficients which are needed for better simulations of practical structures.

Since the geometrical theory of diffraction (GTD) has been successful in simulating a wide variety of practical three dimensional problems, it is appropriate to extend its capability. In doing so one needs more general diffraction coefficients. That is to say, it would be extremely useful for one to generate numerically a diffraction coefficient to simulate an arbitrary junction, i.e., such as the curved edge of a reflector, the leading edge of a wing, etc. It is conceivable, using the procedure described above, to provide a method whereby one could create the desired diffraction coefficient which could be used directly in a general GTD code[4-6] to provide a better simulation of the true structure. To illustrate this point, consider a reflector antenna system in which the reflector has a curved rim rather than the GTD assumed knife edge. One could use the GTD-MM technique to provide the diffraction coefficient with the curved one in the GTD code, and run the original GTD reflector code to obtain the desired result. This would extend the use of general GTD codes[4-6] to include a much broader class of problems.

In addition to the above hybrid technique which starts with the GTD and utilizes the moment method to handle geometries that GTD can not handle alone, another hybrid technique starts with the moment method (MM) and utilizes GTD to handle geometries that the MM can not handle efficiently. Current work being done with the hybrid moment method-GTD (MM-GTD) technique for wire antennas near curved surfaces has been extremely successful. For example, various orientations of a dipole near a circular cylinder have been investigated. One such orientation is shown in Figure B-1 and a typical result for the input impedance is shown in Figure B-2. The results show essentially exact agreement between an exact eigenfunction solution and the hybrid technique. This work has been conducted on ONR Contract No. N00014-76-C-0573 with partial support from the Joint Services Electronic Program.

It is planned that the hybrid MM-GTD technique for wire antennas near curved surfaces be extended to include the important special case where an antenna, such as a monopole, is actually mounted on a curved surface. The procedure to be followed would at the start be quite similar to that in the dissertation by Ekelman (ONR Contract No. N0014-76-C-0573) where the special case of a radial (normal) to a curved surface dipole is successfully treated. The dipole does not, however, touch the curved surface in Ekelman's work.

In the case of a radial monopole-type radiator, geometrical optics (G.O.) cannot be employed directly because G.O. does not allow for fields radial to the direction of propagation. It only allows for fields transverse to the direction of propagation. This may be overcome approximately by using the reflected field due to an image in a planar surface modified by the spread factor for the curved surface in question.

It is expected that some simple experimental verification of the theoretical results for antennas, such as a monopole on a cylinder, will be necessary.

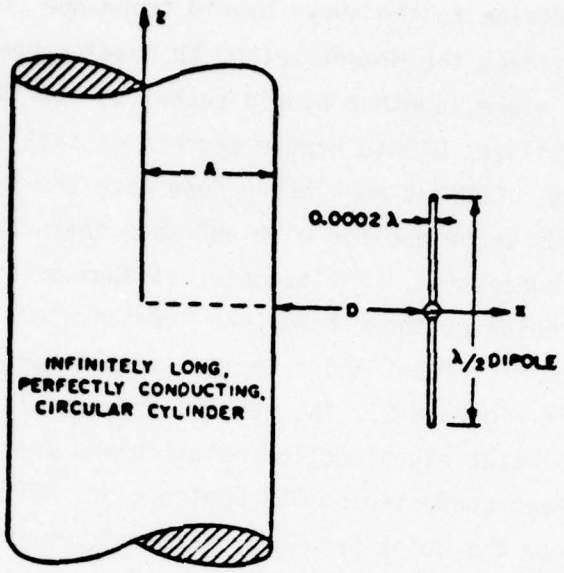


Figure B-1. Dipole near cylinder.

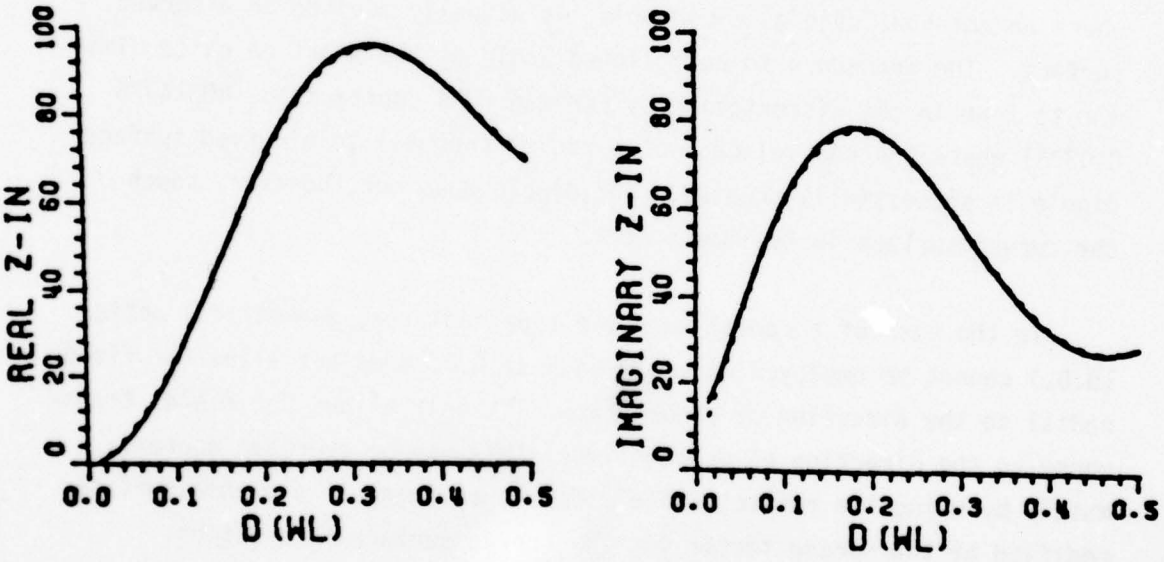


Figure B-2. Input impedance of a half-wavelength dipole a distance D from the surface of a two wavelength diameter circular cylinder.

_____Eigen ---------Hybrid

One very important application of the hybrid technique for a curved surface is in the area of electromagnetic compatability (EMC). Time permitting, we plan to start on the problem of determining the coupling between two antennas on a curved surface. This will involve the use of the so-called creeping wave theory in the GTD which has been ignored thus far in developing the MM-GTD technique for curved surfaces.

Publications and Papers

"A Hybrid Moment Method-GTD Technique for Wire Antennas Near Curved Surfaces" by Ernest P. Ekelman, Jr. and Gary A. Thiele. Presented at URSI/AP Symposium, June 1978. To be submitted to IEEE Transactions on Antennas and Propagation. Partially supported by ONR Contract No. N0014-76-C-0573.

"A Moment Method Calculation of Reflection Coefficient for Waveguide Elements in a Finite Phased Array" by Alan J. Fenn, Gary A. Thiele and Benedikt A. Munk. Presented at URSI/AP Symposium, June 1978. To be submitted to IEEE Transactions on Antennas and Propagation. Partially supported by ONR Contract No. N0014-76-C-0573.

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C. Surface Cell Model

Researcher: N. Wang, Senior Research Associate

The moment method has proven to be a powerful technique for obtaining accurate solutions to electromagnetic problems where complex geometries are involved. A natural and widely used formulation utilizes wire segments, thus a surface is represented by a wire grid. When such a surface gets to be a wavelength or so in extent the size of the impedance matrix begins to tax most computers. Greater computational efficiency can be realized by using surface patch segments rather than wire segments in the moment method when surfaces are involved. This section describes work on surface patch techniques that should lead to increased computational efficiency.

An efficient numerical approach for finding the radar cross section (RCS) of a metal plate containing a resonant slot has been developed. The method employed is based on the surface cell approximation to the reaction integral equation[1]. The total surface current density on the conducting surface is decomposed into two sets of orthogonal components, one is parallel to the slot and the other is perpendicular to the slot. The integral equation is then solved via the method of moments. The current components are expanded into overlapping sinusoidal surface functions along the current flow direction and uniform surface functions in the transverse direction. The same sinusoidal surface functions are also employed to perform the zero-reaction test on the conducting surface. This sinusoidal-Galerkin process reduces the integral equation to a system of simultaneous linear equations for the unknown surface current density on the conducting surface. Once the current density is obtained, it is straightforward to calculate the radar cross section of the slotted-plate.

As an application of this approach the RCS has been determined for a square plate of side length L containing a centered rectangular slot of dimension 2L/3 x 2L/15 as shown in Figure C-1. A surface cell model of the slotted plate is illustrated in Figure C-2a. It is interesting to note that for the calculation of the RCS of the slotted plate, the current component on the conducting surface which is parallel to the slot must be included even for a normal incident plane wave with the electric field polarized perpendicular to the slot (TE case). This is contrary to the case of an unslotted plate in that only the current component parallel to the incident electric field is sufficient for the calculation of the RCS of the solid-plate.

A previous solution for the calculation of the RCS of the slotted plate employing a wire-grid model has been obtained by Miller[2]. This model uses a wire-grid structure to approximate the slotted plate as illustrated in Figure C-2b.

Numerical data for the RCS of the slotted plate obtained employing the surface-cell model are plotted in Figure C-3. Figure C-4 presents the calculated result using the wire-grid model (shown in Figure C-2b) and the measured results both of which were obtained by Miller[2]. Several observations are in order. First, for the wire-grid results there is a downward shift in the antiresonance for the TE case (magnetic field parallel to the slot), whereas the results obtained from the surface cell model show better agreement with the measured results. Secondly, the size of the matrix equation is 24 x 24 for the surface cell model and is estimated to be about 140 x 140 for the wire-grid model. It is concluded from these observations that the surface cell model is definitely superior to the wire-grid model for this particular problem. It remains a task to determine whether the same conclusion can be made for problems involving a conducting surface with arbitrary shape.

A general surface cell with trapezoidal shape has also been developed during the present period. This is an extension from the rec-

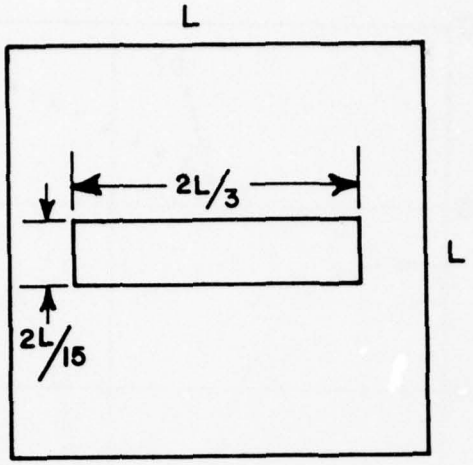


Figure C-1. Metal plate containing a resonant slot.

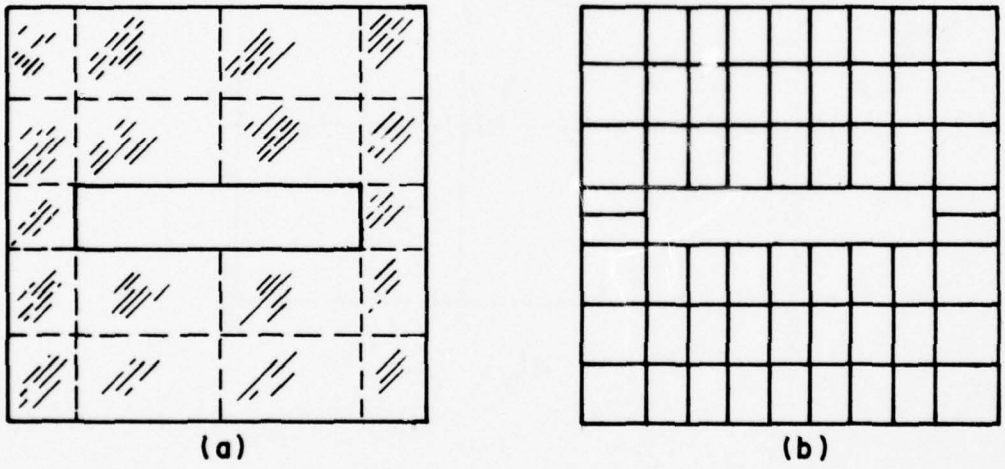


Figure C-2. Models for the slotted plate.

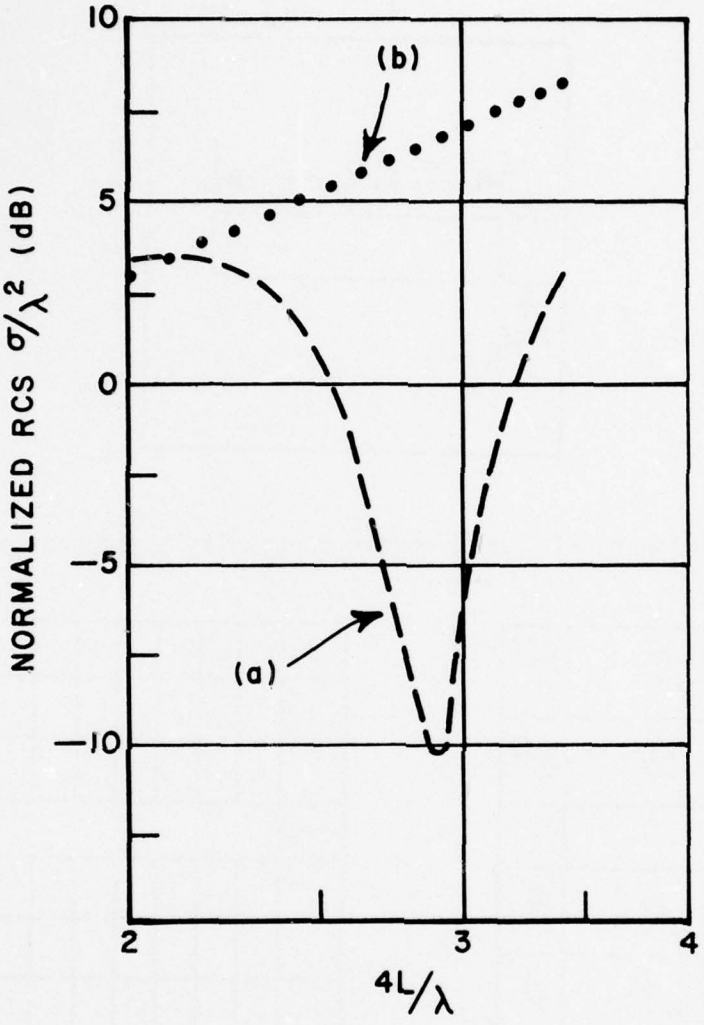


Figure C-3. RCS of the slotted plate (surface cell model)
(a) magnetic field vector parallel to the slot
(b) magnetic field vector perpendicular to the slot.

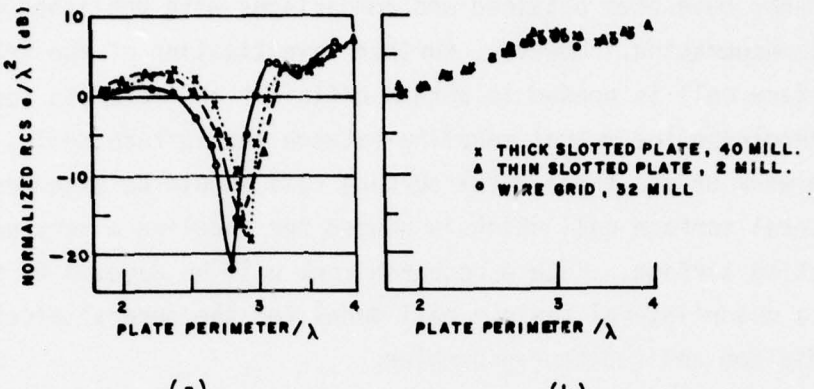


Figure C-4a. Experimental Comparison of the backscatter RCS of a slotted wire grid versus thick and thin slotted plates (normal incidence). (a) Magnetic field vector parallel to slot. (b) Magnetic field vector perpendicular to slot.

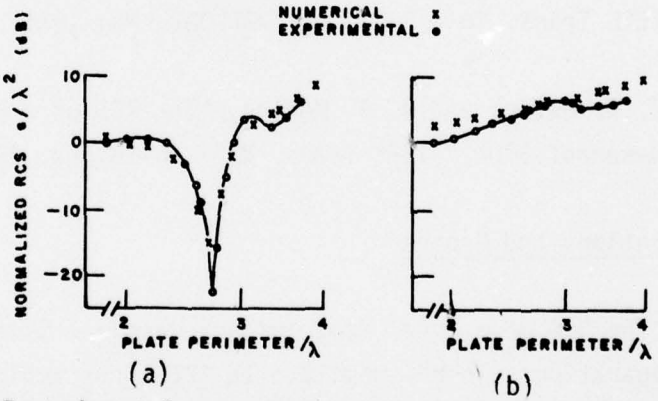


Figure C-4b. Experimental-numerical comparison of the backscatter RCS of a wire grid with resonant slot (normal incidence). (a)Magnetic field vector parallel to slot. (b)Magnetic field vector perpendicular to slot.

tangular surface cell developed previously at OSU[1]. This generalization provides a useful tool for modeling a general conducting surface in an efficient manner. A triangular plate antenna has been used as an example to test the usefulness of the new trapezoidal surface cell. Some preliminary results for the input impedance of the triangular plate antenna have been obtained and comparisons with published measured results are encouraging. However, further investigation of the trapezoidal surface cell is needed to obtain efficient and accurate techniques for determining the mutual coupling between the surface cells. Furthermore, the work on the trapezoidal surface cell should be extended to a quadrilateral surface cell which is needed for modeling a very general conducting surface. Future research work will be devoted to the study of a quadrilateral surface cell model for the general electromagnetic radiation and scattering problem.

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D. Electrically Small Antenna Studies

Researchers: E. H. Newman, Senior Research Associate
R. J. Garbacz, Associate Professor
K. Demarest, Graduate Research Associate

Discussion

An important problem in antenna design is the development of relatively efficient electrically small radiating elements. The antenna efficiency can be defined as

$$E = \frac{R_r}{R_r + R_\ell} \tag{1}$$

where R_r is the radiation resistance and R_ℓ is the loss resistance. Small antennas are generally very inefficient because their radiation resistance is low. The radiation resistance of a small dipole varies as $(\ell/\lambda)^2$, while that of a small loop varies as $(\ell/\lambda)^4$ where ℓ is the maximum extent of the antenna and λ is the wavelength. There are two conventional approaches to improving the efficiency of small antennas. The first is to reduce the loss resistance, say by using thick, highly conducting wires to construct the antenna or by using low loss components in the tuning or matching networks. The second is to increase the radiation resistance, say by top loading a short dipole or ferrite loading a small loop. This section describes a third technique for increasing the radiation resistance that has been studied under the Joint Services Electronics Program.

Small antennas are usually designed on test beds resembling either free space or an infinite ground plane. However, in use they are often mounted on support structures such as a ship, a tank, a man, or an airplane. The basic idea here is to think of the small antenna not as the primary radiator but rather as a probe to excite currents on the

support structure. Since the support structure often is not electrically small it can be an effective radiator. Thus, the radiation resistance and efficiency of a small antenna can be increased by properly locating it on its support structure.

One problem is where to locate the small antenna. Some locations may result in substantial improvements in efficiency, while others may result in little or no improvement. A second and related problem is the selection of an operating frequency which optimizes the efficiency. The optimum location at one frequency may not be the optimum at another frequency. The antenna designer may not have complete freedom in selecting location and frequency; however, knowledge as to how the efficiency varies with frequency and location can help in the selection of the best allowable location for a given frequency.

In order to select the optimum location and frequency one could compute and plot a family of curves of efficiency versus position and frequency. Presented here is a technique which should involve considerably less computation and also give more physical insight. The technique involves the computation of the characteristic modes of the support structure. The theory of characteristic modes has been presented by Garbacz[1] and by Harrington and Mautz[2]. Numerically efficient techniques, using the method of moments, for computing characteristic modes have also been presented by Harrington and Mautz[3] and are applied in this work.

The characteristic modes are real currents on the surface of a conducting body. Denoting $\underline{J}_n$ as a characteristic mode, the choice of $\underline{J}_n$ as a basis set for the current diagonalizes the impedance matrix or operator of the conducting body. The characteristic modes have orthogonality of the radiated fields. Associated with each characteristic mode $\underline{J}_n$ is a real characteristic value or eigenvalue λ_n.

The eigenvalues are important because they tell how well a particular mode radiates. Those modes with small $|\lambda_n|$ are good or effective radiators, while those with large $|\lambda_n|$ are poor or ineffective radiators. In order to substantially improve the efficiency of a small antenna mounted on a support structure, it is necessary to excite modes which are effective radiators, i.e., those with small $|\lambda_n|$. Associated with each eigenvalue is a characteristic angle defined by

$$\alpha_n = 180^o - \tan^{-1}(\lambda_n). \tag{2}$$

Modes with characteristic angles near 180° are effective radiators, while those with characteristic angles near 90° or 270° are ineffective radiators.

A source or probe, with impressed field $\underline{E}^i$, excites the nth characteristic mode with strength

$$V_n = \iint_S \underline{J}_n \cdot \underline{E}^i \, ds \tag{3}$$

where the integral extends over the surface of the body. Equation (3) shows that in order to excite $\underline{J}_n$ as strongly as possible, the probe should be placed at or near the maximum of $\underline{J}_n$. Further, the probe should be oriented so that $\underline{E}^i$ and $\underline{J}_n$ are parallel. Thus, to improve the efficiency of a small antenna we wish to locate it on its support structure where a characteristic mode, with characteristic angle near 180°, is maximum. The design example below will illustrate this procedure for a small loop on a crossed wire.

Design example

A design example is presented to illustrate the use of characteristic modes to select the operating frequency and location for a small loop on a crossed wire. The crossed wire is shown in the insert in

Figure D-1 and could represent a crude model for an airplane shape. As a design restriction we will assume that the loop must be located on the longer vertical wire of length L.

The design is begun by computing the characteristic modes and characteristic angles of the crossed wire versus frequency. Figure D-1 shows a plot of the characteristic angles of the first few modes versus L/λ. The optimum frequencies are those where the various modes are resonant, i.e., $\alpha = 180^{o}$. Figure D-2 shows a plot of the characteristic modes at $L/\lambda = 0.75$ where mode C is nearly resonant. In this figure the solid line represents the current on the vertical wire of length L, while the dotted line represents the current on the horizontal wire of length 2L/3. The arrows indicate the direction of current flow. The characteristic angles of the modes are also shown. Note that modes A and D have angles near 90° and 270°, respectively. Thus, they are poor or ineffective radiators and we have no interest in exciting them. Mode B, with $\alpha = 148^{o}$, is a reasonably good radiator, but it has zero current on the vertical wire where the small antenna must be located. Thus, we will not be able to excite mode B with substantial strength. Finally, mode C is an excellent radiator with $\alpha = 178^{o}$. It has maximum current just above the wire junction, and thus this is the optimum location of the small loop.

Figure D-3 shows a plot of the radiation resistance of a small loop, normalized to its value in free space, versus the loop position on the crossed wire at $L/\lambda = 0.75$. The ratio R_r/R_{ro}, where R_{ro} is the radiation resistance of the loop in free space and R_r is the radiation resistance of the loop on the crossed wire, is equal to the increase in efficiency due to the crossed wire, provided the efficiency is low. Note that as predicted above, the radiation resistance increases substantially (by a factor of about 65) when it is located just above the junction. On the other hand, if a location below the junction ($s<1.0$) is chosen then the increase is less than about a factor of two.

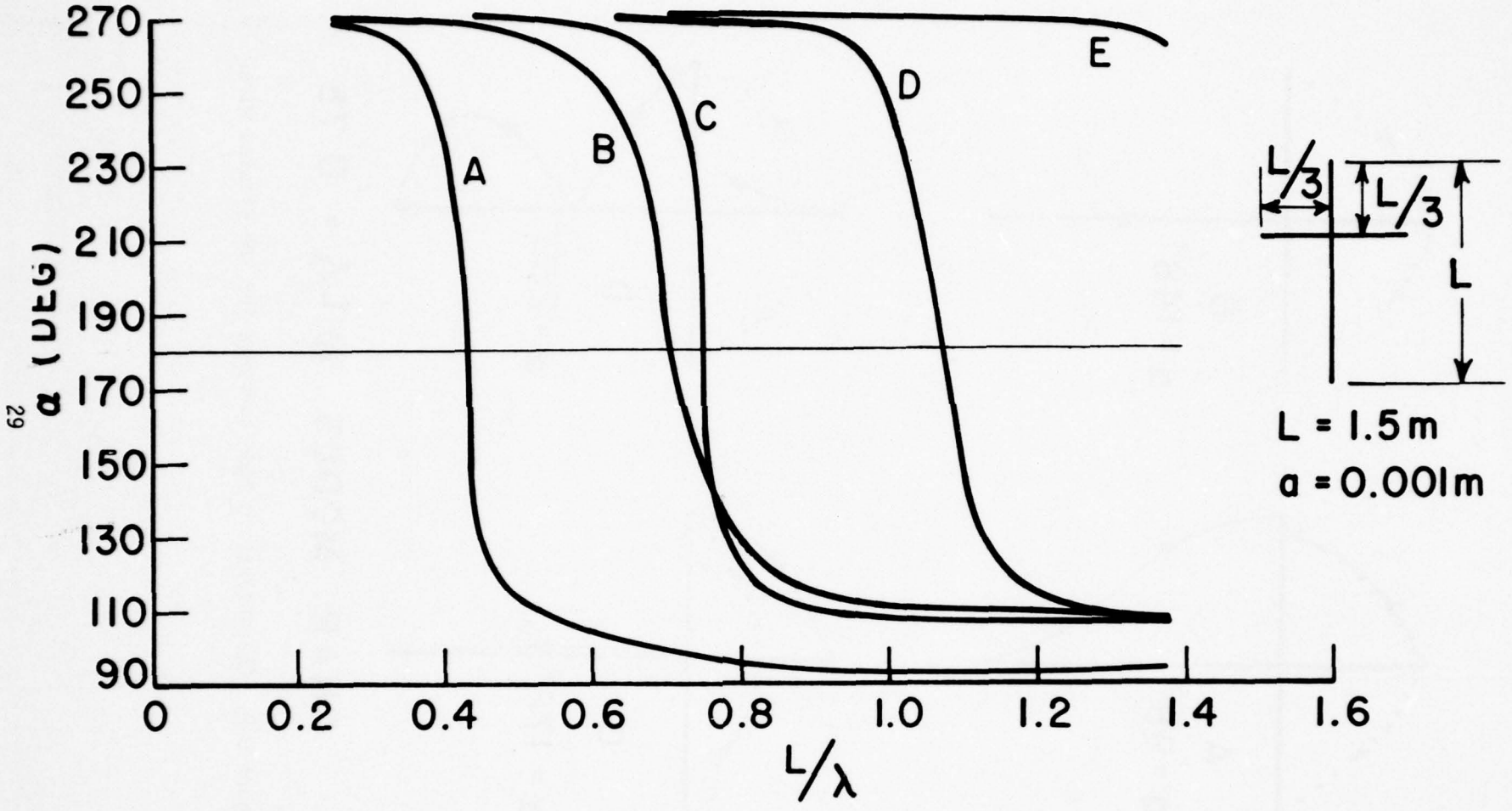


Figure D-1. Characteristic angles for the crossed wire.

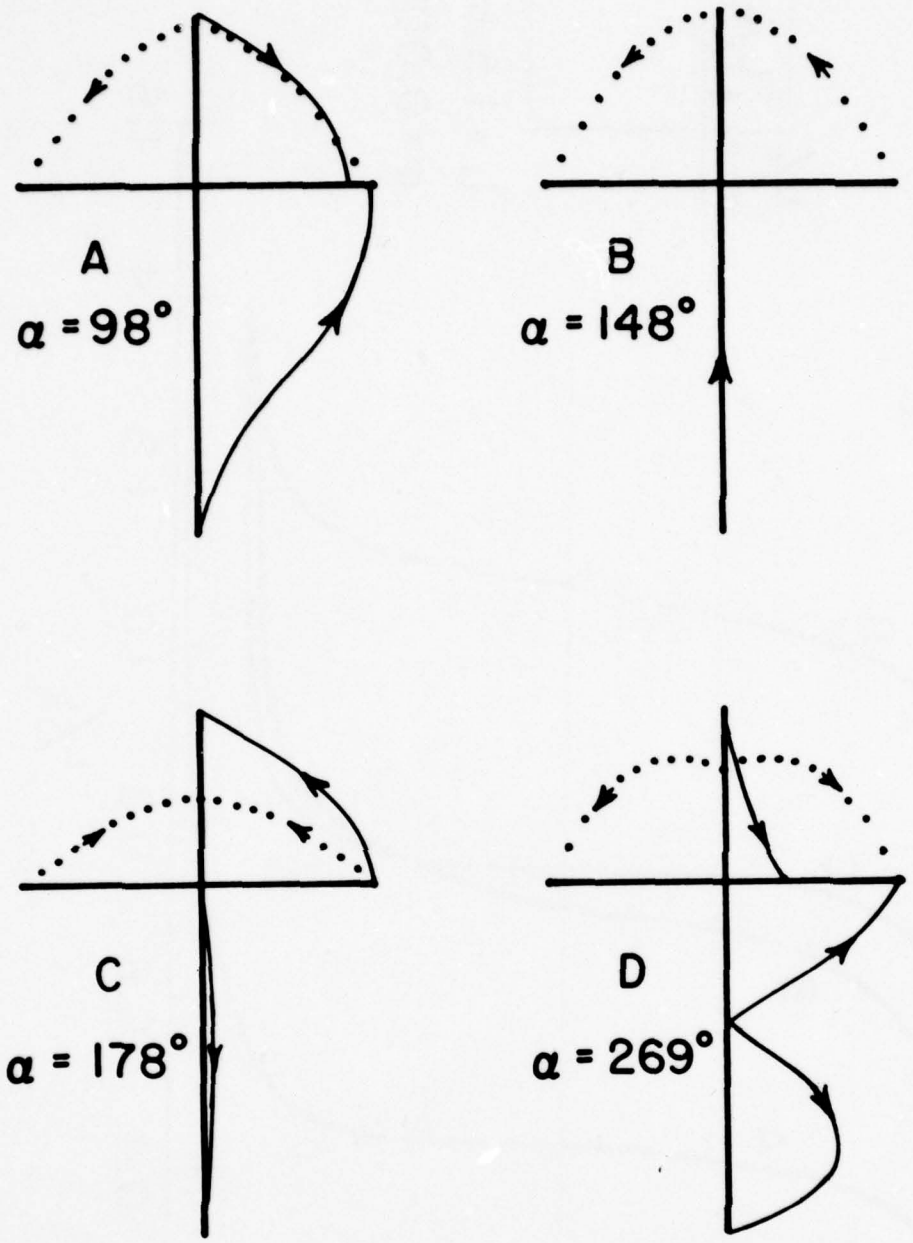


Figure D-2. Characteristic mode currents for the crossed wire.

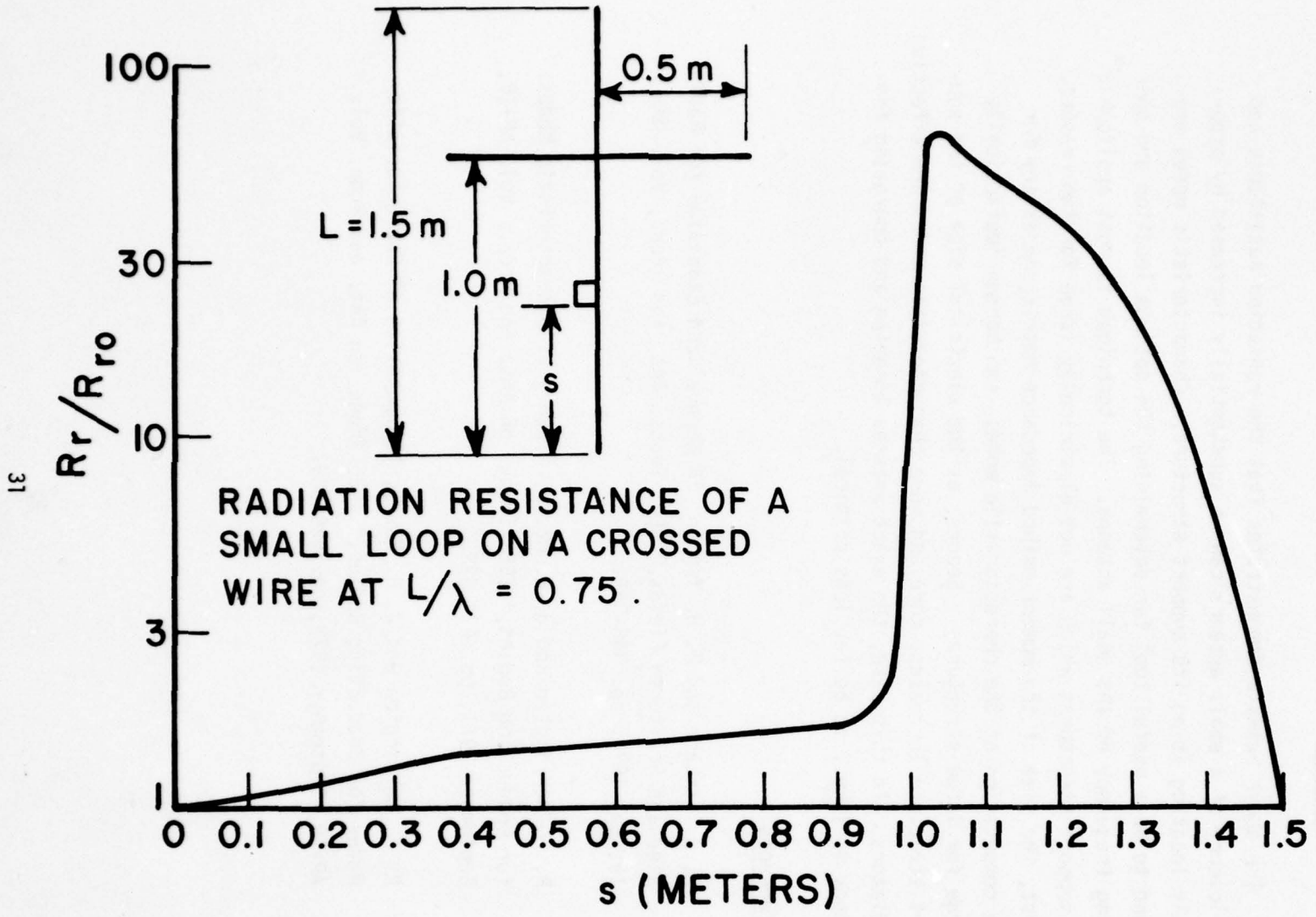


Figure D-3. Radiation resistance of a small loop on a crossed wire.

Summary

The above example demonstrates that the radiation resistance and efficiency of a small antenna can be substantially increased by properely locating it on its support structure. Characteristic modes are found to be a useful tool for determining the optimum location and operating frequency of the small antenna. The technique is most applicable to support structures which are not electrically large for two reasons. First, the size of the moment method impedance matrix, necessary for the computation of the characteristic modes, can become impractically large for large structures. Second, as the electrical size of the support structure increases, more and more charactersitic modes are effective radiators. In this case, the exact antenna location and operating frequency is likely to be far less critical.

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"Small Antenna Location Synthesis Using Characteristic Modes," by E. H. Newman, submitted to IEEE Trans. AP-S.

"Anomalous Behavior of Near Fields Calculated by the Method of Moments," by K. R. Demarest and R. J. Garbacz, submitted to IEEE Trans. AP-S.

F. Time Domain Studies

Research in this area has been concentrated on three topics which are considered to be fundamental to a continuing development of time domain concepts and applications in electromagnetics. The three specific topics, not necessarily in order of the time devoted to each topic, are: the K-pulse; electromagnetic scattering from a thin, perfectly conducting circular disk; and linear difference equation processing. In each case, certain basic ideas and results are being further pursued on other programs and grants at the ElectroScience Laboratory. At the same time, studies of these topics are continuing on this program. It is anticipated that research on one topic, electromagnetic scattering by a thin perfectly conducting circular disk, will soon be completed. Remaining are needed results concerning near fields and the complex natural resonances of the disk. Longer studies are envisioned for the other topics.

1. K-Pulse Studies

Researcher: E. M. Kennaugh, Professor Emeritus

Introduction

Although theoretical and analytical studies of electromagnetic scattering by material objects have primarily addressed the steady-state response to monochromatic excitation, there is growing interest in the transient response of bodies to aperiodic excitations such as a short pulse or an idealized impulsive waveform. In contrast to the steady-state, under transient excitation it is possible to distinguish two separate phenomena: first, the generation of forced currents and surface fields at the incident wavefront as it moves over the object; subsequently, the natural or free oscillations of currents and charges throughout the body after the incident wavefront has passed.

The natural oscillations of a finite body are characterized by a denumerable set of complex frequencies (poles) $s_n = -\sigma_n + j\omega_n$ in the left half-plane. Except for objects such as spheres or infinite cylinders, the determination of the poles and corresponding oscillation modes is a difficult computational task.

A simple relation between the natural oscillation frequencies (poles) of an object and its shape and composition is to be derived. To obtain this relation, we associate subsets of the poles s_n with traveling waves which circumnavigate the object over specified geodesic paths, returning to the point of inception. After one transit, the process would normally repeat ad infinitum. However, if the transfer function for one transit is known or accurately estimated, subsequent transits may be eliminated by insertion of a cancelling waveform, or "kill-pulse", which terminates the process. Combination of the original excitation, starting at t=0, and the delayed"kill-pulse" waveform, beginning the transit time later, defines a composite excitation waveform K(t) which produces non-oscillatory response. The Laplace transform of K(t), or K(s), must then have complex zeroes s_n coincident with the associated pole subset. In those cases for which a finite-duration K(t) can be found such that it produces a finite duration response for the surface charges and currents, we shall call K(t) the K-Pulse of the object.

A New Derivation of the Poles for a Perfectly Conducting Sphere

To derive the poles for a perfectly conducting sphere by the method outlined above, approximations for the transfer functions for TM and TE circumnavigating waves are obtained from the geometrical theory of diffraction. Using the generalized attenuation constant defined in Table I of Reference 1, the transfer function for TM waves is found to be:

$$T_M(s) = -\exp\{-2\pi[s + .808614(s\tau)^{1/3} - .163707(s\tau)^{-1/3}]\} \qquad (1)$$

where $\tau = a/c$ is the propagation time in the external medium for one sphere radius. The function $K_M(s)$ with zeroes at the TM poles of the sphere is then

$$K_M(s) = 1 - T_M(s) \tag{2}$$

The transfer function for TE waves is given by:

$$T_E(s) = -\exp\{-2\pi[s\tau + 1.85576(s\tau)^{1/3} + .114795(s\tau)^{-1/3}]\} \tag{3}$$

and the function $K_E(s)$ with zeros at the TE poles of the sphere is then:

$$K_E(s) = 1 - T_E(s) \tag{4}$$

Clearly, the zeros of K(s) occur when the exponents in T(s) become equal to odd multiples of $\pm j\pi$. With a simple change in variable, the second-quadrant sphere poles are given by the fourth-quadrant roots of the auxiliary polynomials:

$$\text{TM; } x^4 - .80861\, x^2 + (n + 1/2)\, x - .163707 = 0 \tag{5}$$

$$\text{TE: } x^4 - 1.85576\, x^2 + (n + 1/2)\, x + .114795 = 0 \tag{6}$$

where $s_n\tau = (jx_n)^3$. Examples of the exact and approximate poles are given below: (values given are of $s_n\tau$)

N	TM		TE	
	Correct	Approx.	Correct	Approx.
1	-.500+j.866	-.497+j.876	-1.000+j.000	-.982+j.004
2	-.702+j1.807	-.701+j1.813	-1.500+j.866	-1.495+j.868
3	-.843+j2.758	-.842+j2.762	-1.839+j1.754	-1.836+j1.756

By n=7, 3S figure accuracy or better is achieved, with increasing accuracy for larger n.

We conclude that the "kill-pulse" concept provides an alternative method to find the complex poles of a regular body and to relate them more simply to the body shape. The TM and TE pole "strings" defined by Equations (5) and (6) are merely the dominant pole strings, located nearest to the imaginary axis of the complex s-plane. To find additional pole strings by the method of this section, one merely uses the higher mode coefficients, the next of which is given explicitly in Table I of Reference 1. This changes the coefficients in the polynomials of Equations (5) and (6), the roots then give the next pole string.

Although we are primarily interested in the exterior resonances of a scattering body, characterized by complex frequencies with negative real part, it is worth noting that the transfer functions given by Equations (1) and (3) may also be applied to the interior problem for the sphere, in which case roots of Equations (2) and (4) with zero real part are sought. As shown in the following table a corresponding real root of Equations (5) and (6) can be found which gives a good approximation to the interior resonances of a hollow conducting sphere (values given are of $s_n\tau$):

N	TM		TE	
	Correct	Approx.	Correct	Approx.
1	j 2.744	j 2.750	j 4.493	j 4.493
2	j 3.870	j 3.874	j 5.763	j 5.763
3	j 4.973	j 4.976	j 6.988	j 6.988

The K-pulse for a Wire of Finite Length

To illustrate the applicability of K-pulse concepts to scattering and radiation by a finite body, we consider the thin, perfectly conducting wire with a length-to-diameter ratio of 2000. For this object, the circumnavigating wave starts at one end of the wire, returning via two transits of the wire length and two end reflections to begin

a second transit. The transfer function for this path has been computed (using numerical integration of an exact formula) as well as the complex scattering poles (using moment methods) by J. H. Richmond of this Laboratory.

A simple physical model for the transfer function of this path is provided using a lossless transmission line slightly longer than the wire, with an RC termination. The approximate transfer function is

$$T(s) = \frac{.80296 + .11065\ s\tau}{1 + .22525\ s\tau}\ \exp\ (-2.0149\ s\tau) \qquad (7)$$

where $\tau = L/c$, the transit time for one wire length in the external medium. Figure E-1 shows a comparison of the accurate transfer function with the approximation of Equation (7), up to a wire length of 4 wavelengths.

The transform of an approximate K-pulse is obtained by clearing $1 - T(s)$ of all poles in the finite s-plane (except at the origin), and the resulting K-pulse is

$$K(t) = \delta(t) + \frac{4.4395}{\tau}\ U(t) - .49123\ \delta(t-2.0149\tau) - \frac{3.5648}{\tau}\ U(t-2.0149\tau) \qquad (8)$$

where $\delta(t)$ denotes the Dirac delta function and $U(t)$ the unit step. The zeroes of the transform of this approximate K-pulse agree closely with the scattering poles of the wire as determined by J. H. Richmond, within less than 2% error for the first eight dominant poles.

Since the K-pulse should effectively terminate the natural or free oscillations of an object after the forced regime ends, we shall examine the response to our approximate K-pulse for several modes of excitation. In each case, we expect the response to be of finite duration. Figure E-2 shows: (a) input current for a center-fed wire with a K-pulse input

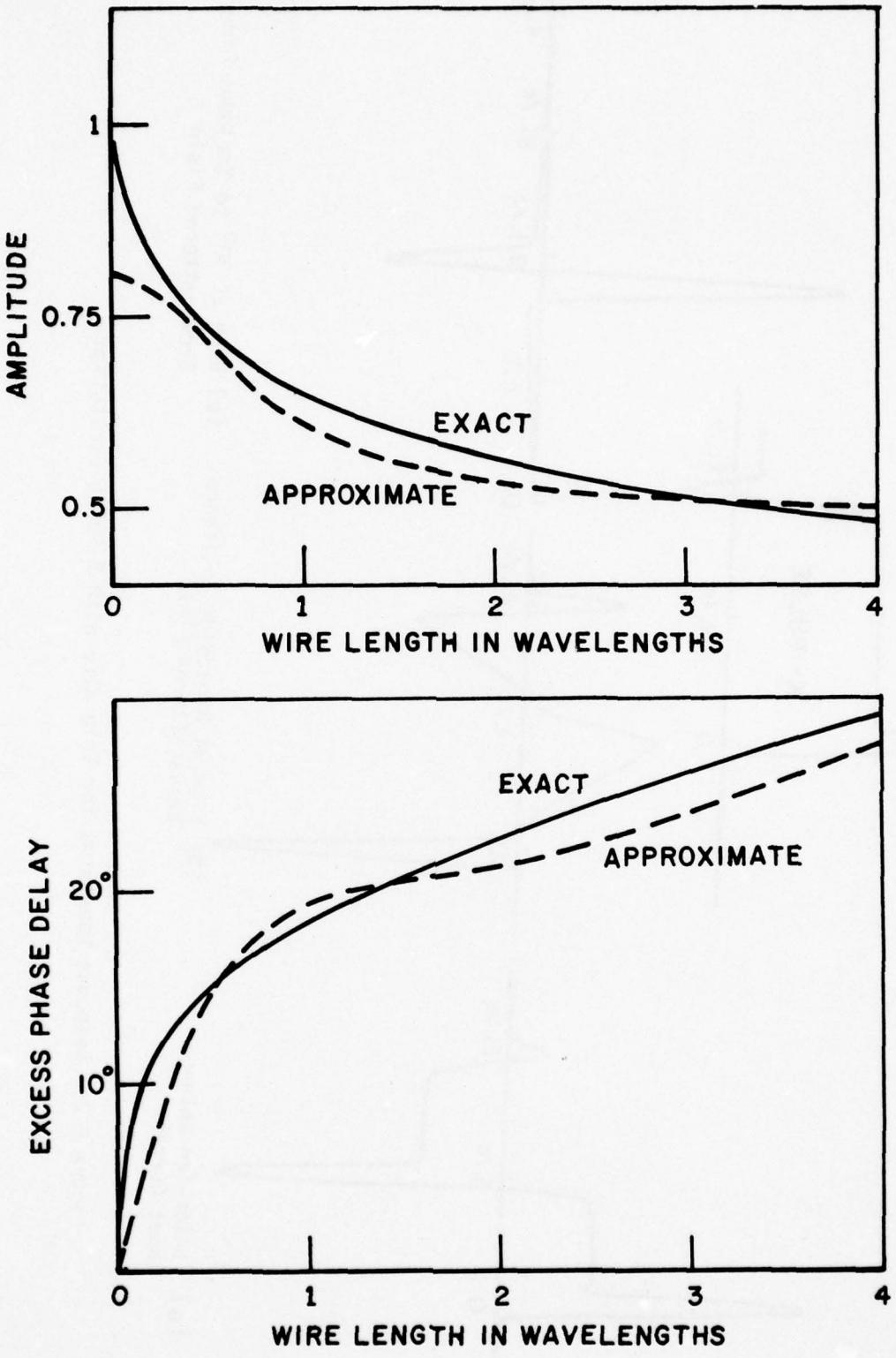


Figure E-1. Transfer Function for Thin Wire

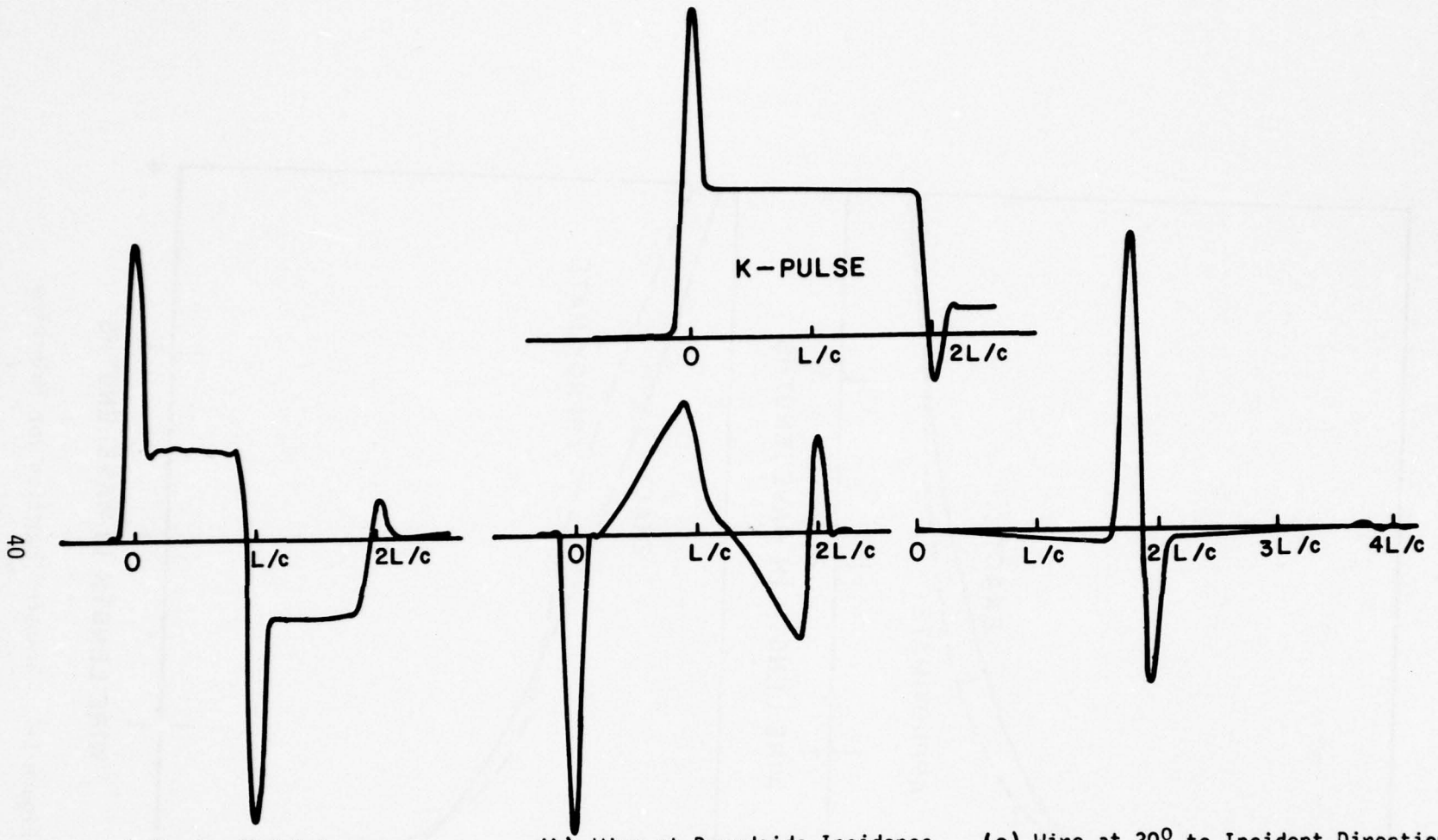


Figure E-2. Response Waveforms for Thin Wire with K-Pulse Excitation.

voltage waveform, (b) far-zone backscattered field from a wire scatterer with a K-pulse incident plane wave at broadside incidence, and (c) far-zone backscattered field from a wire scatterer with a K-pulse incident plane wave at 30° from endfire incidence. In each case, the K-pulse waveform of Equation (8) was used, and the wire had a length-to-diameter ratio of 2000. The results were obtained by Fourier synthesis of monochromatic responses at 200 frequencies.

The response waveforms of Figure E-2 show that the response in each case is of finite duration and sufficiently simple to be approximated by combinations of impulse, step and ramp waveforms. It is possible to obtain simple and accurate approximation formulas for the frequency response of the wire for each of the excitations depicted in Figure E-2 over extremely broad frequency ranges. This has been done, in part, and will be reported later.

Although it might appear that applicability of the K-pulse is limited to very broadband systems, by convolution of the K-pulse with the appropriate pulse waveform of a band-limited system a useful K-pulse of limited bandwidth is obtained. Instead of shaping the excitation waveform by use of the K-pulse, one can design a linear filter or processor to produce a transient-free received signal when a high-Q system is excited by an arbitrary pulse waveform. For the thin wire, this processor would consist of a single-tap delay line which sums weighted values of the signal and its time integral at two times separated by 2.0149 L/c.

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2. The Thin Conducting Disk

Researcher: D. B. Hodge, Professor

At the present time the sphere represents the only radar target of finite extent for which numerical scattering results may be obtained directly and simply from the rigorous eigenfunction solution of the plane wave scattering problem. The rigorous eigenfunction solution of the thin metallic disk problem has been available in the literature for a considerable period of time[1]; however, only limited numerical results have become available due to the difficulty of the numerical computations required.

This state of affairs is quite unfortunate since the disk offers significant advantages as a standard radar calibration target when compared with the sphere. First, precision machining of a disk is much simpler than that of a sphere; and, second, precise alignment of the target for phase measurements is considerably simpler for a disk than for a sphere.

Furthermore, a great deal of basic understanding of scattering mechanisms is potentially available from the study of the thin disk. This is a consequence of the fact that it is the only target of finite extent, other than the sphere, for which a rigorous solution is available; and it is the only case for targets having a sharp edge. Thus, a complete understanding of scattering by a disk would provide another canonical solution to complement that of the sphere.

For these reasons, earlier work at The Ohio State University Electro-Science Laboratory[2,3,4] has been extended to generate a computer program capable of handling the general problem of far field scattering of a plane wave by a thin, metallic disk. This program permits incident plane waves of arbitrary incidence direction and arbitrary polarization and computes the amplitude and phase of both components of the scattered field at any point on the far field sphere.

This program has been completed and successfully tested for cases where prior results exist. The program contains automatic convergence testing for a resulting precision of 5 significant figures and has been used successfully for disk sizes up to ka = 15. The program has been generated in a user-oriented form so that it can readily be used by any investigator without a detailed knowledge of the program. The program requires less than 10 K of core memory and executes in a matter of seconds on the ESL Datacraft 6024 computer.

A report describing this program is in preparation; this report will describe the solution which forms the basis of the program, the computational details of the program, and the usage of the program along with sample check case results.

This effort will be extended to include the computation of the surface currents and fields. This result would serve as a basis for several extensions of our understanding. First, the propagation of surface currents and fields across the disk could be examined in considerable detail shedding light on the characteristics of the impulse response, the GTD formulation, and other approximate techniques. Second, a knowledge of the surface field characteristics would permit an immediate test to determine whether or not the eigenfunction modes are equivalent to characteristic modes. Finally, the development required to reach this objective should provode the basis for determining the natural resonances of the disk.

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Publications

Report in preparation.

3. Difference Equation Processing

Researchers: D. L. Moffatt, Associate Professor
E. M. Kennaugh, Professor Emeritus
L. C. Chan, Graduate Research Associate
C. M. Rhoads, Graduate Research Associate
K. R. Shubert, Graduate Research Associate

Over a decade ago, Kennaugh and Moffatt[1] and their co-workers at the ElectroScience Laboratory suggested that in the low spectral range the electromagnetic scattering from an object could be represented in the frequency domain as

$$\frac{G}{s^2} = \sum_{n=1}^{N} \frac{A_n}{s-\gamma_n}, \qquad (s=j\omega) \tag{1}$$

where the γ_n are simple poles and the A_n the corresponding residues, or in the time domain (transform Equation (1)) as

$$f(t) = \sum_{n=1}^{N} A_n e^{-\gamma_n t} u(t) . \tag{2}$$

The usefulness of the representations is that the poles or complex natural resonances are excitation invarient which has obvious target identification implications[2]. This target identification using complex natural resonances has been successfully exploited in a series of studies[3-8]. A major consideration is how to determine values for the complex natural resonances of a radar target. Various schemes can be used[5], however the most useful appears to be the approach of Prony which was rediscovered by Van Blaricum and Mittra[7]. The Prony approach has the advantage that it can be applied to either measured or calculated data via Equation (2) where both the γ_n's and the A_n's are determined. Since the first paper on Prony's method[9] there have been numerous papers and reports on the applications to noisy data. Prony's method uses discrete time domain samples of Equation (2) and basically is concerned with a linear difference equation which is approximately homogeneous

$$\sum_{n=0}^{N} f_{N+m-n} a_n = \epsilon_m,$$

$$m=0,1,2,\ldots M \tag{3}$$

where ϵ_m is the error, assumed small, and

$$f_{N+m-n} = f((N+m-n)\Delta t), \tag{4}$$

where Δt is a fixed sampling interval. In general, the order of the difference equation (N), the optimum sampling interval (Δt), and the starting and stopping points of the data record ($f_{\underline{o}}$ and $f_{\underline{M}}$) as well as the difference coefficients (a_n) are unknown.

Prony's method is Equation (3) written as

$$f_{N+m} + \sum_{n=1}^{N} f_{N+m-n} \frac{a_n}{a_o} = \frac{\epsilon_m}{a_o} , \tag{5}$$

which is usually written with the a_o normalization absorbed and can be derived from Equation (2) as was done by Prony. The various studies of Prony's method start from Equation (5) with noise usually added at some point.

The more basic time series, however, is Equation (3) which we rewrite as

$$\sum_{n=0}^{N} f^{(\ell)}_{N+m-n} a_n = \epsilon^{(\ell)}_m ,$$

$$m=0,1,2,\ldots M^{(\ell)}$$
$$\ell=1,2,\ldots L \tag{6}$$

where the superscript ℓ denotes, in our case, a different aspect of the target or polarization of the incident field. We suggest that the coefficients in Equation (6) are also fundamental parameters for a given target. The poles in Equation (2) are a convenient interpretation but if the poles are excitation invarient then so also are the coefficients.

It is well known that minimizing the squared error in Equation (5) does not optimize the pole locations. The question then is "do the data (sampled) satisfy in some approximate sense the difference equation in Equation (6)?" Consider Equation (6) first for some given fixed ℓ. There are N+2 relatively standard minimum squared error methods by which the coefficients a_n can be found. These are most readily seen by writing the total squared error for a given ℓ as

$$E_M^{(\ell)} = \sum_{m=0}^{M} \varepsilon_m^{(\ell)2} = \sum_{m=0}^{M} \left(\sum_{n=0}^{N} f_{N+m-n} a_n \right)^2 \tag{7}$$

This can be written as a quadratic form

$$E_M^{(\ell)} = (A)^T (F^{(\ell)})^T (F^{(\ell)})(A) \ .* \tag{8}$$

If we impose the condition

$$\sum_{n=0}^{N} a_n^2 = 1 \ , \tag{9}$$

i.e., a unit norm for the coefficients, then the minimum eigenvalue of

$$(\lambda) = (A)^T (F^{(\ell)})^T \ (F^{(\ell)}) \ (A) \ , \tag{10}$$

is the minimum squared error and the corresponding eigenvector yields the coefficients. Note that this approach does not give preferential treatment to any of the N+1 coefficients.

Consider the Prony method in Equation (5) and recall Wiener's note that interpolation is always a more reliable process than prediction when dealing with noisy data. It was found some time ago that even when the coefficients are found via squaring Equation (5) for all m, i.e., Prony's method, that the equation was best used by renormalizing

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*$(\ )^T$ denotes transpose.

by the coefficient of largest magnitude. That is, if a_r/a_o has largest magnitude, then

$$f_{N+m-r} + \sum_{\substack{n=1 \\ n\neq r}}^{N} f_{N+m-n} \frac{a_n}{a_r} = 0 \qquad (11)$$

was the actual equation used for target identification[10]. This suggested that Equation (3) be written in the form

$$f^{(\ell)}_{N+m-v} + \sum_{\substack{n=0 \\ n\neq v}}^{N} f^{(\ell)}_{N+m-n} \frac{a_n}{a_v} = \frac{\epsilon^{(\ell)}_m}{a_v}$$

$$m=0,1,2,\ldots M$$

$$0 \leq v \leq N \; . \qquad (12)$$

Note that for v=0, Equation (12) is a linear predictor (Prony). For v=N it is a linear postdictor and a linear interpolator for other values of v.

If we set

$$\frac{\partial E^{(\ell)}_M}{\partial\left(\frac{a_j}{a_v}\right)}_{j\neq v} = 0 \qquad (13)$$

for all r+1 values of v then N+1 least squared error normal equation solutions for the coefficients are obtained. These plus the eigenanalysis solution comprise the N+2 solutions. This can also be expressed in quadratic form[11].

It was unknown to us at the time but Dibbern had also suggested this approach for the analysis of voice signals[12], although he does not discuss an eigenanalysis approach. It has been shown for real subsurface radar data that a factor of ten decrease in the normalized total squared error (the normalization is discussed later) is possible if one sets

$$v \lesssim \frac{N}{2} , \tag{14}$$

where for odd orders the optimum v can vary somewhat. Dibbern[12] has demonstrated the same point for voice signals. Both results can be viewed as a partial confirmation that with noisy data interpolation is a more reliable process than prediction.

To discuss normalization we need to discuss the solution equations. It should be remembered that while we continue to retain the superscript record index, the above is for a fixed ℓ. If the total squared error is expanded using the form in Equation (12) one encounters the function

$$E_{M,V}^{(\ell)} = \sum_{m=0}^{M} \left[f_{N+m-v}^{(\ell)} + \sum_{\substack{n=0 \\ n \neq v}}^{N} f_{N+m-v} \frac{a_n}{a_v} \right]^2 , \tag{15}$$

which when the right side is expanded has the function

$$R_n^{(\ell)} = \sum_{m=0}^{M} f_m^{(\ell)} f_{n+m}^{(\ell)} , \quad n=0,1,\ldots \tag{16}$$

where R_o is the input energy to our processor. The normalization alluded to above is $E_{M,v}^{(\ell)}/R_o$. Note now that in all of the above not only is the record index fixed but so also are N, Δt, $f_{\underline{o}}^{(\ell)}$ and $f_{\underline{M}}^{(\ell)}$. In quadratic form

$$\frac{E_{M,v}^{(\ell)}}{R_o} = \frac{1}{R_o} (A_v)^T (R^{\ell}) (A_v) , \tag{17}$$

where it is understood that the coefficients have been normalized by a_v and the R vectors altered.

There is some merit in testing an additional normalization by the norm of the coefficients

$$||a_n/a_v|| = \sum_{n=0}^{N} \left(\frac{a_n}{a_v}\right)^2 . \qquad (18)$$

With this normalization the total normalized square error should mathematically be the same for each of the N+2 methods for solving for the difference coefficients. For the real subsurface radar data used above it is found that there are differences in this total normalized squared error but not of the order of ten. Refering to Equation (2), each set of coefficients leads to somewhat different poles which, particularly for interpolation, may not be physical. This has not been a serious problem for the data treated.

There is no reason why data from several aspects cannot be combined. In other words we find the difference equation which best "fits" several data records. With this approach, assuming an eigenanalysis solution, we first obtain

$$(R) = \sum_{\ell=1}^{L} (R_n^{(\ell)}) , \qquad (19)$$

and then

$$(\lambda) = (A_n)^T (R)(A), \qquad (20)$$

as before. It is this aspect particularly which emphasizes the difference coefficients rather than the poles although the coefficients still have a pole interpretation. With this approach because the signal levels may be quite different for different ℓ it may be advantageous to normalize each contribution to the sum in Equation (19) by its trace. Measured pulse response waveforms for various aircraft models have been synthesized from swept frequency data over a spectral range selected to emphasize substructure responses. The application of multiple aspect difference equations to these data is presently in progress.

Computer programs for applying both the eigenanalysis and extrapolation-interpolation methods for finding the difference coefficients, for fixed or multiple aspects, are available. These programs also include routines which quasi-optimize the order, sample interval and sample range. A limited amount of testing of these programs and concepts has been done using deterministic damped sinusoid signals as a simulation of multiple aspect/polarization data. It can be concluded on this basis that this type of eigenanalysis solution shows considerable promise. More precise conclusions must be delayed until applications to real data are completed. It is intended to continue to explore these new aspects of difference equation processing as applied to electromagnetic data. One idealized set of electromagnetic signals which can be studied is now available from the disk work described above.

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Publications

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F. Adaptive Array Studies

Researchers: R. T. Compton, Jr., Professor
C. D. Chuang, Senior Research Associate

Results from Last Year

During the past year, research on adaptive arrays has concentrated on the problem of time constant variation. Adaptive arrays based on the LMS algorithm have the property that their speed of response depends on signal power. This behavior makes it difficult to handle signals with wide dynamic range because in most applications of adaptive arrays system requirements limit both the minimum and maximum speed of response of the array. As a result, the array can handle only a limited range of signal power without exceeding speed of response bounds. This is a serious problem that hinders the application of adaptive arrays in many practical situations. This problem has motivated our Joint Services Electronics Program research in this area for the year.

During the year, several novel approaches for weight control have been investigated. All of these approaches offer a different time constant behavior than the LMS algorithm. One technique we have studied, which appears particularly promising, is suitable for an array with continuous feedback. The other techniques are suitable only for digital feedback. (Adaptive arrays for use in communication systems usually require continuous control loops in order to have a sufficiently fast response time. Digital feedback loops can be used only in applications where the real-time speed of response can be slow.)

The first approach we have taken is to reexamine the LMS algorithm to see whether its time constant behavior could be altered. The original LMS algorithm (1), which yields a simple continuous feedback loop, or a simple discrete recursive equation, is based on a gradient technique. Because of this, it has the property that its speed of response

depends on signal power, since the squared-error surface from which the gradient is calculated has eigenvalues dependent on signal power. By abandoning the gradient concept and instead basing the feedback on a fixed speed of response concept, an alternative feedback loop has been found that appears to solve this problem. The new feedback loop is similar to the LMS loop but contains an additional feedback path as described below.

For an LMS array, the weights are controlled by the feedback equation:

$$\frac{dw_i}{dt} = 2k\, x_i(t) \left[R(t) - \sum_{j=1}^{2N} w_j\, x_j(t) \right] \qquad (1)$$

where w_i is the ith array weight, $x_i(t)$ is the ith signal in the array, k is a gain constant, N is the number of elements in the array, and R(t) is the Reference Signal. This feedback equation corresponds to the feedback loop shown in Figure F-1.

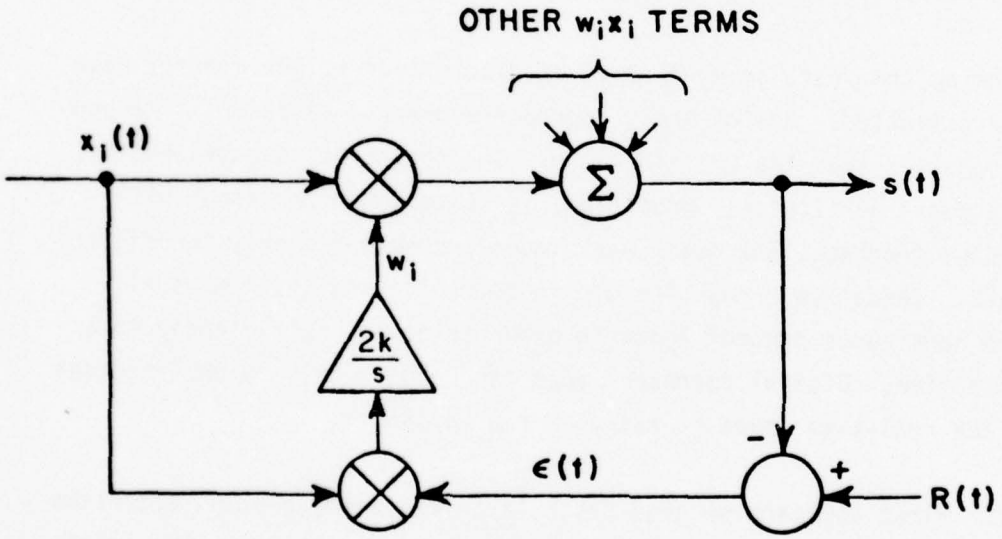


Figure F-1. The LMS feedback loop.

The weights in the new feedback loop obey the equation

$$\frac{dw_i}{dt} = 2k\, A\left\{x_i(t)\left[R(t) - \sum_{j=1}^{2N} x_j(t)w_j - c \sum_{j=1}^{2N} x_j(t)\frac{dw_j}{dt}\right]\right\} \quad (2)$$

where the notation is the same as above, except that $A\{\cdot\}$ denotes a finite time averaging operation. The feedback loop corresponding to Equation (2) is shown in Figure F-2. $A\{\cdot\}$ is a time average taken over an interval short compared with the time constant of the weights but long compared with the RF cycles in the communication signals.
The transient behavior of this loop has been analyzed, and the results show that the loop has the desired behavior, i.e., it yields a time constant essentially independent of signal power.

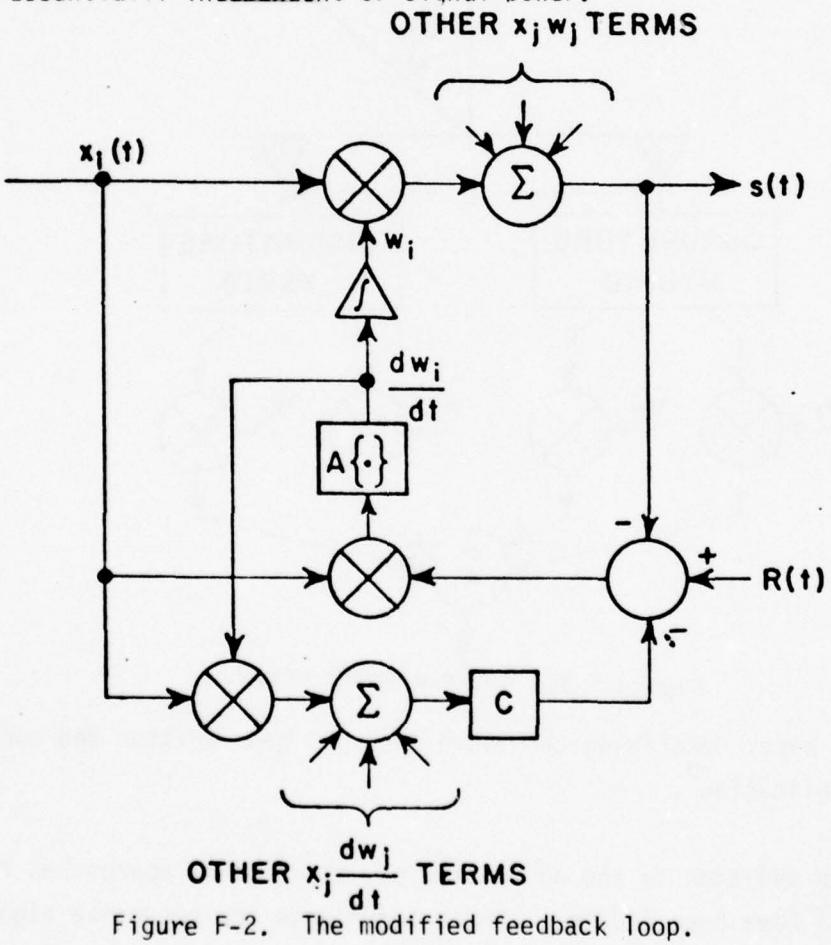


Figure F-2. The modified feedback loop.

Figure F-3 shows an example, a two-element array with desired signal of amplitude A_d arriving from broadside and an interference signal of amplitude A_i arriving from angle θ_i. Figures F-4, F-5 and F-6 show typical sets of weight transients that result with this feedback loop. Figure F-4 shows the case where there is no interference ($A_i = 0$), Figure F-5 shows the case where $A_i = 30$, and Figure F-6 shows $A_i = 3000$. All loop parameters except A_i are the same in Figures F-4-6. The curves illustrate that the speed of response of the weights is the same in each case, i.e., it does not depend on the signal amplitude A_i. This is the desired behavior.

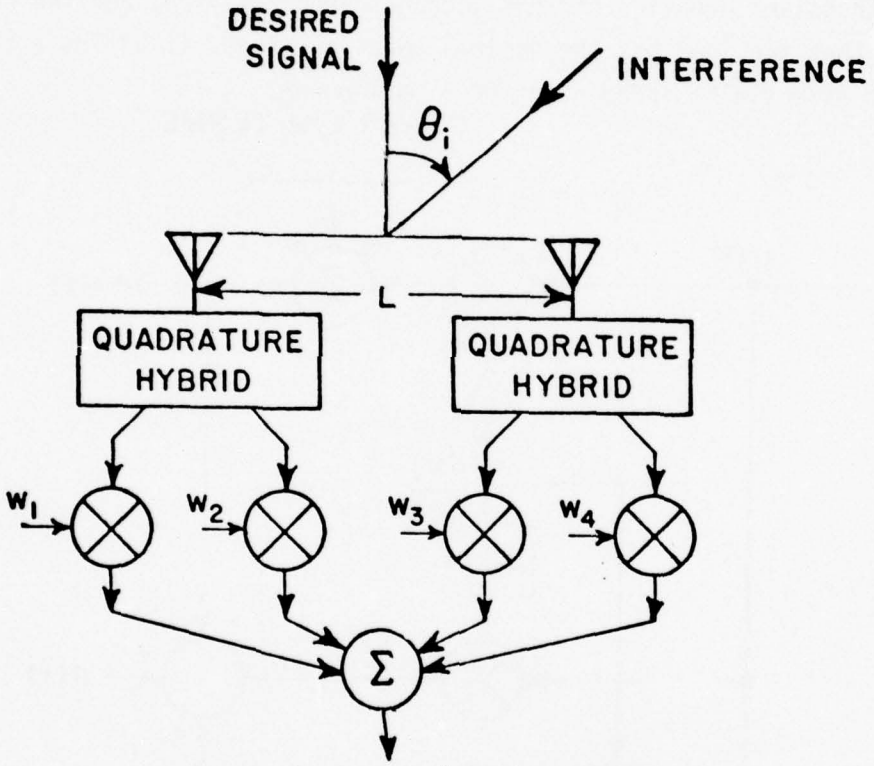


Figure F-3. A two-element array.

A paper describing the above loop has been written and submitted for publication[7].

In addition to the above studies, three other approaches for weight control have been studied. These techniques are recursive algorithms

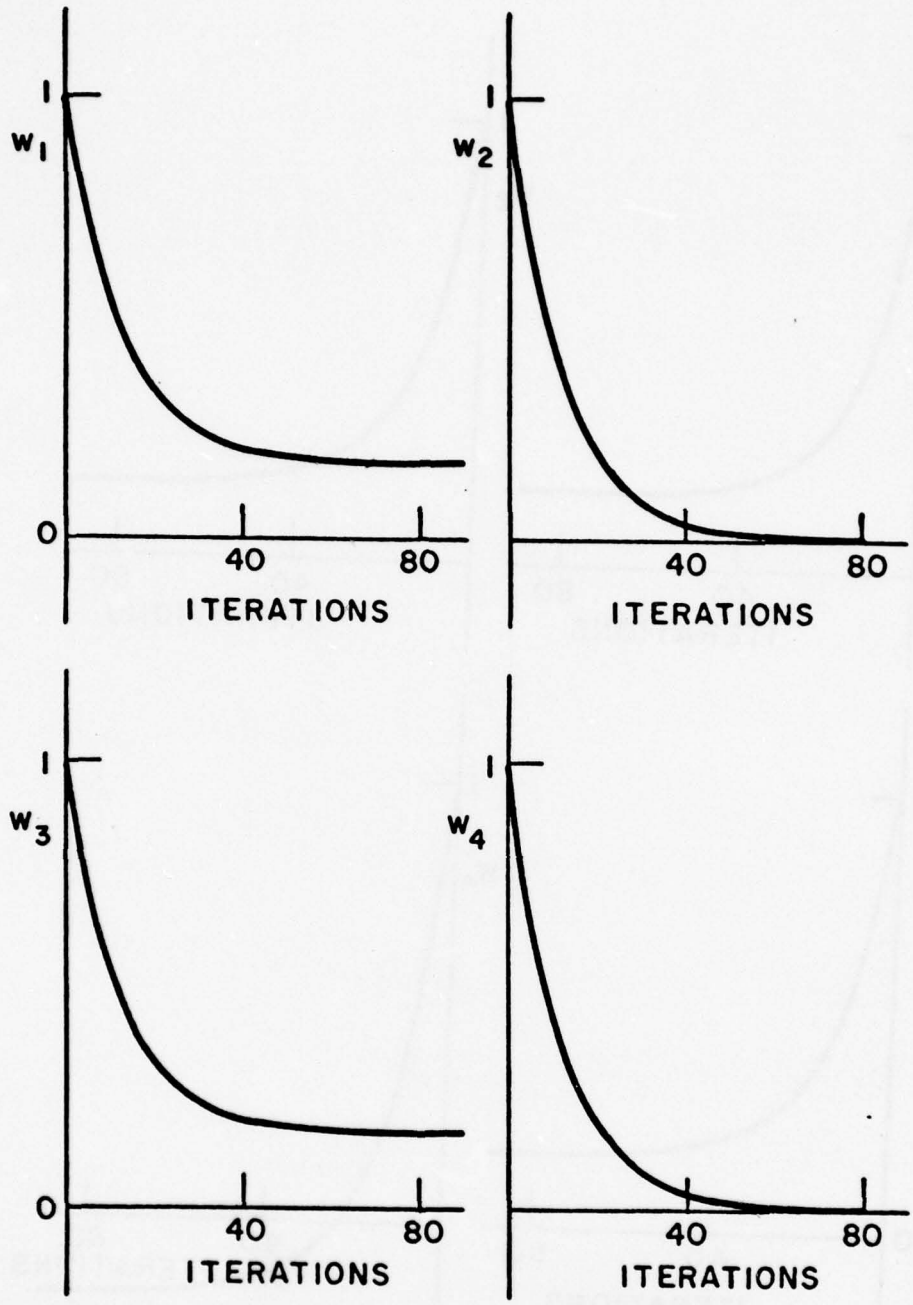


Figure F-4. Weight transients with no interference.

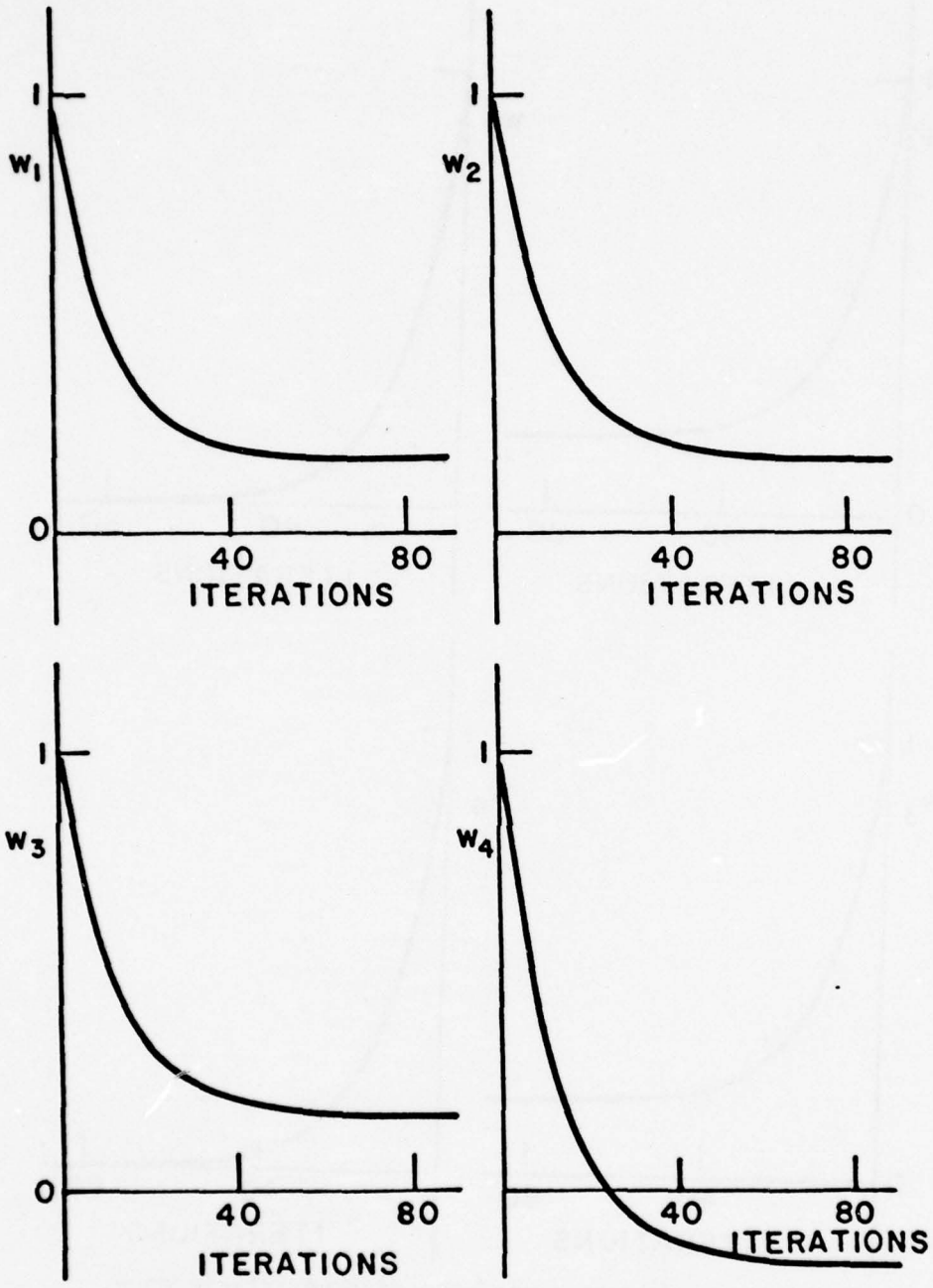


Figure F-5. Weight transients with $A_i = 30$.

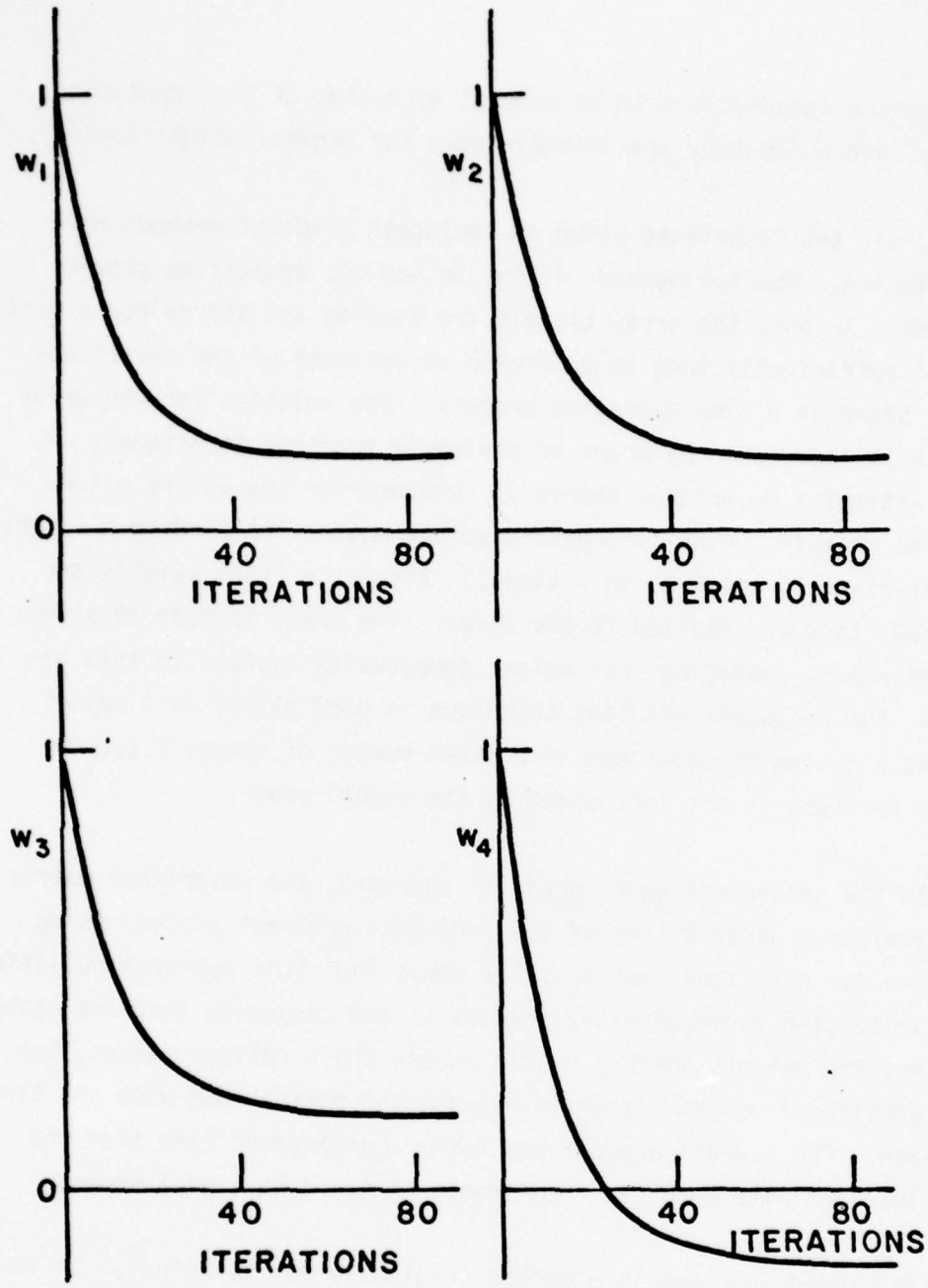


Figure F-6. Weight transients with A_i = 3000.

that require computations to be made at each step of the adaptation process, and hence they are suitable only for digital weight control.

First, two techniques based on conjugate gradient methods have been studied. The two methods differ in how the adaptation process proceeds. In one, the array signals are sampled and stored for a period of time sufficiently long to determine an estimate of the covariance matrix based on a time averaging process. The solution for the array weights is then found by means of conjugate gradient techniques. A given estimated covariance matrix is retained for the entire weight solution process. (The conjugate gradient method for finding n weights is guaranteed to converge in n steps.) After the final weights are obtained, they are applied to the array. The array is made adaptive by continually repeating this weight computation cycle. In this approach, the conjugate gradient technique is used mainly as a way of solving a system of equations in a fixed number of steps; i.e., the number of steps is not influenced by the signal power.

In the second conjugate gradient approach, the covariance matrix is reevaluated at each step of the conjugate gradient process using new data for the signal vector as it comes in. This approach nullifies the finite step convergence properties of the conjugate gradient method. However, the weights quickly settle around their optimum values, but with additional weight jitter (misadjustment noise) than with the first approach. The overall process has faster convergence time than the LMS algorithm with much less dependence of speed on signal power.

The third approach is a method originally due to Baird[3]. It involves a discrete algorithm for continually updating an estimate of the inverse of the covariance matrix, using a recursive matrix inversion lemma, while the weight estimates are updated. This approach was included so it could be compared with the two gradient algorithms discussed above.

All three of the above methods appear preferable to the LMS algorithm from the standpoint of time constant behavior. However, all are more complicated than the LMS algorithms and could be implemented only in digital form. A paper describing these results has been written and will be submitted for publication[4].

Plans for Next Year

During the next year, we plan to continue research on the new continuous feedback loop concept described above. We plan to extend this work in two ways:

(1) To consider alternative types of averaging $A\{\cdot\}$ in the loop. This averaging operation is of critical importance in obtaining suitable performance from the loop. To date, only a finite time average has been studied. This type of average has been shown to work, but it is somewhat inconvenient to implement. The objective of this work will be to determine the simplest form of averaging that will result in the desired performance.

(2) To evaluate the use of AGC circuits and limiters in the new feedback loop to increase dynamic range. Limited dynamic range is a major problem that holds back the application of adaptive arrays. Dynamic range limitations in adaptive arrays are caused by two factors: device and circuit limitations, and speed of response variation with signal power. In the past, AGCs or limiters have frequently been used in LMS loops to reduce the effects of circuit limitations. However, time constant variation is still a problem with the LMS array.

The new feedback loop discussed above appears to solve the problem of time constant variation. As a logical extension of this work, we now plan to investigate the use of AGCs and limiters in conjunction with these feedback loops. The goal will be to determine what total dynamic range may be expected with AGCs in the signal path and either AGCs or limiters in the feedback paths. The study will consider how AGC time constants should be chosen to be compatible with array operation and will consider the effects of weak signal suppression in the limiters. Such work represents a useful continuation of our current work under Joint Services Electronic Program and has an extremely important objective: to increase the dynamic range of adaptive arrays.

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III. CONCLUSIONS

The previous sections have summarized the work at Ohio State supported by the JSEP. This support has been in the areas of (1) Diffraction Studies, (2) Hybrid Techniques, (3) Surface Cell Model, (4) Electrically Small Antenna Studies, (5) Time Domain studies and (6) Adaptive Array studies.

These were not initial start areas under JSEP support. They were partially supported by other programs and some are still being supported by other programs. Appendix I lists all of the current programs at the ElectroScience Laboratory. Contract numbers, principal investigators, funding, etc. are listed in Appendix II. The JSEP program is listed as Project 710816.

The diffraction studies under 710816 have been partially supported by NOSC (784508) and the results are being used in the programs for NOSC, ESD (784641), NASA, Langley (710964), NWC (711095), NASC (711305), Aerospace Corp. (711510) and NADC (711588).

The hybrid technique studies are being partially supported by ESD (711353) and the results are being used essentially by the same programs as the diffraction studies above.

Both surface cell and electrically small antenna studies are being partially supported by ARO (784569). The surface cell results currently are being used in the electrically small antenna studies and some of the results of the electrically small antenna studies are being used on the program with NSA (784719).

Results from time domain studies are being used in target identification and recognition programs which include Columbia Gas (529010), Ft. Belvoir (784460 and 784722), EPRI (784652) and BMD (784785).

The adaptive array studies on 710816 are helping to support the work for NASC (710929).

Numerous publications are in progress based on the JSEP support and these were mentioned in Section II above. Listings of reports and papers published by ESL over the past year are given in Appendices III and IV, respectively.

APPENDIX I
PROJECT TITLES AND ABSTRACTS

Project 710300 Advanced TDMA Techniques and Bit Synchronous Design and Array Component Evaluation

The objectives of this program include (1) development and testing of a bit synchronous time division multiple access digital communications system suitable for use by a large number of small (airborne) terminals in conjunction with larger ground stations, (2) the application of adaptive arrays for up-link antijam protection of this system, and (3) development of techniques, circuits and components for increased data rates, digital control, and interference rejection in high speed digital communications systems.

Project 710816 Block Funded Support for Electromagnetics Research

This is research in the area of electromagnetic radiation and scattering including: (1) extension of the geometric theory of diffraction by developing means to properly treat diffraction from curved wedges, vertices, and near field excitation; (2) the geometric theory of diffraction combined with the method of moments; (3) improvements in the surface cell model by developing optimum basis functions and by proper treatment of curved surfaces; (4) the use of characteristic modes and surface patch modeling to optimize radiation from small antennas on a conducting platform; (5) transient electromagnetic phenomena including optimum design of transient pulse scatterers and antennas; and (6) time constant control methods and optimization of waveform tagging for adaptive arrays.

Project 710929 Communication Application of Adaptive Arrays

This program involves research studies on adaptive arrays in the following areas: (1) continue the experimental research on FM modulation,

and if appropriate, on SSB or FSK modulation; (2) perform studies on the frequency acquisition problem in adaptive arrays; (3) perform studies on phase-envelope coupling in analog modulation; (4) begin preparation of a monograph on adaptive arrays.

Project 710964 Analysis of Airborne Antenna Patterns

The objectives of this program are to: (1) improve the aircraft model for far field pattern computations by considering a more realistic vertical stabilizer; (2) study various ways to model more general antenna types such as a monopole in the presence of directors; (3) examine various flat plate simulation codes; and (4) compare various calculated results with measurements supplied by NASA (Langley).

Project 711095 A Study of Airborne Effects on Antenna Pattern Performance

The objectives of this program are to: (1) examine the roll plane pattern as the jet height is varied for a central fuselage antenna location; (2) examine the roll plane pattern effects the intakes have with a faring plate added; (3) modify the program to determine the roll plane effects of mounting antennas on the jet intake; (4) compare selected results with measurements made at NWC; (5) extend the usefulness of the program to treat the elevation pattern including the jet intake effect; (6) examine the effect of using an array of elements to reduce the jet intake distortion in the roll plane pattern; (7) repeat the above study for conical patterns 40° to 70° about the axis of the fuselage.

Project 711096 TVCM Effects

This is a classified program.

Project 711305 Research on Near Field Pattern Effects

This study seeks to: (1) develop a near field solution for the volumetric pattern of an antenna mounted on a 3-dimensional fuselage structure; (2) extend the present numerical analysis for near field principal plane patterns to treat multiple plates; (3) using these improved solutions examine their validity and usefulness in analyzing various complex airborne antenna problems; (4) compare calculated results with measured results.

Project 711353 Extending the Geometrical Theory of Diffraction Using the Moment Method

This is a 3-year basic research program to develop the theory for further extensions of the GTD using the moment method and to implement that theory into computer programs so that the usefulness of the research in various scattering and antenna problems can be demonstrated.

Project 711510 Low Sidelobe Reflector Antenna Study

Far field patterns are to be calculated and compared with the measured patterns provided by Aerospace Corporation for an available offset reflector and available feed horn. This will provide a verification of the theoretical models and computer codes to be used in developing antenna designs for the desired low sidelobe performance.

Project 711559 Study of Improved IFF Antennas

The objective of this research is to conduct a program that will lead to a low profile or flush mounted IFF antenna capable of pointing a beam into each of the four quadrants in azimuth.

Project 711577 Application of the GTD to the Calculation of Acoustic Backscatter from Mine-Shaped Objects

The objective of this study is to prepare a summary report on the application of the Geometrical Theory of Diffraction (GTD) to the calculation of acoustic backscatter from mine-shaped objects.

Project 711587 Evaluation and Upgrading of the Antenna Calibration Facility at the Measurement Standards Laboratory

The following items of work are included in a twelve-month study: (1) analyze the near field effects when measuring antenna gain at close range; (2) evaluate the facilities and procedures used at NAFS for antenna gain measurement; (3) recommend changes in procedures and/or equipment which will minimize the errors identified in (2); (4) fabricate a set of three similar corrugated horn antennas for evaluation as an improved gain standard; and (5) initiate work to determine the most suitable form for standard antennas for use in calibrating radiation hazard meters in the frequency range 1 to 18 GHz.

Project 783815 Information Processing for Target Detection and Classification

This is an investigation of the multiple target problem which includes the computation of scattering data for multiple targets, the extraction of the pertinent natural resonances and classifications of multiple targets in both resolvable and nonresolvable geometries. Multiple coupled as well as uncoupled targets will be considered. A study is also proposed for the classification of unlisted target classes and extraneous signals.

Project 784299 CTS/Comstar Communications Link Charactization Experiment

The objectives of this experiment are to measure: (1) long term angle of arrival and fade statistics on an 11.7 GHz earth-space propagation path; (2) long term 20 GHz radiometric temperature statistics along the same propagation path, and to relate the resulting data to physical models of the atmosphere and precipitation. As a subsidiary objective the performance of a self-phased millimeter wavelength array for synchronous satellite tracking will be demonstrated.

Project 784311 Electrically Small Antennas (terminated)

Three areas related to small antennas were investigated: wires in the presence of dielectrics/ferrites, closely spaced thin wires, and small antenna location synthesis. Each of these areas resulted in a journal publication.

Project 784346 Radar Cross Section Studies and Calculations (U)

This is a classified program.

Project 784372 A Fundamental Investigation of a Hybrid Technique for General Electromagnetic Scatterers and Antennas (combined with 710816 as of 10/01/78)

The purpose of this project is to describe a procedure for formally combining Moment Method and GTD techniques into a single unified approach called the Hybrid Technique. This technique uses to advantage the strengths of both the Method of Moments and the GTD to treat problems not readily solved by either method alone. Thus, the project is to develop the theory and implement that thoery into computer programs so that other problems may be treated by this technique such as slot antenna arrays on planar surfaces, conformal slot antenna arrays, and wire antennas on or near curved surfaces.

Project 784460 Development of a Subterranean Radar for Tunnel Location

This program seeks to develop video radar techniques for underground sensing of tunnels. Emphasis is placed on antenna development, data collection and signal processing techniques.

Project 784508 Asymptotic High Frequency Techniques for UHF and Above Antennas

The objective is to develop algorithms and techniques to simulate the performance and coupling of UHF and above antennas extending existing computer techniques to include the effects of the complex ship environment.

Project 784558 Radar Identification of Naval Vessels (combined with 710816 as of 10/01/78)

This program deals with the identification of naval vessels by radar. It does not depend on discrimination in azimuth, since this would involve very sharp antenna beams and therefore large antennas, nor on range discrimination, since this would require very short pulses. Instead it depends on the natural resonances of the target and the resultant variation in radar cross-section over a suitable frequency band. These resonances are independent of radar polarization or the aspect angle of the target and offer, therefore, a powerful means for target identification.

Project 784569 Analysis of Electrically Thin, Dielectric Loaded, Cavity-Backed Radiators

During the first year the problem of attaching a wire mode to a surface patch is considered. The second year effort incorporates the effects of dielectric loading. In the third year, the results of the first two years will be combined to yield a mathematical model and computer programs to analyze dielectric filled cavity-backed antennas.

Project 784589 Techniques for Optical Power Limiting

This is a classified program.

Project 784641 Continuing Study of Impact of Inductive or Capacitive Reactance Loading on Circular Cylinders

The objective is to perform theoretical studies on flush mounted antennas in conjunction with reactive type impedance structures to ascertain the feasibility of controlling the tangential electric field component, in magnitude and phase, on perfectly conducting structures such as cylinders and the fuselage of an aircraft to obtain strong circularly polarized radiation in the plane of the horizon.

Project 784652 An Advanced Protytype System for Locating and Mapping Underground Obstacles

The objective of this program is to develop a portable video pulse radar system for locating and mapping underground objects to a depth of 10-15 feet. The emphasis is on improving signal processing techniques and optimizing system performance to improve target resolution.

Project 784659 Radiative Transmission Line Analysis

This project seeks to evaluate and analyze a number of guiding wave structures. The study includes the evaluation of "zigzag" and Yagi lines as possible candidates for use as a line barrier sensor.

Project 784673 Advanced Numerical Optical Concepts

The objective of this program is the development of the technology for optical computing systems.

Project 784677 Conduct a Study of Radar Target Identification by the Multiple-Frequency Resonance and Time Domain Pole Method

Two subject areas of significant interest to the Air Force are covered in this program; improved detection and discrimination of radar targets and control of nonspecular scattering from edges via loading techniques.

Project 784701 A Synergistic Investigation of the Infrared Water Vapor Continuum

This study proposes a thorough 3-year investigation of the water vapor continuum absorption in the 8 μm to 12 μm and in the 3.5 μm to 4.0 μm atmospheric transmission windows. This absorption has been the topic of several previous studies. However, serious questions still remain and the need exists for a definitive study in order to answer questions related to laser radiation propagation through the atmosphere and also for optimization of infrared imaging and sensor systems which depend on 10 μm infrared radiation. The Contractor will use a multi-line stabilized CO_2 laser and a spectrophone to perform precision measurements of the absorption by water vapor broadened by nitrogen, oxygen, and N_2-O_2 mixtures, over a 17-27°C temperature range.

Project 784719 Computer Program Improvement and Documentation for Superdirective Antenna Arrays

Specific tasks to be accomplished are: (a) reorganize computer program so as to be easily documented; (b) identify existing numerical difficulties in program, eliminate or lessen problems; (c) expand program capabilities; (d) make provisions for the user to add other element types to list; (e) provide program output to be accompanied by English descriptions of output; (g) incorporate sidelobe constraint into design procedure and an option to use it in the computer program.

Project 784722 Electromagnetic Mine Detection and Identification

Research in this study is directed toward the special design of an impulse radar for the purpose of detecting buried mines.

Project 784785 Basic Research in 3-Dimensional Imaging for Transient Radar Scattering Signatures

The objective of this study is to perform basic research in 3-dimensional imaging for transient radar scattering signatures. Included in the study are limiting surface imaging, transient measurements, and physical optics inverse diffraction.

Project 784786 Laser Induced Response

The objective of this program is to study microwave radiation from a conducting body illuminated by a strong laser pulse.

Project 711588 On-Aircraft Antenna Pattern Prediction Study

The objectives of this program are: (1) to produce a capability to analytically predict antenna patterns of on-aircraft mounted complex antennas which are both mechanically and electronically scanning; (2) to obtain predicted antenna patterns for several types of antenna arrays utilizing previously existing computer programs developed under Contract N62269-76-C-0554.

APPENDIX II
ELECTROSCIENCE LABORATORY SPONSORING AGENCIES

OHIO STATE UNIVERSITY - ELECTROSCIENCE LABORATORY — ACTIVE PROJECTS — OCTOBER 1, 1978

PROJECT ENGINEER	PROJECT NUMBER	SPONSOR	CONTRACT NUMBER	STARTING DATE	ENDING DATE	AWARD AMOUNT	SOURC
	Facilities Contract		AF 33(600)-31168	04-11-74	12-31-78		
Young	529010	Columbia Gas					
Ksienski	783815	AFOSR	AFOSR-74-2611	01-01-74	12-31-79	333K	6.1
Ksienski	710300	RADC	F30602-75-C-0061	01-01-75	01-15-79	550K	6.2
Hodge	784299	NASA/Goddard	NAS5-22575	09-02-75	01-31-79	288K	6.2
Walter/Newman	784311	ARO	DAAG29-76-G-0067	10-15-75	10-14-78	89K	6.1
Munk	784346	AFAL	F33615-76-C-1024	01-01-76	12-31-78	400K	6.2
Thiele	784372	ONR	N0014-76-C-0573	02-01-76	01-31-79	92K	6.1
Peters	784460	Ft. Belvoir	DAAG53-76-C-0179	06-25-76	12-25-78	432K	6.3
Moffatt	784490	NSF	ENG76-04344	06-01-76	11-30-78	60K	6.2
Walter	784508	NOSC	N00123-76-C-1371	08-01-76	07-31-79	239K	6.2
Moffatt	784558	ONR	N0014-76-C-0179	09-15-76	09-30-78	61K	6.1
Newman	784569	ARO	DAAG29-76-G-0331	09-24-76	09-23-79	90K	6.1
Meadors	784589	AFSC	F33615-77-C-1011	10-18-76	10-17-78	149K	6.2
Pathak	784641	ESD	F19628-77-C-0107	01-06-77	01-05-79	74K	6.2
Caldecott	784652	EPRI	RP7856-1	01-01-77	12-31-78	167K	6.3
Garbacz	784659	AFGL	F19628-77-C-0069	02-04-77	09-30-78	99K	6.1
Collins	784673	BMD	DASG60-77-0045	03-01-77	10-01-79	124K	6.2
Moffatt /Kennaugh	784677	ESD	F19628-77-R-0125	03-01-77	09-30-78	95K	6.2
Rudduck	784698	New Mex. State Univ.	P. O. No. 72281	03-30-77	09-30-78	Terminated	
Nordstrom/Long	784701	ARO	DAAG29-77-C-0010	04-01-77	03-31-79	158K	6.1
Newman	784719	NSA	MDA904-77-C-0527	05-03-77	11-01-78	54K	6.2
Moffatt	784722	Ft. Belvoir	DAAK70-77-C-0114	05-05-77	05-04-80	95K	6.2
Young	784785	BMD	DASG60-77-C-0133	07-01-77	12-31-78	164K	6.1
Meadors	784786	BMD	DASG60-77-C-0134	07-01-77	06-30-79	203K	6.1
Walter /*	710816	ONR	N00014-78-C-0049	10-01-77	9/30/79	483K	6.1
Compton	710929	NASC	N00019-78-C-0131	12-01-77	02-28-79	63K	6.2
Levis	710953	Kirtland AFB	F29601-78-C-0024	01-09-78	09-30-78	Terminated	
Burnside	710964	NASA/Langley	NSG 1498	01-16-78	01-15-79	34K	6.2
Burnside	711095	NWC	N60530-78-C-0115	04-17-78	04-16-79	49K	6.2
Meadors	711096	AFAL	F33615-78-C-1431	04-16-78	12-31-79	50K	6.1
Burnside	711305	NASC	N00019-78-C-0524	09-08-78	09-07-79	59K	6.2
Thiele	711353	ESD	F19628-78-C-0198	09-01-78	08-31-81	123K	6.1
Rudduck	711510	Aerospace Corp.	P. O. 88318	09-01-78	02-28-79	49K	6.2
Munk	711559	NRL	N00014-78-C-0855	09-30-78	10-01-79	30K	6.2
Kouyoumjian/Pathak	711577	NCSC	N61331-78-M-3152	09-25-78	09-30-79	9K	6.2
Caldecott	711587	WPAFB	N00014-76-A-0039-RZ01	09-28-78	09-27-79	50K	6.2
Burnside	711588	NADC	N62269-78-R-0379	09-01-78	08-31-79	74K	6.2

*Burnside/ Compton/ Kouyoumjian/Moffatt/Newman/ Thiele/Wang

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REPORTS PUBLISHED BY ESL SEPTEMBER 1977 TO OCTOBER 1978

2902-27 VOLUMETRIC PATTERN ANALYSIS OF AIRBORNE ANTENNAS, C.L. Yu, W.D. Burnside & M.C. Gilreath, December 1977.

4232-6 LASER ATMOSPHERIC ABSORPTION STUDIES - FINAL REPORT, R.K. Long, E.K. Damon, R.J. Nordstrom, J.C. Peterson, M.E. Thomas & J. Sherman, April 1978.

784299-6 GAIN DEGRADATION AND AMPLITUDE SCINTILLATION DUE TO TROPOSPHERIC TURBULENCE, D.M. Theobold & D.B. Hodge, February 1978, Revised June 1978.

784299-7 SPECTRAL CHARACTERISTICS OF EARTH-SPACE PATHS AT 2 and 30 GHz, R.A. Baxter & D.B. Hodge, August 1978. Thesis

784311-6 THE CIRCUMFERENTIAL VARIATION OF THE AXIAL COMPONENT OF THE CURRENT IN CLOSELY SPACED THIN-WIRE ANTENNAS, P. Tulyathan & E.H. Newman, October 1977.

784311-7 ELECTRICALLY SMALL ANTENNA STUDIES, E.H. Newman and C.H. Walter, December 1977.

784311-8 ELECTRICALLY SMALL ANTENNA STUDIES - Semiannual Report, 1 January 1978 to 30 June 1978. E.H. Newman & C.H. Walter, June 1978

784346-8 EFFECTS OF TRANSMISSION LINES AND ANTENNAS INCORPORATED WITH METALLIC RADOMES, C.J. Larson, May 1978.

784372-5 A HYBRID TECHNIQUE FOR COMBINING THE MOMENT METHOD TREATMENT OF WIRE ANTENNAS WITH THE GTD FOR CURVED SURFACES, E.P. Ekelman, Jr. & G.A. Thiele, July 1978. Dissertation.

784372-7 MOMENT METHOD CALCULATION OF REFLECTION COEFFICIENT FOR WAVEGUIDE ELEMENTS IN A FINITE PLANAR PHASED ANTENNA ARRAY, A.J. Fenn, G.A. Thiele & B.A. Munk, September 1978. Dissertation.

784409-2 ACOUSTIC SCATTERING MODEL - FINAL REPORT, 1 April 1976 to 31 March 1977, R.G. Kouyoumjian & C.A. Klein, March 1978.

784428-2 A PHYSICAL OPTICS APPROACH TO THE ELECTROMAGNETIC FIELD SCATTERED BY SIMPLIFIED SHIP-SEA MODELS, D.J. Ryan, November 1977. Thesis.

784428-3 ELECTROMAGNETIC SCATTERING FROM SIMPLE SHIP-SEA MODELS, J. Huang and W.H. Peake, December 1977.

784460-4 AN ANTENNA FOR USE IN AN UNDERGROUND (HFW) RADAR SYSTEM, C.A. Tribuzi, November 1977. Thesis

784490-1 CHARACTERIZATION OF SUBSURFACE ELECTROMAGNETIC SOUNDINGS, D.L. Moffatt, L.C. Chan & G.A. Hawisher, September 1977

784491-4 COMPUTER SOLUTIONS FOR USE IN ESTIMATING PROGRESS IN IN-SITE COAL GASIFICATION, J.H. Richmond, October 1977

784491-5 COMPUTER SOLUTIONS FOR USE IN ESTIMATING THE PROGRESS OF IN-SITE COAL GASIFICATION, J.H. Richmond, February 1978.

784508-7 ASYMPTOTIC HIGH FREQUENCY TECHNIQUES FOR UHF AND ABOVE ANTENNAS, W.D. Burnside, R.J. Marhefka, R.C. Rudduck & C.H. Walter, November 1977.

784508-8 USER'S MANUAL FOR PLATES AND CYLINDER COMPUTER CODE, R.J. Marhefka, March 1978.

784508-9 ASYMPTOTIC HIGH FREQUENCY TECHNIQUES FOR UHF AND ABOVE ANTENNAS - Sixth Quarterly Report - 1 November 1977 to 31 January 1978, W.D. Burnside, R.J. Marhefka, R.C. Rudduck, C.H. Walter and R.G. Kouyoumjian, March 1978.

784508-10 ASYMPTOTIC HIGH FREQUENCY TECHNIQUES FOR UHF AND ABOVE ANTENNAS - Seventh Quarterly Report, 1 February 1978 to 30 April 1978, R.C. Rudduck, R.J. Marhefka, W.D. Burnside, R.G. Kouyoumjian & C.H. Walter, June 1978.

784508-11 FAR FIELD REFLECTOR ANTENNA COMPUTER CODE - USER'S MANUAL, R.C. Rudduck, S.H. Lee & W.D. Burnside, July 1978.

784558-1 RADAR IDENTIFICATION OF NAVAL VESSELS, D.L. Moffatt & C.M. Rhoads, December 1977.

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784569-5 NEAR FIELDS OF A VECTOR ELECTRIC LINE SOURCE NEAR THE EDGE OF A WEDGE, D.M. Pozar & E.H. Newman, June 1978.

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784575-1 PATTERN PREDICTION OF WIRE ANTENNAS ON SATELLITE STRUCTURES - FINAL REPORT, G.A. Thiele, January 1978.

784583-3 AN ASYMPTOTIC RESULT FOR THE SCATTERING OF A PLANE WAVE BY A SMOOTH CONVEX CYLINDER, P.H. Pathak, March 1978.

784583-6 AN ITERATIVE APPROACH FOR COMPUTING AN ANTENNA APERTURE DISTRIBUTION FROM GIVEN RADIATION PATTERN DATA, E.L. Pelton, R.J. Marhefka & W.D. Burnside, June 1978.

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784650-1 METEOROLOGICAL RADAR CALIBRATION, D.B. Hodge, February 1978.

784650-2 POWER LAW RELATIONSHIPS FOR RAIN ATTENUATION AND REFLECTIVITY, D.M.J. Devasirvatham & D.B. Hodge, January 1978.

784650-3 AN ANALYSIS OF MULTI-FREQUENCY HIGH RESOLUTION RADAR RAIN RATE DATA, D.M.J. Devasirvatham, December 1977.

784659-2 SURFACE WAVES ON PERIODIC ARRAY OF IMPERFECTLY CONDUCTING VERTICAL DIPOLES OVER THE FLAT EARTH, J.H. Richmond & H.B. Tran, February 1978.

784659-3 SURFACE WAVES ON A LOSSY GOUBAU LINE OVER IMPERFECT FLAT EARTH, J.H. Richmond, H.B. Tran & R.J. Garbacz, February 1978.

784685-2 EDGE DIFFRATION POINT ANALYSIS USED IN NEAR-FIELD ON-AIRCRAFT ANTENNA STUDIES, E.L. Pelton & W.D. Burnside, October 1977.

784685-3 NEAR FIELD PATTERN ANALYSIS FOR APERTURE OR MONOPOLE ANTENNAS MOUNTED ON AN AIRCRAFT IN THE PRINCIPLE PLANES, E.L. Pelton, N. Wang & W.D. Burnside, January 1978.

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NATURAL RESONANCES VIA RATIONAL APPROXIMANTS, D.L. Moffatt & K.A. Shubert, Reprinted from IEEE Transactions on Antennas and Propagation, Vol. AP-25, No. 5, pp. 657-660, September 1977.

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REFERENCE LOOP PHASE SHIFT IN ADAPTIVE ARRAYS, D.M. DiCarlo & R.T. Compton, Jr. Reprinted from IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-14, No. 4, pp. 599-607, July 1978.

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