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I DIRECTORS OVERVIEW

This report represents the fourteenth annual summary of The Ohio State University Joint Services Electronics Program (JSEP).

There have been a total 29 Ph.D. and 21 M.Sc degrees in Electrical Engineering obtained under partial JSEP sponsorship. There are currently 8 Ph.D. and 1 M.Sc. students being partially supported under JSEP.

As may be seen in the Annual report Appendix, 12 reprints have been included in the period September 1990 to September 1991. In addition, 13 papers have already been accepted for publication in the coming year, and additional 10 papers have been submitted, and an additional 9 papers are in preparation.

II DESCRIPTION OF SPECIAL ACCOMPLISHMENTS AND TECHNOLOGY TRANSITION

The transfer of the compact range and target identification technology initiated under JSEP support for time domain studies continues to make large advances. Using other sources of support, design for a mini chamber has now been tested and performs beyond our expectations. Signals of the order of 80 dB below a square meter can be measured in this facility. This range is designed to study smaller targets at higher frequencies.

The research has proven to be of intense interest to DoD and the Aerospace industry and our Compact Range consortium represents a major cross section of the Aerospace and Electronic Industries, including additional major support from several DoD agencies. In fact, the total support in these experimental studies substantially exceeds our JSEP support. We are being contacted by various organizations to aid them in the design of new ranges. This research is truly guiding a major portion of this technology in the USA and has been extremely important for stealth technology advances. However, these advances were only possible because of the initial JSEP

support. This continues to be a case where a small investment of basic research funds have been leveraged to generate much larger support and have achieved major contributions for DoD. This has also lead to OSU-ESL involvement in Ultra Wide Band radar systems.

Our target identification work, also partially funded at one time under JSEP Time Domain studies, is also being funded by several other agencies and continues to be rather vigorous. Again, JSEP funds have been leveraged to initiate larger programs which have been supported continuously since JSEP funding in this area was terminated.

Our JSEP research continues to focus on fundamental Electromagnetic related topics. There are three major electromagnetics areas that were pursued in the past year and a closely related study in Adaptive Arrays. The diffraction studies have provided a tool for designing tapered resistive cards for reducing scattered fields from edges. We are also examining the effect of terminations for open-ended waveguides. Our search for an adequate corner diffraction coefficient has been rewarding in that an improved uniform corner diffraction coefficient has been generated and is discussed in yet another dissertation.

Professor Richmond's untimely death led to a termination of the nonlinear scattering portion of the integral Equation work unit. After a discussion with Dr. Davis of ONR, it was decided that these funds should be used to initiate Dr. R. Lee's research on finite element methods.

The Hybrid Approach represents novel analyses involving more than one basic technique such as was done originally at the ESL by combining diffraction and integral equations which was one of the earlier such solutions. One of our initial efforts involved the scattering from structures that resembled jet intakes and exhausts. Several decades ago, these were supposedly geometries whose scattering properties would never be treated analytically with any degree of success. Our recent work has been overcoming most of these difficulties as will be seen in the deep cavities as

discussed in the appropriate section. Both government and industry are becoming the primary supporters for this effort and again JSEP support has been used in the initial stages of study that have been carried to the extent that others are now providing the major funding. Research on more shallow antenna cavities has continued under JSEP support and we expect that this effort will also be of general interest to many. We are considering these same techniques to evaluate the electromagnetics environment on naval ships. This represents an important topic for future research and should have a substantial impact for the Navy. An additional Navy contract through SCEE in this area has been negotiated in support of this area.

Another topic of interest here is the electromagnetic properties of stripline systems. To treat such devices rigorously requires the inclusion of a very complex Sommerfeld type integral. Asymptotic forms of this integral have been obtained that greatly simplify such analyses. The form of the solution remains uniformly valid even for lateral field and source point separation as small as a third of a wavelength and has been extended to include double layers. This and future efforts should contribute substantially to the design of MMIC structures.

These asymptotic forms coupled to a judicious choice of basis functions for appropriate choice of boundary conditions for the geometry (coupler, bend, transformer, etc.) not only simplify the analysis, but contribute substantially to understanding the physical mechanisms involved. The hybrid approach is being used to generate solutions for structures where neither moment method nor asymptotics alone can be expected to produce accurate answers.

Technology transition continues to take several forms for our program. First, of course, are the students graduating in this program who carry the knowledge gleaned in their research programs to other users. Second, there are the published papers, both oral and written, which generally attract the attention of other DoD sponsoring agencies. Such agencies in turn provide additional funding and in general make use of our JSEP research and extend it to better their own programs.

Yet another method takes the form of computer codes developed under non-JSEP sources that make extensive use of JSEP research. As we have noted previously, the results of these studies are of great importance in the analysis and control of the radiation and scattering from complex shapes.

This continues to be a major task at the Ohio State University ElectroScience Laboratory (OSU-ESL) which is funded by a variety of DoD agencies. A major objective of the ESL funded by other sources is to provide a general computer code (or codes) for the evaluation of the RCS of Aerospace vehicles, but a variety of theoretical analysis must be generated before this goal can become a reality. The OSU-ESL continues to provide to DoD users a variety of complex computer codes at minimum cost for radiation from antennas on aircraft, reflector antennas and integral equation formulations based on previous research activities to industrial organizations with DoD approval for use in DoD activities. In fact, last year 107 additional copies of these very complex user friendly codes were issued.

The Diffraction Studies Work Unit is now directed toward a) finding techniques to represent the EM scattering/radiation or continually more complex physical geometries and b) to improve the accuracy/applicability of those and related techniques. For the past several years, this research has been focussed on studies of several diffracting mechanisms that have proven to be exceedingly difficult to treat. These include corner diffraction, caustic field representation, diffraction by planar discontinuities in nonconducting structures. In addition, further improvements in Generalized Ray Expansion representations have been made. It should be observed that the goal of reducing the complexity of extremely difficult EM analyses to the extent that they prove to be useful to the practicing engineer is being met in a reasonable fashion.

The Diffraction Studies Work Unit in this past year has continued to extend the newly developed UTD corner diffraction for plane wave illumination so that it may be also used for spherical wave or more generally a quadratic wavefront type

illumination. Further extensions to include edge wave effects are also in progress. Generalized surface boundary conditions developed recently were employed to develop a UTD analysis of the diffraction of waves which are obliquely incident on the junction between two planar penetrable material boundaries. Further improvements in the Generalized Ray Expansion have been made for analyzing interior cavity configurations. Work is in progress to predict the scattering by obstacles illuminated by focal region fields.

The Integral Equation Study has been directed toward the analysis of the interaction of electromagnetic wave with exotic media. In particular, we have considered chiral media, artificial media, and nonlinear media.

A chiral medium is formed by embedding chiral objects (i.e., objects whose mirror image can not be produced solely by rotating and translating the original object) in a regular or achiral dielectric. A linearly polarized wave will rotate its polarization as it propagates through a chiral media. Our contributions to the interaction of electromagnetic waves with chiral media include *both basic theory and numerical techniques*. Contributions to basic theory include the chiral volume equivalence theorem which allows a chiral scatterer to be replaced by free space and equivalent electric and magnetic volume polarization currents. We also developed image theory for analyzing chiral objects over a perfect electric or magnetic ground plane. Numerical solutions, based upon the method of moments, have been developed to analyze the scattering from chiral cylinders, with or without a half-plane. The eigenfunction solution for scattering by a multilayer circular chiral cylinder was developed to check these moment method solutions. Finally, we solved the problem of a microstrip transmission line on a chiral substrate.

An artificial dielectric is formed by placing a large number (per cubic wavelength) of electrically small scatterers in some background or host dielectric. By properly selecting the size, shape, density, and material composition of these small scatterers, it may be possible to engineer artificial dielectrics with the desired permittivity. The

permittivity of artificial dielectric was then found by determining the normal modes of the triple infinite array of scatterers. This technique was applied to artificial dielectrics comprised of 2D dielectric rods and 3D short dipoles.

During this period research was begun on the interaction of electromagnetic waves with nonlinear media. Initially, problems involving nonlinear elements at the terminals of periodic arrays were considered. Unfortunately, this work ended with the death of Professor Richmond.

Research on array processing techniques has yielded several significant new techniques during the last three years:

1. A method has been developed for using multiple beam adaptive arrays in random access packet radio networks. This technique allows average throughputs of 3 to 4 packets per slot in slotted systems and 2 to 3 packets per packet length in unslotted systems. Average delays are also substantially reduced in comparison with those in conventional packet radio systems. Moreover, this technique yields these high throughputs and small delays without the need for high bandwidth as in spread spectrum packet radio.
2. A second method of using array processing techniques in packet radio systems has also been proposed and is currently under study. This technique makes use of angle estimation techniques. It promises to provide an additional increase in throughput and reduction in delay over the multiple beam technique described above.
3. Methods have been found for estimating the polarizations of incoming signals along with their arrival angles. These methods take advantage of the ESPRIT algorithm but generalize its application to an array of cross-polarized antenna elements. There appear to be several important applications for this work.

III DIFFRACTION STUDIES

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1 Introduction

The goal of this research is to develop uniform ray solutions to predict the phenomena of high frequency EM radiation and scattering from electrical large complex objects. Due to the local nature of high frequency fields, such phenomena can be studied from the asymptotic treatment of the radiation and scattering from simpler canonical configurations which locally model the geometrical and electrical properties in the neighborhood of points of reflection, or diffraction, etc. that might exist on a complex radiating/scattering object.

During the past period, substantial progress has continued toward incorporating useful extensions to the uniform geometrical theory of diffraction (UTD) expressions for predicting the EM radiation in the presence of perfectly conducting corners in a finite metallic plate, and in dealing with the diffraction by edges in non-conducting planar as well as wedge type configurations. Likewise, substantial progress has been made in developing a more systematic version of the generalized ray expansion (GRE) for describing the EM fields coupled into electrically large arbitrarily shaped open cavities illuminated by an external source, as well as in developing a spectral representation for focal region fields which is in a form useful for studying

the phenomenon of high frequency scattering by obstacles placed in such complex fields. These accomplishments, which are next described below, are expected to play a useful role in present and future EM technology.

2 Research Progress

a Extensions to the Recently Developed UTD Solution for a Corner in a Perfectly-Conducting Planar Surface

In late 1988, an approximate form of the UTD based corner diffraction coefficient was developed, under our JSEP Diffraction Studies Unit, to describe the diffraction of an EM plane wave by a corner in planar, perfectly-conducting surface. However, that corner diffraction coefficient was found to contain spurious effects which had to be suppressed thereby leading to an algorithm for computing this coefficient which was not as robust for practical use as desired. Consequently, in the couple of years that followed, work on ways to overcome the drawbacks of this corner diffraction coefficient continued till finally the work culminated in the development of a new UTD corner diffraction coefficient which overcame all the drawbacks of the previous corner diffraction coefficient. The development of this UTD corner solution was reported in the past JSEP annual report. The new UTD corner coefficient constitutes an important result in that it adds to the class of practical problems which can be treated by the UTD; it was developed by formulating the solution in the spectral rather than the spatial domain (as done previously) and then reducing the spectral integral asymptotically in a uniform fashion, so that the new corner coefficient remains valid everywhere away from the neighborhood of tip (or corner). This new corner diffraction coefficient is based on a high frequency approximation for the current on the perfectly-conducting plane angular sector containing the corner; this approximation includes only the geometrical optics and the edge diffracted components of the surface current, whereas it excludes the tip (or corner) diffracted wave contribution to the current. The latter contribution is not easy to find, even though

it is embedded in the rather complicated but exact eigenfunction series solution for the EM waves scattered by a corner in a plane angular sector given by Satterwhite and Kouyoumjian¹. Nevertheless, the approximation for the current which is being used at present is sufficiently accurate to obtain a transition function within the UTD solution for this corner. The transition function, which is an integral part of any UTD solution, in this case allows the corner diffracted field to properly compensate for the discontinuities in the waves diffracted by the edges of the plane angular sector. The edge diffracted fields as usual compensate for the discontinuities in the geometrical optics incident and reflected ray fields which result from their shadowing by the surface of the plane angular sector. The edge diffracted fields become discontinuous because the edges truncate to form the corner in the plane. Furthermore, the transition regions adjacent to the geometrical optics and edge diffracted ray shadow boundaries overlap in the regions close to the geometrical optics shadow boundaries; this made the development of a corner transition function a difficult task. Despite the complexity of the analysis, the final result for the UTD corner diffraction coefficient fortunately turns out to be relatively simple and more efficient to apply than the cumbersome exact eigenfunction or numerical solutions, none of which isolate the corner diffraction effect as does the present UTD solution. As indicated in the past JSEP annual report, the accuracy of this UTD corner solution is found to be very good when predicting the radiation by antennas near rectangular plates upon comparison with results obtained using other independent numerical approaches.

Since this new UTD corner solution is obtained for the case of plane wave excitation which is produced by a distant source, it is important to deal with other cases of interest which arise when the excitation is not due to a distant source. For example, it is of interest to find a UTD corner solution for spherical wave illumination which results from a source placed near a corner when the observer is also located near

¹R.S. Satterwhite and R.G. Kouyoumjian, "EM Diffraction by a Perfectly Conducting Plane Angular Sector," Technical Report 2183-2, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering, 1970.

that corner. Here, near implies that the source/observer can be physically close to the plane angular sector containing the corner, but still far in terms of the electrical distance from the corner (i.e. about a couple of wavelengths or more from the corner). In addition, a more general ray optical illumination of the corner such as that due to an incident wavefront with two distinct principle radii of curvature is also of great interest in UTD applications. Both of these, the incident spherical wave and the more general incident wavefront illumination of the corner are being considered; the UTD result for the latter more general case should, as a check, reduce to the spherical wave illumination case. Currently, the new arguments of the UTD corner transition functions are being developed to deal with the non-plane wave illumination and the corresponding UTD corner solutions are close to being completed. In the future phases of this study, these more general UTD corner solutions will be tested for accuracy once they are completed, and additional extensions to this UTD corner solution will be investigated to allow it to contain better information on the interaction between the pair of edges forming the corner, as well as to include the edge wave effects which are absent in the present solution. The latter edge wave effects can become important for grazing angles of incidence and scattering.

b Diffraction by Non-Conducting and Penetrable Surfaces.

Firstly, the diffraction of EM waves by a planar structure consisting of a junction between two thin material half planes has been analyzed and a UTD result obtained for the total field surrounding the structure in the case of a plane wave obliquely incident on the junction. A couple of years ago, a UTD solution was developed, under JSEP, to analyze the corresponding two-dimensional situation in which the plane wave was incident perpendicular to the junction. The analysis of the present three dimensional (3-D) situation pertaining to the case of oblique incidence on the junction is far more complex because the solution based on the Weiner-Hopf technique by itself is non-unique! Thus, in order to obtain a unique solution it is

necessary to study, in detail, the behaviour of the fields within the material but in the neighborhood of the junction. The latter study was performed by obtaining a quasi-static solution for the fields in the material near the junction; once the quasi-static fields were obtained, they were compared with the Wiener-Hopf solution containing undetermined constants (resulting in its non-uniqueness). A comparison of the two solutions in the neighborhood of the junction provided a solution for the undetermined constants in the Wiener-Hopf solution, thus making the latter solution unique. Furthermore, such a procedure for obtaining a unique solution can be viewed as providing a physical requirement which must be satisfied when dealing with EM wave diffraction by material junctions. This important physical requirement may be interpreted as a new junction condition that relates the undetermined constants in the Wiener-Hopf solution to the field and its derivatives near the junction; a knowledge of the latter is of course obtained from the quasi-static solution. It is noted that the planar materials on either side of the junction are replaced by a set of generalized or (higher order) surface boundary conditions which were also developed over the previous couple of years under JSEP. Thin planar materials may be accurately approximated by a set of second order generalized surface boundary conditions; the use of these generalized surface boundary conditions is crucial, because without it the Wiener-Hopf technique could not be applied to obtain the desired UTD solution. It is noted that the construction of a unique solution for the 3-D situation of diffraction of EM waves by junctions in planar material boundaries (that can have different thicknesses and material parameters either side of the junction) constitutes an important step in extending ray methods for analyzing the radiation and scattering from ever more realistic (or practical) configurations. The accuracy of this 3-D solution has been verified by comparison with with an exact formulation which was solved by the method of moments (MM) for the case of a planar 2-part material slab of infinite width excited by a plane wave obliquely incident on the 2-part junction (edge); the comparison has been found to be excellent.

It is proposed in the future phases of this study to extend the above methodology to analyze the 3-D EM scattering by a perfectly conducting half plane completely coated on both faces with different, thin material slabs. The solution will be developed via the generalized reflection method of Malunzhinets, because the Wiener-Hopf method does not work in this case even with the use of the generalized surface boundary conditions approximated to second order. This configuration is also of significant practical interest.

Secondly, an improvement to a solution that was obtained in the previous year has been completed recently for analyzing the fields near an impedance wedge excited by a line source which is also located near the edge. This is accomplished by including a higher order term in the asymptotic evaluation of the integral representation for the fields. The inclusion of such a higher order term has been found to be essential if one needs to avoid slope discontinuities in the field pattern near the line source excited wedge. This work sets the stage for analyzing the corresponding 3-D, point source excited impedance wedge configuration where both the source and field points are near the wedge but outside the close neighborhood of the edge. It is anticipated for the present that a closed form asymptotic solution for the 3-D case will be possible only for certain wedge angles (e.g. the entire plane, a half plane and a right angled wedge).

c Scattering by Open-Ended Waveguide Cavities of Arbitrary Shape

In the previous year, it was reported under JSEP that a Gaussian Beam (GB) expansion was developed for representing the fields coupled into the open end of a semi-infinite waveguide cavity when it is excited by an external source. In this GB method, the aperture field at the open end is first expanded in a set of well focussed GB's, and a suitable way to find the coefficients of expansion which correspond to the initial launching parameters of these well focussed (or relatively wide waisted) GB's is developed so that their propagation within the cavity can be tracked approximately

like rays along their beam axis as they undergo multiple reflections at the cavity walls. These GB's, which serve as the interior cavity field basis functions, evolve according to the rules of beam optics in this approximations; however, it is important to note that the GB's in this particular expansion propagate along paths which do not depend on the external illumination but depend only on the cavity shape and the initial launching directions of the GB's. Thus, the GB's need to be tracked only once within the cavity independent of the excitation; only the initial GB launching amplitudes change with excitation. Since the well focussed GB's distort at each bounce (or reflection) at the slowly varying cavity walls, they can be tracked within the axial (or real ray) approximation with reasonable accuracy as long as the length through which they are tracked down the cavity is not much more than four times the width of the cavity. The latter requirement results from the fact that the axial (or real ray) tracking approximation does not take beam distortion into account during the process of reflection. Ways to overcome the limitations of the axial beam tracking approximation can be found. For example, the GB's could be tracked as complex rays (since GB's are actually a bundle of complex rays with only the axial beam direction being a real ray), or a set of GB's could be re-started in the axial (real ray) tracking approximation once the length to width criteria alluded to above is violated, and so on. On the other hand, it appears that both of the above approaches for overcoming the limitations of the GB axial tracking approximation are rather cumbersome and computationally intensive at the present time. Therefore, a procedure referred to as the Generalized Ray Expansion (or GRE) was developed, as indicated in the past JSEP annual report, to overcome the above difficulty of the GB axial tracking approach. While the GRE is also computationally intensive, it is not as cumbersome as the remedies involving complex ray tracking or beam restarting that have been suggested above.

In the GRE, a dense set of thin ray tubes is launched radially from an array of lattice points in the aperture at the open end. The basic idea here is the same

as in the GB approach, except that sufficiently thin ray tubes instead of GBs are launched into the cavity in this GRE approach. This GRE approach will be referred to as the "forward GRE" in which the initial ray launching amplitudes are based on certain assumptions which are the same as those employed in the GB approach. Furthermore, the initial ray launching directions and the ray paths in the GRE are also independent of the external source illumination of the cavity. Thus the rays need to be tracked only once through the interior cavity region since their paths remain unchanged by the external excitation; only the initial ray launching amplitudes (but not directions) change with excitation. Furthermore, unlike other conventional ray launching schemes which have been used previously, the GRE (as well as the GB approach) includes effects of waves coupled into the cavity via diffraction by the edges at the open end. During the past period, a better justification for the forward GRE scheme has actually been established via the "reverse GRE" in which the field at an array of lattice points in any plane or cross section of the cavity can be found in the presence of external illumination using the reciprocity and equivalence principles. Therefore, point sources (or more general source distributions) centered at these interior lattice points are allowed to radiate to the open end in the reciprocal cavity configuration; these fields arriving from the lattice points are then reacted (using the reciprocity principle), with the field distribution in the aperture at the open end when it is illuminated by an external source as in the direct or original configuration. The result of this reaction is that one obtains the fields at the array of interior lattice points that results from the external illumination in the original configuration. Thus, the interior fields in the original case are obtained by evaluating the fields in the reciprocal case, where it is assumed in the reciprocal case that the fields from the interior lattice points arrive at the open end via rays launched from those lattice points. The reciprocal case requires one to track rays in the reverse sense as compared to those in the forward GRE. Under certain conditions, which are generally met in practice, the reverse (or reciprocal) GRE is found to yield the

forward GRE. This study therefore clearly outlines the assumptions required and the limitations present in the forward GRE procedure so that when these limitations are exceeded, as might happen in a few special cases, then one can still employ the reverse GRE concept to find the fields coupled into the open cavities. In addition, the reverse GRE suggests a "modified forward GRE" procedure which can also overcome the limitations of the usual forward or conventional GRE. Calculations based on both the usual forward GRE and the reverse GRE have been made and compared with modal solutions in special cases to provide a reference. It is found that the three methods all agree reasonably well with each other, except in some special cases where a modified rather than the usual forward GRE was needed for improved accuracy. Furthermore, the GRE has also been employed to deal with cavities possessing relatively arbitrary shapes that can be modeled using a super-ellipse for the cavity cross-section which can change along the length of the cavity, and using a lofting function (polynomial) which can allow the cavity to bend along its length. An example of a relatively arbitrary cavity shape which has been studied is one whose cross section can change continuously from rectangular (at the open end, say) to a circular or elliptical one (at the other end) while the cavity exhibits an S-bend along its length. Other more general shapes have also been studied.

In the future phases of this study, the GRE/GB schemes will be developed to launch rays/beams into a complex environment which is not necessarily a cavity. In particular, work has already been initiated to employ GB's to efficiently deal with large reflector antennas, and to employ GRE to deal with antennas in a complex shipboard environment (see Hybrid studies for more details).

d Scattering by Obstacles Illuminated by Focal Region Fields:

The ray methods encounter difficulties in the neighborhood of ray caustics where a family of rays merge or intersect. Ray caustics frequently occur when using ray methods for analyzing high frequency scattering from obstacles. Hence, it is impor-

tant to deal with the phenomena of ray caustics. Ray caustic regions are also referred to as focal regions. A uniform ray solution which remains valid within the transition region associated with smooth caustics of rays reflected or diffracted from both, two and three dimensional objects has been developed recently under JSEP such that it is in a form useful for engineering applications. The transition region not only includes the caustic itself, but also includes its neighborhood which lies in both, the lit and the dark sides of a smooth caustic. The uniform ray solution remains bounded and continuous throughout the caustic transition region and reduces to the conventional GTD solution outside the caustic transition region, whereas the conventional GTD solution becomes singular on the caustic and remains inaccurate near the caustic. Clearly, there are situations where the fields reflected and diffracted from one obstacle could then illuminate another obstacle which may be present nearby. If the fields reflected and diffracted from the first obstacle produce a caustic of reflected or diffracted rays in the neighborhood of the second obstacle, then one cannot, in general, use ray methods to find the fields reflected and diffracted from the second obstacle, when it is illuminated by the caustic (or focal) region fields produced by the first obstacle, simply because the caustic (or focal) region fields are not ray optical. The focal region fields are given in terms of expressions, which involve transition functions. In the case of smooth caustics, the transition function which destroys the ray optical nature of the field contains the Airy integral and its derivative. Clearly, it therefore becomes necessary to describe the focal region fields produced by the first obstacle, in terms of a superposition of ray fields before one can continue to apply ray methods to analyze the scattering from the second obstacle illuminated by these focal region fields.

It was indicated in the past JSEP annual report that a spectral (PWS) integral representation was developed for describing the fields which remain valid at and near smooth caustics of rays. Thus, this representation in terms of PWS components is preferable to the one involving transition functions when dealing with the scattering

by obstacles illuminated by focal region fields. At present, work is continuing on this topic in that the PWS components which are ray optical are being employed to systematically synthesize (via superposition over the PWS components) the fields scattered by obstacles when they are illuminated by focal region fields.

As a separate issue, some work has also been initiated to study the behaviour of the focal region ray fields in the time domain. An inversion of the frequency domain ray fields which pass through focal regions to obtain the corresponding fields in the time domain leads to non-causal results. This aspect of non-causality of the transform of the focal ray fields from the frequency domain to the time domain is under investigation, and procedures are being studied to eliminate the occurrence of such non-physical (non-causal) solutions by proper analysis.

3 List of Papers - JSEP Diffraction Studies

Published:

1. P. H. Pathak and R.J. Burkholder, "High Frequency EM Scattering by Open-Ended Waveguide Cavities," *Journal Radio Science*, Vol. 26, No. 1, pp. 211-218, January-February 1991.
2. R.G. Rojas, H.C. Ly, P.H. Pathak, "EM Plane Wave Diffraction by a Planar Junction of Two Thin Dielectric/Ferrite Half-Planes," *Journal Radio Science*, Vol. 26, No. 3, pp. 641-660, May-June 1991.
3. R.G. Rojas, H.C. Ly, P.H. Pathak, R. Tiberio, "EM Plane Wave Diffraction by a Three-part Thin, Planar Dielectric/Ferrite Slab," *Journal Radio Science*, Vol. 26, No. 5, pp. 1267-1280, September-October 1991.

Accepted for Publication:

1. G. Pelosi, R. Tiberio, R.G. Rojas, "Electromagnetic Field Excited by a Line Source Placed at the Edge of an Impedance Wedge," *Journal of Electromagnetic Waves and Applications*.
2. R.G. Rojas, "Integral Equations for the Scattering by Three Dimensional Inhomogeneous Chiral Bodies," in press, *Journal of Electromagnetic Waves and Applications*.
3. R.J. Burkholder, R-C. Chou and P.H. Pathak, "Two Ray Shooting Methods for Computing the EM Scattering by Large Open-Ended Cavities," for publication in *Computer Physics Communications*, (invited).
4. R.J. Burkholder and P.H. Pathak, "An Analysis of the EM Scattering from an Open-Ended Waveguide Cavity Using Gaussian Beam Shooting." To appear in IEEE Proceedings, special issue on Electromagnetics, expected October 1991.
5. P.H. Pathak, "High Frequency Methods for Antenna Analysis," IEEE Proceedings, (invited). To appear in January 1992.

Submitted for Publication

1. M.C. Liang, P.H. Pathak and C.W. Chuang, "A Generalized Uniform Ray Solution for Diffraction by a Perfectly-Conducting Wedge with Convex Faces," submitted to *Journal Radio Science*.
2. R.G. Rojas, "Integral Equation for EM Scattering by Two Dimensional Chiral Bodies," submitted to *IEEE Transactions on Antennas and Propagation*.

3. K.C. Hill and P.H. Pathak, "On the Nature and Evaluation of the Transition Function for a UTD Corner Diffraction Coefficient," submitted to ACES journal.

Papers in Preparation:

1. R.G. Rojas and L.M. Chou, "Generalized Impedance/Resistive Boundary Conditions for a Planar Chiral Slab."
2. K.C. Hill and P.H. Pathak, "A Uniform Stationary Phase Evaluation of a Double Integral with Algebraic ."
3. K.C. Hill and P.H. Pathak, "An Approximate UTD Corner Diffraction Coefficient."

Conferences/Oral Presentations:

1. K.C. Hill and P.H. Pathak, "A UTD Solution for the EM Diffraction by a Corner in a Plane Angular Sector," 1991 International IEEE Transactions on Antennas and Propagation and National Radio Science Meeting, London, Ontario, Canada, June 24-28, 1991.
2. G. Manara, P.H. Pathak, G. Pelosi and R. Tiberio, "A UTD Description of Surface and Space Wave Excitation at the Edge of an Impedance Wedge," 1991 International IEEE Transactions on Antennas and Propagation and National Radio Science Meeting, London, Ontario, Canada, June 24-28, 1991.
3. R.G. Rojas, L.M. Chou, "Generalized Impedance/Resistive Boundary Conditions for a Planar Chiral Slab," presented at the International IEEE Transactions on Antennas and Propagation and National Radio Science Meeting, International Symposium, London, Ontario, Canada, June 1991.
4. R.G. Rojas, M. Otero, "Diffraction by a Resistive Strip Attached to an Impedance Wedge," presented at the International IEEE Transactions on Antennas and Propagation and National Radio Science Meeting, International Symposium, London, Ontario, Canada, June 1991.

Short Course:

1. P.H. Pathak and R.J. Marhefka, Short Course on: "Asymptotic High Frequency Methods for EM Antenna and Scattering Analysis," (invited), at the International IEEE Transactions on Antennas and Propagation and National Radio Science Meeting.

Invited Lectures:

1. P.H. Pathak, "Asymptotic High Frequency Techniques for EM Antenna and Scattering Analysis," presented at the Spanish URSI meeting, Ca'ceres, Spain, September 24-27,1991.
2. P.H. Pathak, "EM Scattering by Open Cavities," presented at the Air Force Institute of Technology, Dayton, Ohio, November 1990.

IV INTEGRAL EQUATION ANALYSIS OF EXOTIC MEDIA

Researchers:

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M. Peters, Graduate Research Assoc.

This section will summarize our work in integral equation studies from September 1990 to September 1991. In overview, our recent research has centered on integral equation and method of moments (MM) solutions for unusual or novel media. In particular, we are developing MM solutions for scattering by a chiral bodies, an MM solution for the chiral microstrip transmission line, and also MM solutions for the analysis of artificial media. During this year, our research has culminated in two PhD dissertations [1, 2], and an *IEEE Press book* has been published on the method of moments [3].

1 Chiral Media

A chiral media has constitutive relationships of the form

$$\mathbf{D} = \epsilon\mathbf{E} - j\xi\mathbf{B}$$

$$\mathbf{H} = \frac{1}{\mu}\mathbf{B} - j\xi\mathbf{E}$$

where ξ is the chiral admittance. In an regular or a chiral media, $\xi = 0$. The non-zero ξ in a chiral media results in an additional coupling between the electric and magnetic fields, and causes the polarization of a plane wave to rotate as it propagates through the chiral media.

Over the past three years we have developed a number of basic electromagnetic theorems and computational techniques associated with a chiral media. This work can be summarized as follows:

1. Development of the volume equivalence theorem for a chiral media and its application to MM solutions for scattering by chiral cylinders [4, 5, 6]
2. Development of image theory for a chiral media [7]
3. Development of an eigenfunction solution for scattering by a multilayer chiral cylinder [8].

Our recent work in a chiral media has concentrated on the chiral microstrip transmission line [9], and is summarized below.

Figure 1 illustrates the geometry for a microstrip transmission line on a chiral substrate. The main problem is to determine the current, \mathbf{J} , and propagation constant, β , for waves on this transmission line, and especially how these are effected by the chirality of the substrate. In brief, the solution begins by formulating an electric field integral equation for the current on the microstrip line. The integral equation is solved via a spectral domain MM solution. This required the development of a new set of left and right circular vector potentials for expanding the fields in the chiral substrate [1, 9]. Once the MM solution is formulated, the determinant of the MM impedance matrix is set to zero, thus yielding the propagation constant and corresponding current distribution for waves on the microstrip transmission line.

As an example of the data which can be generated by this technique, Figure 2 shows a plot of normalized guide wavelength versus frequency for various values of the substrate chirality, ξ_c . For example, at 15 Ghz, as ξ_c is increased from zero (i.e. an achiral substrate) to 0.005, the normalized guide wavelength decreases from about 0.53 to about 0.28. Figure 3 shows a plot of normalized guide wavelength versus substrate thickness. At 2 Ghz and $T = 6\text{mm}$, increasing ξ_c from zero to 0.005, results in the normalized guide wavelength decreasing from about 0.58 to about 0.53. These

CHIRAL MICROSTRIP

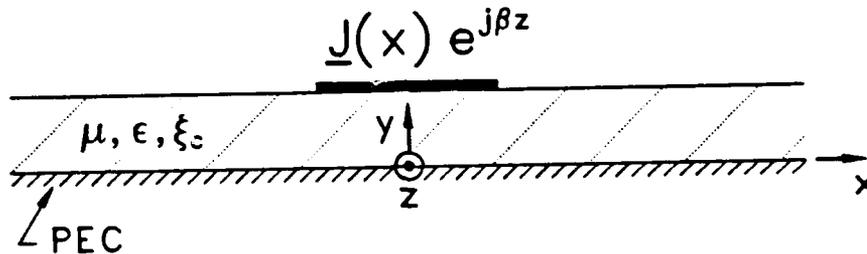


Figure 1: A microstrip transmission line on a chiral substrate.

two figures illustrate that the chirality of the substrate can have a significant effect on the propagation of waves on the microstrip line.

2 Artificial Media

As illustrated in Figure 4, an artificial medium is created by suspending a large number of small scatterers, such as spheres, discs, or dipoles, in some host or background medium. A field propagating in this artificial medium will induce electric and/or magnetic dipole moments in the scatterers. The result is that the artificial medium appears to be a dielectric and/or a ferrite medium. An artificial chiral media can be created from a 3D infinite periodic array of helices. The most interesting feature of artificial media is that by properly choosing the size, shape, density, and material composition of the small scatterers, it may be possible to “engineer” a medium with desirable permittivity, permeability, and dispersion characteristics.

Our research is directed toward the use of integral equation and MM techniques for the analysis of artificial media. The advantages of the MM approach are accuracy and the ability to treat scatterers of complex shape and/or material composition. Essentially, one uses the periodic MM (PMM) to obtain the impedance matrix for an infinite periodic array of scatterers filling all space. By setting the determinant

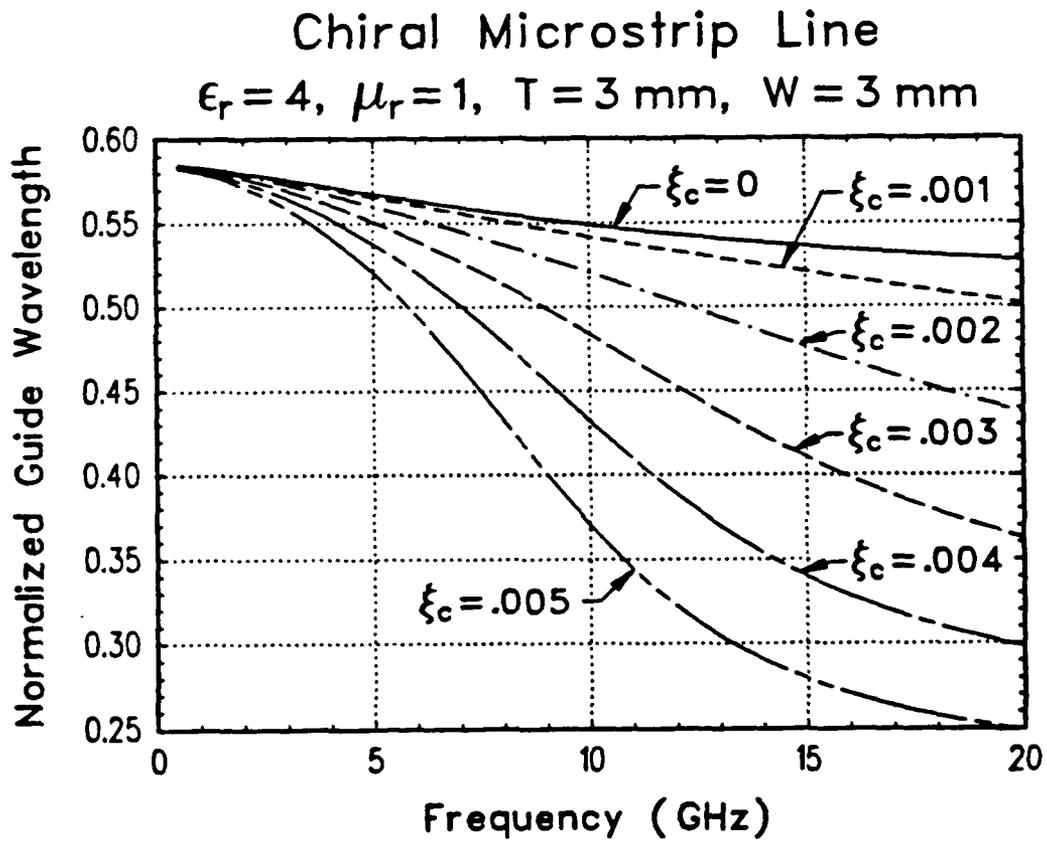


Figure 2: Normalized guide wavelength (λ_g/λ) versus frequency for the fundamental mode of chiral and chiral microstrip lines, for a range of chiral parameters.

Chiral Microstrip Line

$\epsilon_r = 4, \mu_r = 1, W = 3 \text{ mm}$

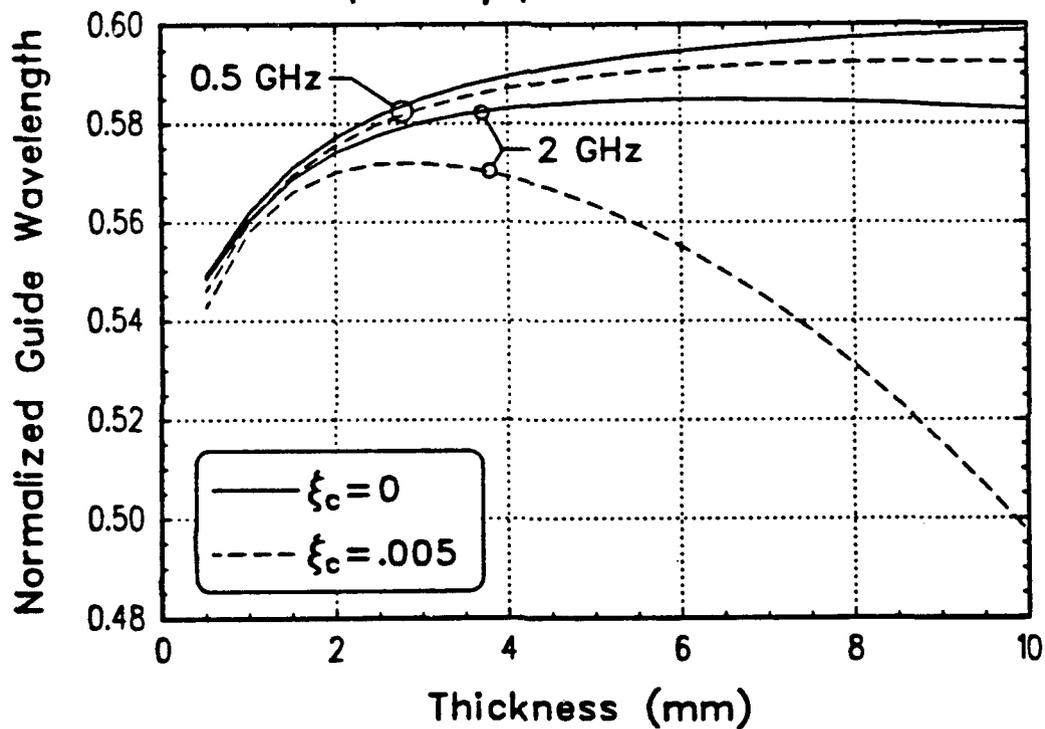


Figure 3: Normalized guide wavelength (λ_g/λ) versus substrate thickness for the fundamental mode of chiral and chiral microstrip lines, at two frequencies.

ARTIFICIAL DIELECTRIC/FERRITE MEDIA

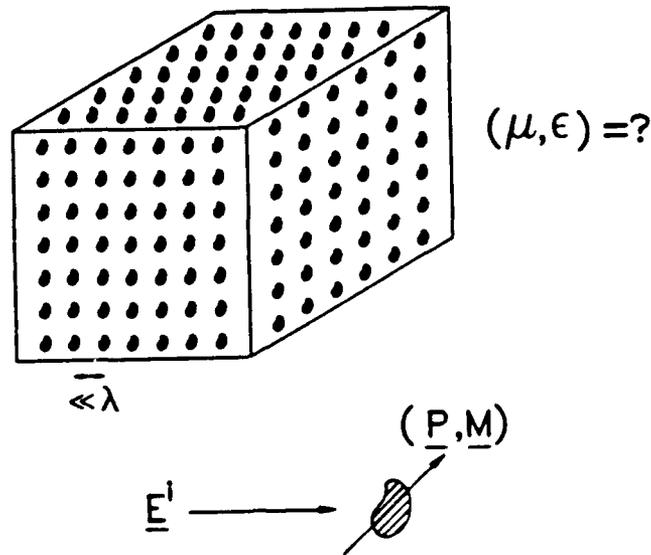


Figure 4: An artificial medium is modeled by a periodic array of small scatterers.

of this matrix to zero one can determine the normal modes of the system and in turn deduce the equivalent permittivity and permeability of the artificial media. At present we have applied this method to the 2D problem of an infinite periodic array of thin dielectric cylinders, and the 3D problem of an infinite periodic array of short dipoles [2, 10]. For example Figure 5 shows a 2D array of dielectric rods of radius $a = 0.001\lambda$. The figure shows a plot of the effective relative permittivity of the artificial dielectric as a function of rod spacing, for rods of relative permittivity $\epsilon_r = 20, 100, \text{ and } 500$. As expected, as the density of the rods or the permittivity of the rods increases, the effective permittivity of the artificial dielectric increases. The figure shows data computed by the MM and by an approximate solution, and the results are virtually identical.

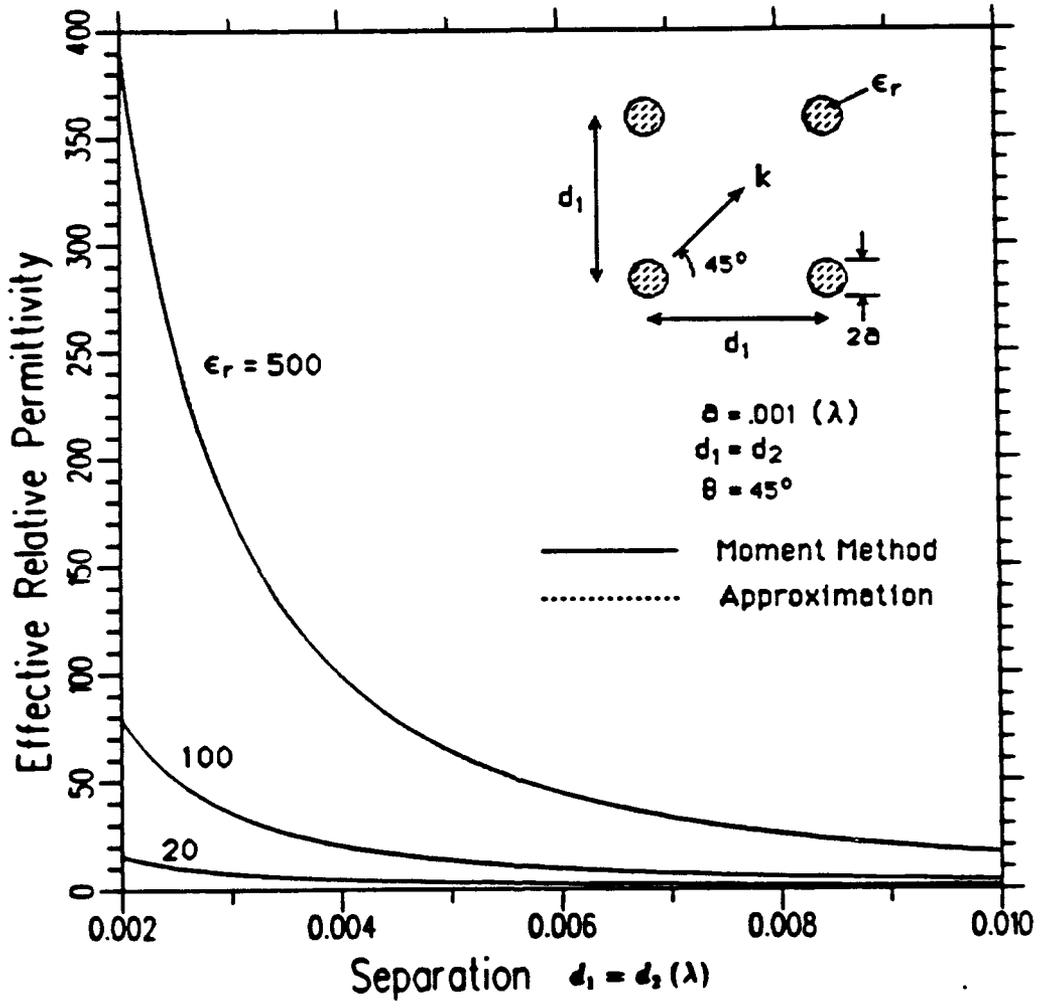


Figure 5: Lattice separation versus effective relative permittivity for a 2-D array of dielectric rods of radius 0.001λ .

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- [4] M.S. Kluskens and E.H. Newman, "Scattering by an Arbitrary Cross Section Chiral Cylinder," IEEE Antennas and Propagation/URSI Symposium, San Jose, California, June 1989.
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- [6] M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section in the Presence of a Half-Plane," *Journal Electromagnetic Waves and Appl.*, In Press.
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- [10] J.L. Blanchard and E.H. Newman, "Integral Equation Analysis of Artificial Media," In Preparation.

3 Integral Equations JSEP Publications

Published

1. M.S. Kluskens and E.H. Newman, "Scattering by a Multilayer Chiral Cylinder," *IEEE Transactions on Antennas and Propagation*, Vol. AP-39, No. 1, pp. 91-96, January 1991.
2. M.E. Peters and E.H. Newman, "TM Scattering by a General Sheet Impedance Discontinuity," *IEEE Transactions on Antennas and Propagation*, Vol. AP-39, No. 3, pp. 359-366, March 1991.
3. M.S. Kluskens and E.H. Newman, "Image Theory for Chiral Bodies," *IEEE Transactions on Antennas and Propagation*, Vol. AP-39, No. 5, pp. 676-677, May 1991.
4. J.H. Richmond, "On Variational Aspects of the Moment Method," *IEEE Transactions on Antennas and Propagation* Vol. AP-39, No. 4, pp. 473-480, April 1991.

Accepted for Publication

1. E.H. Newman and K. Kingsley, "An Introduction to the Method of Moments," *Computer Physics Communications*, (invited paper) .
2. M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section in the Presence of a Half-Plane," *Journal Electromagnetic Waves and Applications*.
3. M.S. Kluskens and E.H. Newman, "A Microstrip Line on a Chiral Substrate," *IEEE Transactions on Microwave Theory and Technology*.

Submitted for Publication

None

In Preparation

1. J.L. Blanchard and E.H. Newman, "Integral Equation Analysis of Artificial Media,"

PhD Dissertations

1. M.S. Kluskens, "Method of Moments Analysis of Scattering by Chiral Media," PhD dissertation, The Ohio State University, Department of Electrical Engineering, 1991.

2. J.L. Blanchard, "Integral Equation Analysis of Artificial Dielectrics," PhD dissertation, The Ohio State University, Department of Mathematics, 1991.

Books

1. E.K. Miller, L. Medgyesi-Mitschang, and E.H. Newman, *Computational Electromagnetics: Frequency Domain Method of Moments*, IEEE Press, New York, 1991.

V HYBRID STUDIES

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1 Introduction

The goal of hybrid studies is to develop procedures for combining different analytical numerical or even experimental techniques so as to predict EM radiation and scattering phenomena which is otherwise intractable or inefficient to predict by any one technique alone. There are many complex and important EM phenomena which fall into the latter category, and thus require the use of hybrid methods for their prediction. The hybrid studies thus far on JSEP primarily dealt with a combination of high frequency techniques such as the UTD with the numerical moment method (MM). This hybrid UTD-MM procedure, or more generally the hybrid combination of high frequency techniques with numerical methods, is of importance in predicting the radiation and scattering from complex shapes which contain portions that are electrically large and those that are electrically small. The electrically large portions can be handled via high frequency approximations, while the electrically small portions can be treated via the conventional numerical procedures, all within the self consistent framework of integral equation formulations for radiation and scattering. Significant progress is being made in the development of such a hybrid procedure which would ultimately be able to predict, for example, the radiation and scattering

from complex shapes such as an aircraft with appendages, antenna windows, other perturbations and details which produce significant effects. In addition, a related hybrid combination of asymptotic high frequency and MM procedures is being developed for analyzing printed circuits and antennas, as well as their integration, as is necessary for transitioning from the feed lines via circuit elements to an array of radiating elements or antennas. Conventional procedures for treating the above situations are expected to become highly cumbersome and inefficient. Furthermore, another hybrid procedure, supported partly under JSEP, has been developed to predict the EM scattering from open cavities containing a large, complex obstacle in which the cavities can be of relatively arbitrary shape. The shape dominated cavity region (from the open end being illuminated to the back end close to the obstacle) can be handled via the GRE (described under Diffraction Studies in JSEP) or other procedures, whereas the cavity region close to the obstacle may be handled via analytical, numerical or even experimental procedures. The two separate analyses of the two regions can be combined systematically in this hybrid scheme through a generalized reciprocity integral. Such a cavity can model a jet inlet or exhaust configuration which can contribute significantly to the overall radar cross section of a modern aircraft.

The progress in the above areas is described next.

2 Hybrid Analysis

a Hybrid analysis of stripline configurations

During the previous year, it was reported under JSEP that stripline antennas/arrays together with their feed networks, passive stripline circuit components, etc. could be handled more efficiently and in a far more tractable fashion than is possible by conventional procedures if one employs a hybrid approach. Such a hybrid approach would involve a combination of asymptotic high frequency and numerical moment method techniques within a self-consistent integral equation formulation. Indeed,

the asymptotic high frequency technique involves the use of a uniformly asymptotic form of the grounded or ungrounded substrate (or substrate-superstrate) Green's function which constitutes the kernel of the relevant integral equation. An asymptotic, closed form of the Green's function is far more efficient to use than the standard spectral integral form which is slowly convergent. Such a Green's function has been developed previously under JSEP. Furthermore, the asymptotic form of the Green's function which becomes increasingly accurate with increase in the source and field point separation along the substrate/superstrate is also found to remain remarkably accurate when the lateral source and field point separation (i.e., separation along the substrate/superstrate) becomes as small as a quarter of a free space wavelength or so, due to the uniform nature of the asymptotic approximation obtained for this Green's function. This Green's function has also been tested in the past, under JSEP support, and has been found to accurately provide the mutual coupling between a pair printed dipoles on a grounded dielectric substrate, etc.

The next step is to develop a hybrid scheme for treating (analyzing/designing) stripline components and large antenna arrays in a relatively efficient manner. This hybrid scheme would of course employ the asymptotic closed form of the single or double layer (substrate-superstrate) Green's function alluded to above. Furthermore, in order to further enhance the efficiency of the full wave MM solution of the integral equation, whose kernel is the layered Green's function (which will be expressed asymptotically in closed form) and whose unknowns constitute the currents on the stripline circuit elements or feed lines and radiating (antenna) elements, it would be useful to choose a mixed set of only a few basis functions for accurately representing the unknown currents. In particular, one could employ the conventional (sub-sectional) basis set only near the stripline discontinuities, whereas the well chosen entire domain functions such as the propagating modes on the striplines or physically meaningful entire domain functional forms away from the discontinuities would drastically cut down the total number of unknowns to be solved via the

MM procedure. This entire domain basis set would clearly have to depend on the specific stripline configurations being studied. With this view in mind, work has started on the evaluation of the entire domain or modal field behavior on a class of lines such as the microstrip line, the slot line and the coplanar line. Since the feed lines and the circuitry are generally covered or packaged, a study has been initiated on the evaluation of the propagation constants of electromagnetic modal fields for a class of microwave planar transmission lines with a top cover and also the evaluation of the mutual coupling between these lines. The radiation of higher order modes, the effect of the top cover height and the finite width lateral ground planes of single or coupled microstrip lines, slotlines and coplanar waveguides embedded in multilayer dielectric slabs will also be investigated. The method being used is a combination of the Generalized Scattering Matrix technique and the Wiener-Hopf procedure (GSMT/WH). Although a large number of papers can be found in the literature related to the study of such lines, very few authors have used the present technique. The most commonly used method to handle the present problem is the Spectral Domain approach; however, the GSMT/WH scheme being used here has the advantage of providing much more physical understanding of the behavior of the fields and currents in these transmission line structures. Note that in contrast to the Spectral Domain approach, it is not necessary to assume basis functions for the currents or fields with the GSMT/WH technique because these currents and fields can be obtained from the analysis. These current forms in fact provide the entire domain basis functions to be used in the MM analysis as described earlier. In particular, the Wiener-Hopf solution for the scattering of a complex plane wave by a perfectly conducting half-plane embedded in a single layer dielectric region with perfectly conducting bottom and top covers has been obtained. The scattering matrix formulation has also been completed to get the dispersion curves of single layer microstrip (MS), slotlines (SL) and coplanar waveguides (CW). These results have

been compared with results obtained by other independent methods found in the literature.

The following tasks will be completed in the coming year, namely, an analysis of the leakage of the higher order modes near their cut-off frequency will be performed and the influence of the height of the top cover on the solution will be studied. Also, the effect of the finite width of the lateral ground planes for SL and CPW will be examined to see if some useful design rules for the size of these lateral ground planes can be obtained. Furthermore, the scattering matrix for a PEC half-plane embedded in a multilayer dielectric region with top and bottom PEC ground planes will be developed. In addition, dispersion curves, leakage of higher order modes, characteristic or modal impedance, etc., will also be studied for multilayer MS, SL and CPW. These results will then be used in the future phases of this study to deal with the analysis/design of realistic printed circuit antenna arrays with feed lines and circuit components, as indicated earlier. It would be particularly efficient to use this hybrid scheme to analyze/design such components and arrays up in the 30 GHz frequency range; present conventional techniques would become very cumbersome and inefficient in this case.

b Hybrid analysis of EM scattering by obstacles within an electrically large open cavity configuration

During the past period, work has continued partly under JSEP support to develop hybrid techniques for predicting the EM scattering by electrically large open waveguide cavities of relatively arbitrary shape containing a large interior obstacle, when this cavity-obstacle configuration is excited by an external source. The fields coupled from an external source, via the open end being directly illuminated, are tracked within the relatively arbitrarily shaped cavity using the GRE (see a description of the GRE in Diffraction Studies unit of this JSEP annual report for 1990), or the conventional ray shooting approach, to the region containing the interior obstacle but

with the obstacle absent. The interior obstacle plane wave characteristics are found separately for just the local region of the cavity containing the obstacle. Presently, these obstacle scattering characteristics are found numerically using a MM procedure on just the obstacle region; however, such a numerical procedure has also been employed in the present study to simulate a possible measurement procedure (yet to be developed in a practical sense) which would provide these characteristics. The two separate pieces of information, namely the one connected with high frequency (GRE or other) ray tracking within the arbitrarily shaped cavity from the open end which is illuminated to the vicinity of the interior obstacle but as if the obstacle was absent, and the other one connected with the interior obstacle scattering characteristics restricted to the local cavity region containing the obstacle, respectively, are then properly combined through a generalized reciprocity integral over a conveniently chosen waveguide cavity cross section near the interior obstacle. The latter integral then directly furnishes the field scattered into the exterior by the interior obstacle when the cavity-obstacle configuration is illuminated by an external source. An advantage of this hybrid combination of the separate field analyses pertaining to the strongly shape-dependent cavity portion, and the strongly obstacle-dependent cavity portion, respectively, is that the analysis of the entire cavity-obstacle configuration does not have to be re-done if either the cavity shape is modified or if the interior obstacle is changed; only the analysis pertaining to the cavity shape or the obstacle then needs to be repeated. Furthermore, such an analysis directly provides information on how various obstacles affect the overall RCS of a cavity with a given shape, or on how various cavity shapes influence the overall RCS for a given interior obstacle. Numerical results have been obtained for some simple conical, hemispherical and other obstacles located within S-shaped open cavities whose cross section changes from rectangular to circular near the obstacle. A comparison with other independent methods valid for circular cylindrical cavities shows good agreement.

In the future phases of this study, this hybrid procedure for analyzing the scat-

ing from cavity/obstacle configuration will be modified and extended to deal with the radiation and scattering by electrically large antennas radiating in the presence of a complex environment. Examples of the latter might include antennas in a complex shipboard environment, and AWACS type antennas on an aircraft. Procedures involving GRE rays whose launching directions and paths remain independent of the complex geometries in whose presence the rays are launched will be investigated. Procedures different from those employed in the cavity/obstacle configuration will be developed to launch the GRE rays, and the analysis of mutual coupling or radiation/scattering associated with such antennas in complex environments will be formulated. The hybrid procedures to be developed for such cases will not require one to find new ray paths if the antenna beams are steered electronically or mechanically, or if the antennas are changed. Furthermore, only those portions of the complex environment that get modified will affect the rays impinging on such portions resulting in the modification of only the latter set of rays rather than all the rays launched from the antennas.

c Hybrid analysis of EM scattering by antenna cavity configurations

The EM scattering by antenna cavities is being studied using hybrid methods under JSEP support. Previous work under JSEP included a hybrid combination of asymptotic high frequency and modal techniques for the analysis of the scattering from two-dimensional (2-D) antenna cavity shapes for which the modes can be found analytically, as well as a hybrid moment method/asymptotic method analysis for 2-D cavities with dominant mode waveguide fed antennas. The analysis of electromagnetic scattering from a 3-D dielectric filled rectangular antenna cavity recessed in a ground plane and backed with an array of identical slots fed by dominant mode rectangular waveguides has also been completed.

In the past year, work has begun on more generally shaped 3-D antenna cavities. The mutual coupling between slot antennas in circular and rectangular and

other cavities have been computed using ray methods. This work is currently being extended to more arbitrary cavity shapes. The mutual coupling results are also currently being incorporated into the hybrid analysis of the electromagnetic scattering from these more general 3-D cavity shapes. This work dealing with the isolated antenna cavity is important not only in its own right because the scattering from such antenna cavities can contribute significantly to the overall RCS of aircraft or missiles when they contain such antenna cavities, but it is also important for later inclusion in a hybrid procedure (discussed in Item "d") for estimating the radiation and scattering from such antennas when they are actually placed within the aircraft/missile or other complex structures.

d Hybrid analysis of EM scattering from complex structures

A hybrid combination of asymptotic high frequency and moment method (MM) techniques is being developed to analyze the EM radiation and scattering from electrically large complex structures which cannot be handled accurately and efficiently by either method alone. Basically, a self consistent integral equation formulation for the unknown currents on the radiating object provides the starting point. The kernel of the integral equation can be chosen to be a special Green's function approximated in an accurate fashion using high frequency methods such as the UTD; this can be done, for example, in treating the electrically large fuselage of an aircraft or missile shape. Choosing a special Green's function restricts the unknowns to the regions not included in the Green's function. Thus, with a proper UTD Green's function, the unknown currents in the case of an aircraft or missile shape are restricted to only the fins, other protruding control surfaces, appendages, antenna windows, etc., which in most typical cases are electrically small. Furthermore, the unknown currents restricted to electrically small regions may be represented in terms of the conventional subsection (MM) type basis functions, whereas, on the electrically large regions they may be represented by only a few entire domain UTD or

high frequency based approximations away from localized regions of structural discontinuities such as edges, tips, junctions, etc. where the subsectional basis set may be used. The integral equation for the entire configuration with an asymptotically approximated kernel and just a few mixed basis functions for the unknown currents can then be solved efficiently via the MM. Such a hybrid MM based solution would be far more efficient than the one using a free space Green's function in the kernel of the integral equation, and the one using subsectional basis functions to represent the unknown current over the entire radiating object where parts of it could get extremely large in terms of the wavelength. The configuration being presently studied is a finite perfectly conducting plate of relatively arbitrary shape on an electrically large perfectly-conducting convex cylinder. Such a configuration can simulate, for example, a fin on a fuselage of an aircraft or missile. This geometry is too large to be analyzed efficiently by the moment method; yet, no asymptotic solution exists for it in the general case. For this geometry, the conventional subsectional basis function is used to represent the unknown current on the fin which is assumed to be electrically small, while the cylinder contribution will be taken into account via the special Green's function which is approximated using high frequency asymptotics (or UTD). In this past year, the high frequency Green's function approximation for a source and observation point both arbitrarily close to the surface of a circular cylindrical conductor was derived. This important result will be used in the construction of the MM solution for the scattering by a circular cylinder with simple fins. This method will then be generalized to ellipsoids and other non-circular convex shapes. Additionally, fins that are not electrically small will also be considered. In the future phases of this study effects of additional perturbations such as other appendages antenna windows/antenna cavities, etc. will be included.

3 List of Papers - JSEP Hybrid Studies

Published

1. A. Nagamune and P.H. Pathak, "An Efficient Plane Wave Spectral Analysis to Predict the Focal Region of Parabolic Reflector Antennas for Small and Wide Angle Scanning," *IEEE Transactions on Antennas and Propagation*, Vol. AP-38, No. 11, pp. 1746-1756, November 1990.
2. S. Barkeshli and P.H. Pathak, "Reciprocal Properties of the Dyadic Green's Function for Planar Multilayered Dielectric/Magnetic Media," *Microwave and Optical Technology Letters*, Vol. 4, No. 8, pp. 333-335, August 1991.

Accepted for Publication

1. S. Barkeshli and P.H. Pathak, "On the Dyadic Green's Function for a Planar Multi-Layered Dielectric/Magnetic Media," *IEEE Transactions on Microwave Theory and Techniques*.
2. M. Marin and P.H. Pathak, "An Asymptotic Closed-Form Representation for the Grounded Double Layer Surface Green's Function," *IEEE Transactions on Antennas and Propagation*.

Submitted for Publication:

1. P.H. Pathak and R.J. Burkholder, "A Reciprocity Formulation for Calculating the EM Scattering by an Obstacle within an Open-Ended Waveguide Cavity," submitted to *IEEE Transactions on Microwave Theory and Techniques*.

Papers in Preparation:

1. P.H. Pathak, A. Nagamune and R.G. Kouyoumjian, "An Analysis of Compact Range Measurements."
2. P.H. Pathak, P. Law, and R. J. Burkholder, "High Frequency Electromagnetic Scattering by a Large Obstacle/Termination within an Open Cavity Structure."
3. M. Hsu, R-C. Chou, P. Pathak and C.W. Chuang, "Analysis of the Asymptotic HF EM Coupling Between Sources Anywhere in the Vicinity of a Circular Cylinder."
4. P. Munk and P. Pathak, "Analysis of EM Scattering by an Array of Waveguide Fed Slots in a Dielectric Filled Rectangular Cavity Opening into a Ground of a Plane."

Conference/Oral Presentations

1. R-C. Chou, R. J. Burkholder, and P. H. Pathak, "High Frequency Scattering by Complex Open Cavity Structures," 1991 International APS and URSI Radio Science Meeting, June 24-28, 1991, London, Ontario, Canada.
2. Mimi Hsu, R-C. Chou, and P.H. Pathak, "Hybrid Analysis (MM-UTD) of EM Scattering From Complex Structures," 1991 International APS and URSI Radio Science Meeting, June 24-28, 1991, London, Ontario, Canada.
3. R.J. Burkholder, P.H. Pathak, C. Chuang, and R-C. Chou, "EM Characterization of Complex Termination Inside Electrically Large Open Cavities," 1991 International APS and URSI Radio Science Meeting, June 24-28 1991, London, Ontario, Canada.
4. G.A Somers and P.H. Pathak, "The EM Scattering by a Material Loaded Step with a Lip in a Ground Plane and by a Pair of Material Loaded Partially Overlapping Semi-Infinite Ground Planes," 1991 International APS and URSI Radio Science Meeting, June 24-28, 1991, London, Ontario, Canada.
5. P.H. Pathak and R.J. Burkholder, "A Reciprocity Formulation for the EM Fields Scattered into the Exterior by an Obstacle within an Electrically Large Open-Ended Cavity," PIERS, Boston, Massachusetts, July 1991.
6. S. Barkeslili and P.H. Pathak, "On a Closed-Form Asymptotic Representation of the Planar Single and Double Layered Grounded Material Slab Green's Functions and their Applications to an Efficient Analysis of Arbitrary Microstrip Geometries," International Conference on Directions in EM Wave Modeling, Sponsored by WRI, Polytechnic University in cooperation with IEEE AP/MTT Societies, Penta Hotel, New York, October 22-24, 1990.

Invited Papers:

1. P.H. Pathak, "High Frequency EM Scattering by Non-Uniform Open Waveguide Cavities Containing an Interior Obstacle, " International Conference on Directions in EM Wave Modeling, Sponsored by WRI, Polytechnic University in cooperation with IEEE AP/MTT Societies, Penta Hotel, New York, October 22-24, 1990.
2. P.H. Pathak, "Analytical Prediction of EM Scattering by Complex Obstacles within Electrically Large Open Cavities," AGARD EPP Meeting, Ottawa, Canada, May 1991.

3. P.H. Pathak, R.C. Chou, R.J. Burkholder and R. Lee, "Progress and Future Directions in Cavity Scattering Research at the Ohio State University," Workshop on HF EM Modelling of Scattering by Jet Engine Cavities, Wright Patterson AFB, Dayton, Ohio, August 1991.

Theses/Dissertations:

Master's Thesis: P. Munk, "EM Scattering by a Dielectric Filled Rectangular Antenna Cavity Recessed in a Ground Plane and Backed with an Array of Rectangular Waveguide Fed Slots."

VI FINITE ELEMENT

Researcher: R. Lee, Ph.D (Phone: 614-292-1433)

1 Introduction

Due to the unexpected death of Jack Richmond, the research topics were changed during the latter six months of this year's contract. In these six months, the research has been in the area of finite element methods for electromagnetics. The two major problems that we considered are 1) the effect of discretization error on the finite element solution to the Helmholtz equation, and 2) the problem of electromagnetic scattering from a three-dimensional object in free space. The first problem is of considerable interest because the discretization error may cause us to rethink how we solve electrically large problems. The second topic has received a great deal of attention from researchers. Because very little progress has been made on the three-dimensional truncation problem for finite elements, we plan to concentrate our research in this area.

2 Discretization Error

In the past several years the use of the finite element method in electromagnetics has increased rapidly because of its versatility at handling very complex, arbitrary geometries. A primary consideration in any approximate numerical technique is the sources of potential errors in the solution. Without a good understanding of the causes of numerical error, one cannot have any confidence in the accuracy of their solution. In the finite element method, a major source of error is introduced by the spatial discretization of the problem domain into elements. Within each element, the behavior of the fields is described by a polynomial approximation. This approximation creates a numerical error, which we will henceforth refer to as the discretization error.

Currently, there is a widespread belief that the solution accuracy is dependent mainly on the nodal density per wavelength if we exclude geometrical considerations. The nodal density used to generate results in the literature is usually between 10 and 20 nodes/ λ where λ is the wavelength. To determine whether this belief is true, we characterize the discretization error by means of a dispersion analysis for a two-dimensional problem. From the dispersion analysis, we find that the error can be obtained analytically for the case of an infinite mesh. Several factors, excluding geometrical considerations, which affect discretization error are the electrical size of the mesh, the electrical size of the elements in the mesh, the order of the function used to approximate the fields in each element, the boundary conditions which is applied, and the type of field excitation.

The fact that the discretization error increases with the electrical size of the finite element mesh has serious implications with respect to the approximate radiation boundary conditions which is used by many researcher to truncate their mesh. The radiation boundary condition requires the mesh to extend a significant distance away from the geometry of interest in order to obtain an accurate solution. More rigorous truncation techniques, such as the hybrid FEM/integral equation technique or the bymoment method, allows for the use of a coarser mesh to obtain the same accuracy because the mesh can be truncated close to the geometry of interest.

The choice of the type of element used to approximate the fields in a mesh may significantly affect the accuracy of the solution. For example, the solution from a mesh composed of elements which use a quadratic polynomial approximation for the fields produces a much smaller error when compared to the solution generated from elements with a bilinear polynomial approximation for the fields. Thus, the use of quadratic elements is computationally more efficient than the use of bilinear elements.

The fact that the boundary condition affects the discretization error must also be considered in the choice of boundary conditions. In the past, the choice of boundary

truncation techniques depended on the computational efficiency and accuracy of the technique itself. From our study, it is now evident that we must also consider the effect of the boundary truncation technique on the discretization error.

3 3-D Electromagnetic Scattering

Over the past six months, we have been developing a scheme to handle the truncation of the finite element mesh around an arbitrary three dimensional object in free space for the purpose of electromagnetic scattering. The scheme is based on a bymoment method, which was developed by the principal investigator for the two dimensional case. Up to this point, the formulation is available on paper and has not been implemented on a computer. A description of the formulation is presented below.

4 Finite Element Solution

In the finite element solution of three-dimensional electromagnetic boundary value problems, a vector-variational expression must be considered which is weakly equivalent to the original source-free vector wave equation. The variational expression is derived from the method of weighted residuals in conjunction with vector identities involving differential operators. The vector variational expression for the magnetic field \bar{H} in a homogeneous, isotropic region is thus obtained as

$$\int_V \left[\frac{1}{j\omega\epsilon} (\nabla \times \bar{H}) \times \nabla \phi_i + j\omega\mu \bar{H} \phi_i \right] dv = - \oint_S (\hat{n} \times \bar{E}) \phi_i ds \quad (1)$$

where V is the portion of interest of the problem domain domain which is ultimately enclosed by the artificial boundary surface S , and \hat{n} denotes the outward normal unit vector on that surface, as shown in Figure 6. The parameters μ and ϵ denote the permeability and permittivity of the particular subregion of the problem domain under consideration, respectively. It must also be noted that it is assumed that the vector quantity $\hat{n} \times \bar{E}$, which is related to the tangential component of the electric field, is continuous across interelement boundaries inside the finite element mesh. The functions ϕ_i are chosen from a set of real weighting functions containing

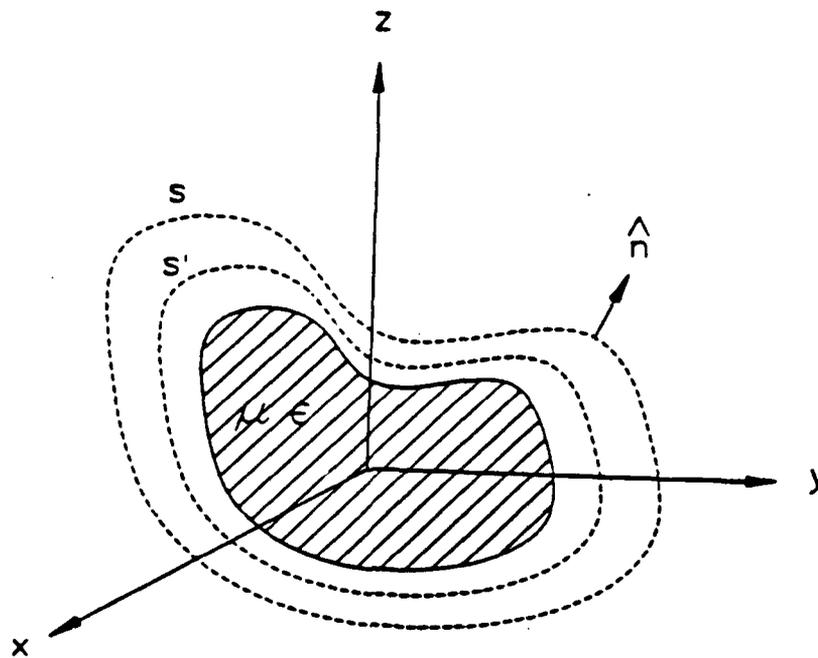


Figure 6: The scattering object and the two artificial boundary surface S and S' .

20 linearly independent quadratic polynomial functions of three cartesian variables. This choice is in accordance with the conventional Galerkin approach, in which the weighting functions and the shape functions are selected from the same set of functions.

However, the vector variational Equation (1) has the inherent numerical disadvantage that it results in non-physical spurious solutions for \bar{H} due to the fact that the fields in the interior region are expanded in terms of polynomial shape functions which are not divergenceless, whereas it is known that the physical fields must have zero divergences if the entire problem domain is free of radiating sources. Instead of trying to use a set of expansion functions which do not give rise to spurious modes, an additional term can be added to the variational expression (1) to enforce the condition that the magnetic field \bar{H} satisfy the divergence relation $\nabla \cdot (\mu \bar{H}) = 0$ in

the interior region. The new vector variational expression is thus given by

$$\begin{aligned} \int_V \left[\frac{1}{j\omega\epsilon} (\nabla \times \bar{H}) \times \nabla \phi_i + j\omega\mu\bar{H}\phi_i + \frac{1}{j\omega\mu\epsilon} \nabla \cdot (\mu\bar{H}) \nabla \phi_i \right] dv \\ = \oint_S \left[-(\hat{n} \times \bar{E}) \phi_i + \hat{n} \frac{1}{j\omega\mu\epsilon} \nabla \cdot (\mu\bar{H}) \phi_i \right] ds \end{aligned} \quad (2)$$

It must be noted at this point that the traditional "Penalty Method" has not been used in the above variational expression, since the added divergence term is clearly not weighted by an arbitrary positive real coefficient as it is the case in the penalty method. That positive real coefficient is implicitly chosen to be equal to one, which has been found to be the numerically most stable choice ensuring the highest degree of accuracy in the solution. Consequently, the vector variational expression (2) actually becomes weakly equivalent to the vector Helmholtz equation. It must also be noted that in this variational expression, it is assumed that both of the vector quantities $\hat{n} \times \bar{E}$ and $\nabla \cdot (\mu\bar{H})$ are continuous across interelement boundaries.

5 The Bymoment Method Approach

In the three-dimensional bymoment method, a finite set of linearly independent expansion functions defined in an unbounded region of free-space is used to express two z-directed Hertz vector potentials on the outer artificial boundary surface S where the finite element mesh is truncated. Two plausible choices for the expansion functions are the spherical harmonics and the solutions to a multipole expansion on the artificial surface S. The multipole expansion has reportedly been successfully applied in integral equation methods. In order to describe the proposed technique, the relevant steps are shown for the case where the expansion functions are spherical harmonics. For the special case in which the scattering object is a sphere, this choice clearly is the most natural one. The two Hertz vector potentials can consequently be written on the surface S as

$$\Pi_c = \sum_{n=0}^N \sum_{m=0}^n a_{mn}^{e,o} \psi_{mn}^{e,o} (k_0 \bar{R}) , \quad \Pi_m = \sum_{n=0}^N \sum_{m=0}^n b_{mn}^{e,o} \psi_{mn}^{e,o} (k_0 \bar{R})$$

$$\bar{\Pi}_e = \hat{z} \Pi_e, \quad \bar{\Pi}_m = \hat{z} \Pi_m, \quad k_0 = \omega \sqrt{\mu_0 \epsilon_0} \quad (3)$$

where $\{a_{mn}^{e,o}\}$ and $\{b_{mn}^{e,o}\}$ denote two sets of coefficients to be determined by the "coupling procedure" on the artificial boundary surface S' shown in Figure 6; μ_0 and ϵ_0 are the permeability and the permittivity of free-space, respectively; k_0 is the corresponding free-space wave number, and the spherical harmonics $\psi_{mn}^{e,o}(k_0 \bar{R})$ are given by

$$\psi_{mn}^{e,o}(k_0 \bar{R}) = h_n^{(2)}(k_0 r) P_n^m(\cos \theta) \{ \cos m\phi, \sin m\phi \} \quad (4)$$

In the above expressions, the superscripts "e" and "o" denote even and odd modes, respectively, while the $h_n^{(2)}$ functions represent the spherical Hankel functions of the second kind, which is in accordance with the $e^{+j\omega t}$ type time-harmonic dependence used throughout this proposal. The P_n^m functions are associated Legendre functions, and the angular variables θ, ϕ lie in the ranges $0 \leq \theta \leq \pi$ and $0 \leq \phi \leq 2\pi$, respectively. The radial variable r lies in the range $0 \leq r < \infty$, and the integer indices m, n are defined by $0 \leq n \leq N$ and $0 \leq m \leq n$, where the integer N controls the number of expansion functions.

Since the region exterior to the scattering object is assumed to be free-space, the electric and magnetic fields in this region can be derived from the electric and magnetic Hertz vector potentials in the following manner:

$$\begin{aligned} \bar{E} &= \nabla \times \nabla \times \bar{\Pi}_e - j\omega\mu_0 \nabla \times \bar{\Pi}_m \\ \bar{H} &= \nabla \times \nabla \times \bar{\Pi}_m + j\omega\epsilon_0 \nabla \times \bar{\Pi}_e \end{aligned} \quad (5)$$

The terms which appear in the surface integrals on the right-hand-side of the vector variational expression (2) can then be separated into electric and magnetic "parts" as a consequence of the principle of superposition, which is valid in all systems of linear equations. Furthermore, knowing that the divergence term $\nabla \cdot (\mu \bar{H})$ on the right-hand-side must vanish due to the fact that there are no magnetic monopole charges in nature, it is sufficient to concentrate on the $\hat{n} \times \bar{E}$ term which is related to the tangential component of the electric field on the artificial boundary surface S .

Together with the concept of electric and magnetic "parts", the expansion functions $\psi_{mn}^{e,o}(k_0 \bar{R})$ can be used directly in the formulation of the boundary conditions based on the $\hat{n} \times \bar{E}$ term by the following relations:

$$E_x = \frac{\partial}{\partial x} \frac{\partial}{\partial z} \psi_{mn}^{e,o}, \quad E_y = \frac{\partial}{\partial y} \frac{\partial}{\partial z} \psi_{mn}^{e,o}, \quad E_z = \left(\frac{\partial^2}{\partial z^2} + k_0^2 \right) \psi_{mn}^{e,o} \quad (6)$$

("Electric Part" : $\Pi_m = 0$)

$$E_x = -j\omega\mu_0 \frac{\partial}{\partial y} \psi_{mn}^{e,o}, \quad E_y = j\omega\mu_0 \frac{\partial}{\partial x} \psi_{mn}^{e,o}, \quad E_z = 0 \quad (7)$$

("Magnetic Part" : $\Pi_e = 0$)

where $\hat{n} = \hat{x}n_x + \hat{y}n_y + \hat{z}n_z$ is the outward normal unit vector on the artificial boundary surface S, and the integer subscripts m, n again lie in the ranges given by $0 \leq n \leq N$, $0 \leq m \leq n$, and N is the particular integer that controls the total number of expansion functions and boundary conditions.

Once the finite element solution of the variational expression (2) is obtained for each of the electric and magnetic boundary conditions with the indices m, n (for both even and odd modes), the total solutions for the \bar{H} field can again be constructed by means of the principle of superposition. Clearly, the same two sets $\{a_{mn}^{e,o}\}$ and $\{b_{mn}^{e,o}\}$ of undetermined coefficients associated with the two Hertz potential functions will appear in the finite element solution of the \bar{H} field:

$$\bar{H} = \sum_{n=0}^N \sum_{m=0}^n \left[a_{mn}^{e,o} \bar{\Lambda}_{mn}^{(E)} + b_{mn}^{e,o} \bar{\Lambda}_{mn}^{(M)} \right] \quad (8)$$

where ${}^{e,o}\bar{\Lambda}_{mn}^{(E)}$ and ${}^{e,o}\bar{\Lambda}_{mn}^{(M)}$ denote the electric and magnetic finite element vector solutions, respectively, corresponding to the even or the odd boundary condition of the pair of integer indices m, n.

To evaluate the unknown sets of coefficients $\{a_{mn}^{e,o}\}$, $\{b_{mn}^{e,o}\}$ (for the above specified ranges of the integers m and n, and "e" and "o" denoting even and odd modes), the interior and exterior vector solutions for the \bar{H} field must be coupled on the second artificial boundary surface S' which is completely encapsulated by the surface

S, as shown in Figure 6. The formulation for the "coupling procedure" is based on the fact that since the surface S' lies outside the scattering object in an unbounded region of free-space, the two Hertz potential functions have to satisfy the free-space scalar Helmholtz equation in the absence of impressed sources in the problem domain in conjunction with two Lorentz-Gauge type relations. To accomplish the "coupling procedure", the total magnetic field must be separated into its known incident and unknown scattered parts, the latter of which also satisfies the Helmholtz equation in free-space, again with no impressed sources present in the problem domain. Finally, a set of linearly independent testing functions Φ_j which satisfy both the free-space scalar Helmholtz and the radiation condition at infinity must be introduced on the artificial boundary surface S' . Clearly, in the special case where the scattering object is a sphere, the most natural choice for the testing functions is the same set of spherical harmonics used above to expand the two Hertz vector potentials. In that case, one can set $\Phi_j = \psi_{kl}^{e,o} = \Phi_{kl}^{e,o}$, where the integer subscripts k, l lie in the ranges given by $0 \leq l \leq N$, $0 \leq k \leq l$, the superscripts "e" and "o" denote even and odd modes, respectively, and N is the particular integer which controls the total number of testing functions. By applying a scalar version of Green's theorem on the three cartesian components of the finite element solution for the \bar{H} field and the testing functions Φ_j , and then subtracting the two resulting identities, the following two systems of linearly independent equations are obtained:

$$\begin{aligned}
& \sum_{n=0}^N \sum_{m=0}^n a_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon,o \Lambda_{mn}^{(E)x}}{\partial n} - \epsilon,o \Lambda_{mn}^{(E)x} \frac{\partial \Phi_j}{\partial n} \right] ds \\
& + \sum_{n=0}^N \sum_{m=0}^n b_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon,o \Lambda_{mn}^{(M)x}}{\partial n} - \epsilon,o \Lambda_{mn}^{(M)x} \frac{\partial \Phi_j}{\partial n} \right] ds \\
& + \sum_{n=0}^N \sum_{m=0}^n b_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon,o \Lambda_{mn}^{(M)z}}{\partial n} - \epsilon,o \Lambda_{mn}^{(M)z} \frac{\partial \Phi_j}{\partial n} \right] ds \\
= & \int_{S'} \left[\Phi_j \frac{\partial H_x^i}{\partial n} - H_x^i \frac{\partial \Phi_j}{\partial n} \right] ds + \int_{S'} \left[\Phi_j \frac{\partial H_z^i}{\partial n} - H_z^i \frac{\partial \Phi_j}{\partial n} \right] ds \quad (9) \\
& \sum_{n=0}^N \sum_{m=0}^n a_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon,o \Lambda_{mn}^{(E)y}}{\partial n} - \epsilon,o \Lambda_{mn}^{(E)y} \frac{\partial \Phi_j}{\partial n} \right] ds
\end{aligned}$$

$$\begin{aligned}
& + \sum_{n=0}^N \sum_{m=0}^n b_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon_{,o} \Lambda_{mn}^{(M)y}}{\partial n} - \epsilon_{,o} \Lambda_{mn}^{(M)y} \frac{\partial \Phi_j}{\partial n} \right] ds \\
& + \sum_{n=0}^N \sum_{m=0}^n b_{mn}^{e,o} \int_{S'} \left[\Phi_j \frac{\partial \epsilon_{,o} \Lambda_{mn}^{(M)z}}{\partial n} - \epsilon_{,o} \Lambda_{mn}^{(M)z} \frac{\partial \Phi_j}{\partial n} \right] ds \\
= & \int_{S'} \left[\Phi_j \frac{\partial H_y^i}{\partial n} - H_y^i \frac{\partial \Phi_j}{\partial n} \right] ds + \int_{S'} \left[\Phi_j \frac{\partial H_z^i}{\partial n} - H_z^i \frac{\partial \Phi_j}{\partial n} \right] ds \quad (10)
\end{aligned}$$

where the superscripts "i" denote the known incident parts of the three cartesian components of the \bar{H} field, as indicated by the superscripts "x", "y", and "z". At this point, it must be noted that the first system of equations involves the x and z components of the magnetic field, while the second system of equations involves the y and z components of it. Thus, it is ensured that even if one of the three cartesian components of \bar{H} becomes zero over certain portions of the artificial boundary surface S' , the system of equations still remains non-trivial.

It is clear that once the two sets of coefficients $\{a_{mn}^{e,o}\}$ and $\{b_{mn}^{e,o}\}$ are determined as a result of the above outlined "coupling procedure", the finite element solution for the two Hertz vector potentials and the total magnetic field \bar{H} by means of the three-dimensional bymoment method approach has been successfully completed.

6 List of Papers - JSEP Finite Element Studies

Journal Publication Submitted

1. R. Lee and A.C. Cangellaris "A Study of Discretization Error in the Finite Element Approximation of Wave Solutions," submitted to *IEEE Transactions Antennas and Propagation*.

Conference Presentation

1. R. Lee, "A Study of Discretization Error in the Finite Element Method," 1991 International URSI Meeting, London, Ontario, Canada.

VII ARRAY STUDIES

Researchers:

R. T. Compton, Jr., Professor (Phone: 614-292-5048)

1 Introduction

During the past year, research has continued on the use of array signal processing to achieve high throughput in packet radio networks.

In conventional packet radio communication systems, it is assumed that a packet radio terminal can receive only one packet at a time [1]. When two incoming packets overlap in time, both packets are destroyed¹. Such collisions are the main factor limiting the average throughput and increasing the average delay at a packet terminal. When two packets collide, there is no throughput and the packets must be retransmitted after a random delay.

The purpose of the current research is to overcome this limitation. Under JSEP, we previously studied the use of adaptive antennas as a means of improving throughput in packet radio systems. We showed that a multiple-beam adaptive array (MBAA) could produce large increases in throughput and reductions in delay in a packet system [7, 8, 9].

An MBAA is an adaptive array in which several output signals are formed simultaneously from the same set of antenna elements. Each output signal is obtained by using a different set of weights to combine the element signals and therefore has a different array pattern. By forming multiple patterns, each with a beam on one packet and nulls on the others, it is possible to receive several packets simultaneously without collisions. The resulting system operates with much higher throughputs and smaller delays than a conventional packet system.

¹In some systems, a *capture* effect may occur [2, 3, 4, 5, 6]. Capture allows one packet to be received even if interfering packets are present. Capture can occur, for example, when different packets have different powers. However, even with capture, a conventional packet receiver can still receive only one packet at a time.

In addition to separating packets from different angles, an MBAA using cross-polarized elements can also separate packets with different electromagnetic *polarizations*. In a network using MBAA's, this capability could be used to allow terminals to transmit two packets simultaneously in the same slot on orthogonal polarizations. The two signals with different polarizations would not interfere if the MBAA's at the receiving terminals can separate them. Transmitting two packets simultaneously per slot will yield an additional increase in throughput and reduction in delay.

When MBAA's are used in a packet system, packets are received and demodulated in real time. To permit rapid adaptation of the array patterns, two changes are made to the packet protocol. First, a preamble is added to the beginning of every packet [7, 8, 9]. The array patterns are adapted during this preamble, before the message portion of the packet begins. Second, the slot length is made longer than the packet length by an *uncertainty interval*. The start times of individual packets are randomized over this uncertainty interval. These changes are necessary to receive packets in real time.

During the past year, we have considered an alternative method of array processing, other than MBAA's, for improving packet radio network performance. It became apparent that a further improvement in performance could be obtained by relaxing the requirement for real time reception of the packets. In this new method, instead of demodulating the packets in real time, the signals on the array elements are sampled and stored in memory. From the stored samples, the number of packets arriving in each slot and their arrival angles are estimated. A weight vector is then calculated for each incoming packet to produce a beam maximum on that packet and nulls on all other packets. By applying these weight vectors to the stored element signals, several array output signals can be produced, each containing only one packet. In this way, every packet incident on the array can be received.

This approach has two advantages over an MBAA. It avoids the need for an uncertainty interval, and it eliminates the need for a packet preamble. The result is

that less of the channel resource is used for overhead. Hence, this approach gives a higher channel efficiency as measured in information bits per slot.

The disadvantage of this approach is that it introduces a fixed delay into the channel, i.e., the delay required to store the samples, do the angle estimation, calculate the weights, and combine the element signals. However, this delay does not depend on traffic conditions in the network, and it is much smaller than the delay introduced by collisions in a conventional packet system with heavy traffic. Thus, the net result is to *reduce* the overall delay in the network.

The JSEP research described below was motivated by this idea. Most of the research during the past year involved the problem of angle estimation with arrays. Although several well-known techniques are available for angle estimation with arrays [10], the packet radio application described above raised several new issues in angle estimation.

First, since the previous MBAA technique [7, 8] included a preamble on the packets, the question arose whether there is an advantage to using a preamble for angle estimation. The presence of a fixed preamble means that the packet waveform would be known during the preamble. Since estimators usually provide better estimates the more is known about the signal, it was of interest to determine how much a known packet waveform improves the angle estimates. Our work on this question is summarized below in Section 2.

Second, the question arose whether it would be possible to estimate the electromagnetic polarizations of signals along with their arrival angles. This issue is important for the packet radio network problem because, if polarizations can be estimated, then it is possible for terminals in a network to transmit two packets simultaneously per slot *on orthogonal polarizations*. Doing so would nearly double the throughput capability of a network. Further discussion of this technique and our work on this topic are described in Section 3.

2 Angle Estimation with Known Waveforms

To determine whether there is an advantage to using a preamble on the packets, we studied the performance of Maximum Likelihood (ML) estimators for signals with known and unknown waveforms. The advantage of ML estimation is that when a minimum variance estimator exists, it is the ML estimator. The disadvantage is that ML estimation usually requires a search over a multidimensional parameter space. However, the practicality of the estimators was of less interest here than their error performance.

During the year, we have written three papers dealing with ML angle estimation for signals with known waveforms [11, 12, 13]. First, in [11], we formulated the ML angle estimator for the simple case where one signal with a known waveform is incident on the array. (For this case, the ML estimate can be obtained by solving for the roots of a polynomial.) We showed that the ML estimator for a signal with known waveform consists of a matched filter behind each element (matched to the known waveform), followed by an angle estimator. We compared the error performance of ML estimators for a signal with known and unknown waveforms and showed that a known waveform results in an improvement of about 5 dB in the error variance.

Next, in [12], we formulated the ML estimator for the case where one signal is incident on the array with a known waveform and several interfering signals are also incident with unknown waveforms. (This situation occurs in an unslotted packet system, where packets can arrive at any time.) With multiple signals present, the solution for the ML estimates is more complicated than for a single signal, of course. However, to avoid the need for a computationally expensive multidimensional search, an algorithm was presented that combines the merits of the IQML (Iterative Quadratic ML) approach of Bresler and Macovski [14, 15] with the Alternating Maximization approach of Ziskind and Wax [16]. This algorithm transforms the multidimensional search problem into an iterative one-dimensional search problem. The performance of this estimator was compared with one that first uses the IQML estimator to es-

timate all the signal angles and then determines which signal is the desired one by correlating with the known waveform. The performance of these estimators was also compared with the Cramer-Rao (CR) bounds. We showed that a known signal waveform results in a smaller estimation error variance only when the angles of an interfering signal and the signal with the known waveform are close. Otherwise, a known waveform improves performance only if the desired signal carrier phase angle is known, an unlikely situation in practice.

Finally, in [13], we considered the ML estimator for the case where several signals with known waveform are incident on the array. (This situation occurs in a slotted packet system with known preambles on the packets.) For this case two computationally efficient, iterative algorithms for calculating the estimates were presented. One is based on the Alternating Maximization (AM) approach of Ziskind and Wax [16] and the other on the Estimate Maximize (EM) approach of Feder and Weinstein [17]. Our approaches differ from the AM algorithm and the EM algorithm, however, in that we considered a uniform linear array of elements and obtained the angle estimates by finding polynomial roots rather than by searching over parameter space. We compared the performance of these two estimators with each other and with that of a suboptimal estimator that first estimates the angles without using the signal waveforms (the IQML estimator [14]) and then determines which angle estimate corresponds to which waveform. The performance of these estimators was also compared with the CR bounds.

When all signals have known waveforms, the results are similar to those with one known waveform signal and several unknown waveform signals. A known waveform improves the performance only when the carrier phase angles of the signals are known. Since this would rarely be the case in a practical situation, there appears to be little advantage to including a preamble on the packets.

3 Estimation of Packet Angles and Polarization

The second work area in array signal processing involved the problem of estimating the electromagnetic polarizations of incoming signals along with their arrival angles. As mentioned above, the motivation for this problem is the possibility of using polarization diversity by transmitting two packets simultaneously on orthogonal polarizations in one slot. If the polarizations of packets arriving at a terminal can be estimated along with their directions, then it is possible for one terminal in a network to transmit two packets simultaneously on orthogonal polarizations in the same slot. The two packets can be destined for two different receiving terminals in the network or for the same receiving terminal. In either case, both transmitted polarizations are received by all terminals within range of the transmitting terminal. Since the polarizations of the packets will usually become altered between the transmitter and the receiver because of reflections and other imperfections in the transmission path, the incoming signal polarizations must be estimated at each receiving terminal.¹ Once the polarizations have been estimated, then two weight vectors for combining the element signals can be calculated and used with the sampled element signals to receive both of the packets without interference. Each weight vector receives one of the packets and nulls the other. This technique should nearly double the average throughput of a packet network, especially at high traffic levels.

Aside from this packet radio network application, polarization estimation techniques should also be useful in several other fields, such as in signal intercept problems and for compact range diagnostics [18].

Very little work has been done previously on the problem of estimating signal polarization. In [19], Schmidt used polarization differences of signals to improve their angle estimates. Ferrara and Parks [20] presented a method for incorporating signal

¹In most cases, the two polarizations will no longer be orthogonal at the receiving terminal, but they will still be different. Occasionally, however, two packets transmitted on orthogonal polarizations may even arrive at the receiving terminal with the same polarization. In this case the situation is similar to a packet collision in a conventional packet radio network. The probability of this case is taken into account in a statistical throughput analysis of the network.

polarization in Capon's minimum variance estimator [21], in the angular response spectrum of Borgiotti and Kaplan [22], and in the MUSIC spectrum of Schmidt [19, 23]. Also, Ziskind and Wax [24] used the Simulated Annealing technique of Kirkpatrick *et al.* [25] to find maximum likelihood estimates of signal polarizations and arrival angles.

However, none of these techniques is very practical for the application envisioned here. With the MUSIC algorithm, for example, the dimensionality of the parameter search becomes much too high to be practical. (E.g., with 3 signals, a search over 12 parameters is required: two spatial angles and two polarization angles for each signal.) The method in [24] could be used in principle, but simulated annealing is extremely slow to converge. Our goal was to find a more direct method than either of these techniques.

We have developed several methods of estimating polarization along with arrival angles, mostly based on the ESPRIT algorithm [26]. We have written four papers in this area [27, 28, 29, 30].

First, in [27] we studied the problem of estimating polarizations and directions for the case where the signal direction is specified by one spatial angle. We considered an linear array consisting of N pairs of cross-polarized elements, as shown in Figure 7. We showed how the ESPRIT algorithm [26] could be used with this array to estimate the polarization of each incoming signal along with its arrival angle. Combined polarization and angle estimates were obtained by exploiting several invariance properties of the cross-polarized elements.¹

Figure 8 shows a typical result from [27]. It shows the variance in dB (relative to 1 degree squared) of the direction and polarization estimates for a linearly polarized signal incident from elevation angles $\theta = 10^\circ, 30^\circ, 50^\circ$ and 70° . The variances are shown as functions of β , the orientation angle of the linear polarization. The polarization angle has little effect on either the direction or polarization estimates

¹In this work, the incoming signals were assumed to be completely polarized. I.e., they were not *partially* polarized [31].

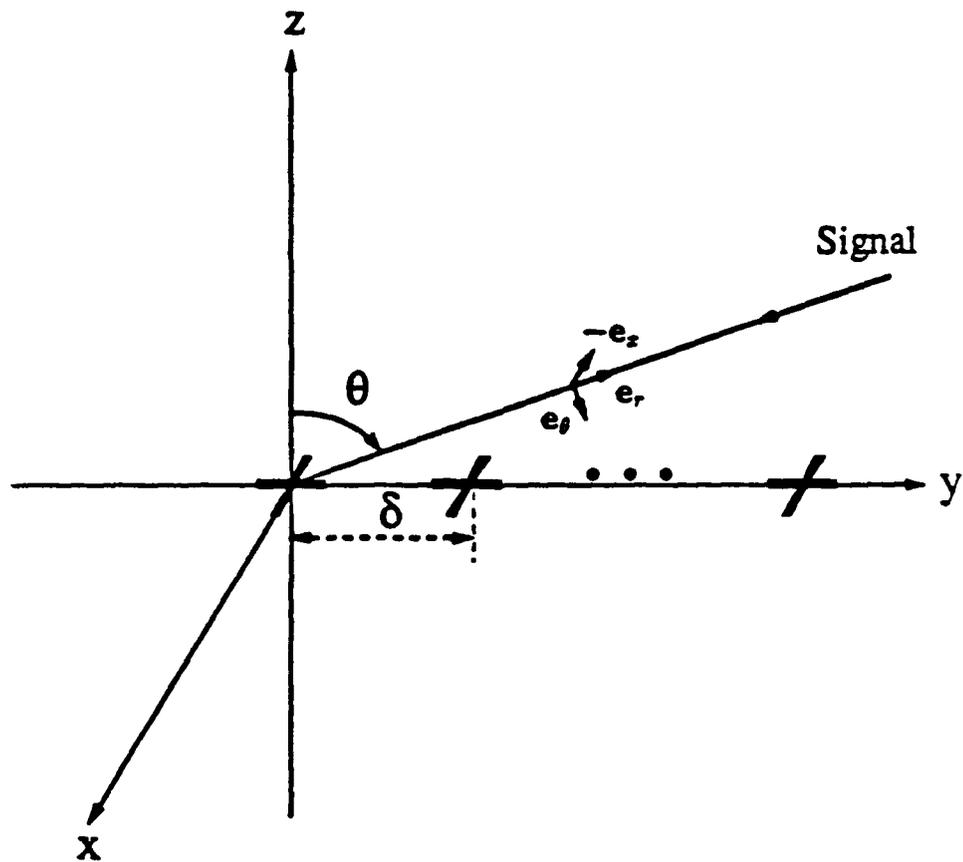


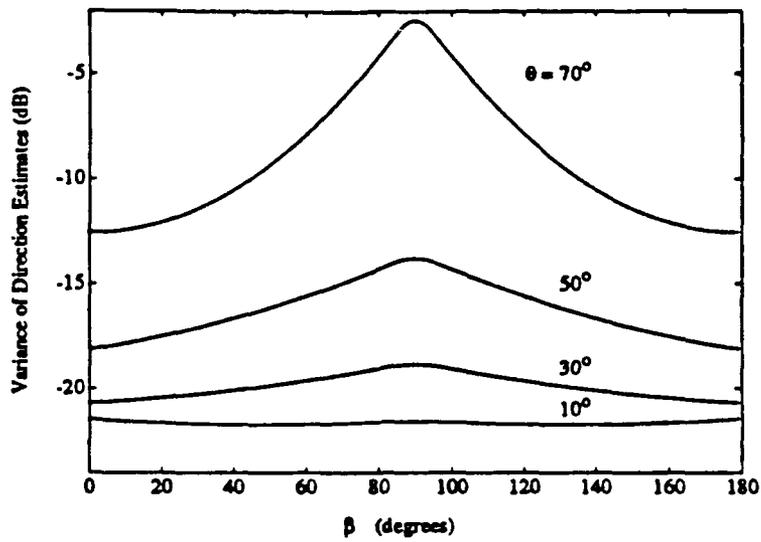
Figure 7: A uniform linear array of crossed dipoles

when θ is small, but it has a larger effect when θ is large. Figure 9 shows the error variances for a different case, when the incident signal is elliptically polarized with ellipticity angle α . Further discussion of these results may be found in [27].

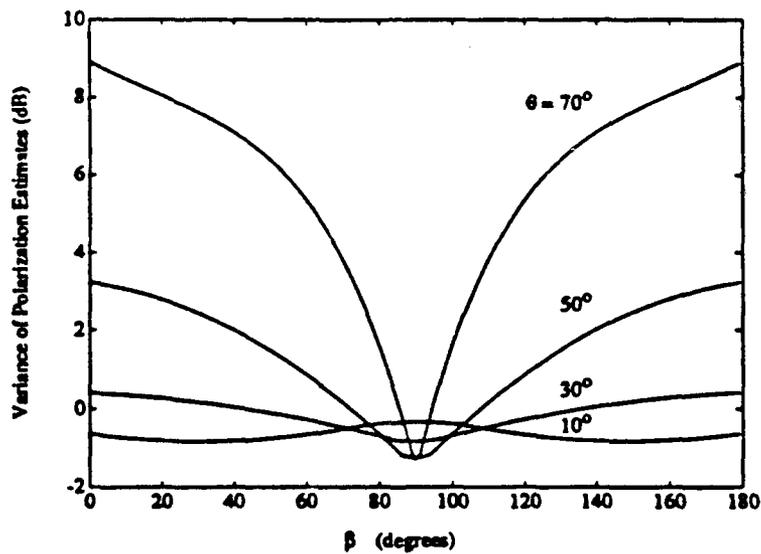
Next, in [28], we showed how angle estimation could be done with an array of cross-polarized elements in such a way that the signal polarization does not affect the angle estimation process. For this problem, it was assumed that estimating the signal polarizations was not of interest. Rather, the goal was to obtain an estimator that works properly regardless of signal polarization. We showed how an array of cross-polarized elements that respond to any signal polarization could be used for this purpose [28].

Next, in [29], we extended the angle and polarization estimation technique of [27] to the case where one or more of the incoming signals are completely coherent. (The standard ESPRIT method breaks down with coherent signals.) When two or more signals are coherent, subarray averaging [32, 33] must be used to restore the rank of the covariance matrix required in the ESPRIT estimator. It was shown in [29] how subarray averaging may be applied to the problem of estimating signal polarizations as well as angle arrivals.

Finally, in [30], we have also presented a method for using the ESPRIT algorithm with a two-dimensional array of cross-polarized dipoles to estimate signal arrival angles and polarizations when the signal directions are specified by two spatial angles. Figure 10 shows the two-dimensional array of cross-polarized elements used. Each signal direction is specified by two angles θ and ϕ , as shown in Figure 10. By exploiting several invariance properties of this array, we showed how to use ESPRIT to estimate the two spatial angles and both polarization parameters for each signal incident on the array. Figure 11, 12, and 13 show typical performance results with this estimation technique. First, Figure 11 shows the variance of the direction and polarization estimates in dB (relative to 1 degree squared) for the case of a linearly polarized signal arriving from $\phi = 0^\circ$ with $\theta = 10^\circ, 30^\circ, 50^\circ$ or 70° . The estimate

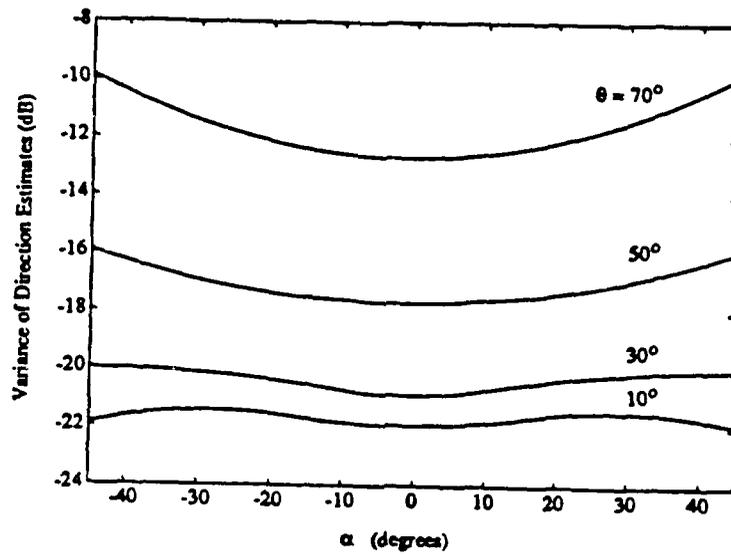


(a) Variance of direction estimates.

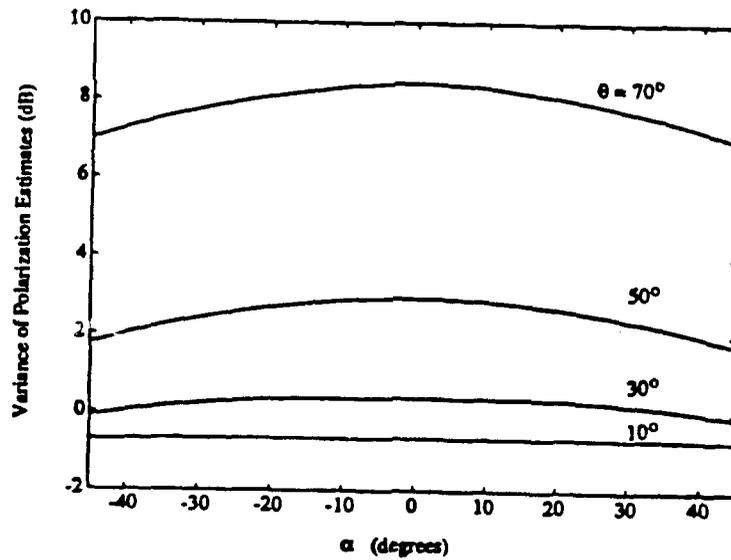


(b) Variance of polarization estimates.

Figure 8: Variance of estimates versus orientation angle β for a linearly polarized signal



(a) Variance of direction estimates.



(b) Variance of polarization estimates.

Figure 9: Variance of estimates versus ellipticity α for an elliptically polarized signal.

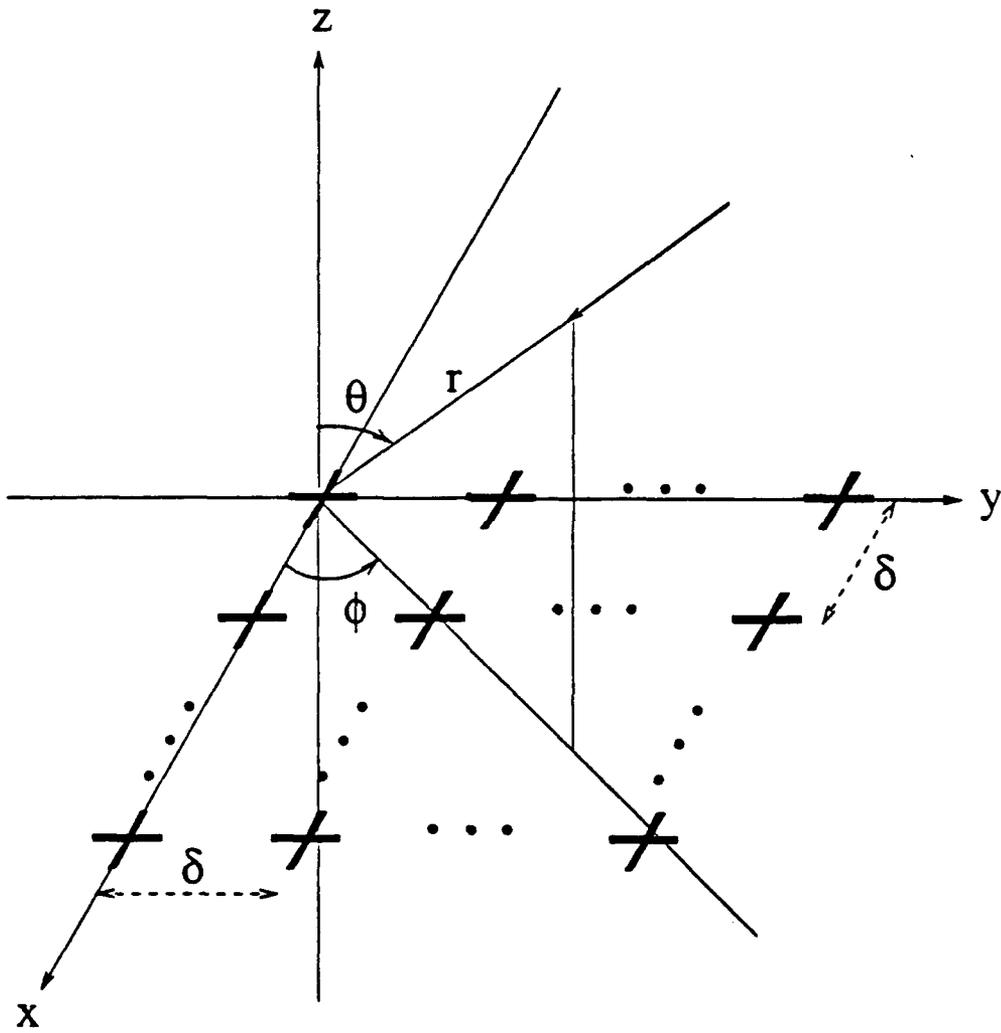


Figure 10: Two-dimensional crossed dipole array

variances are shown as functions of β , the orientation angle of the linear polarization. These curves are for a 20 dB signal-to-noise ratio (SNR) and 31 data snapshots from the array aperture.

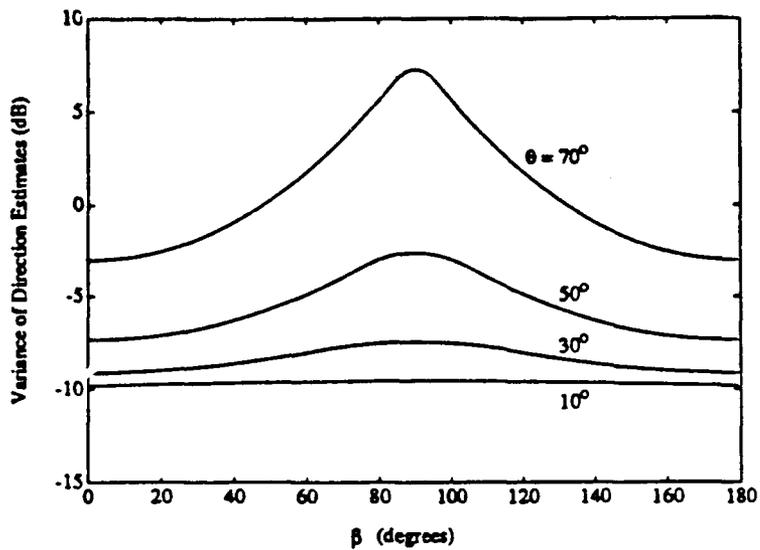
Next, Figure 12 shows an example of how the direction and polarization error variances are affected by the SNR of the signal. These curves are for a circularly polarized signal incident from $\phi = 90^\circ$ and from the same four values of θ as in Figure 11 and with 31 snapshots.

Finally, Figure 13 shows how these variances depend on the number of snapshots.

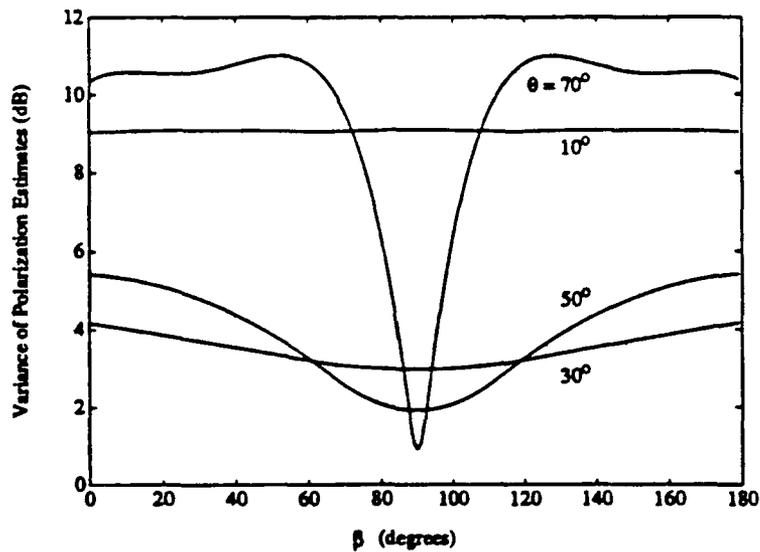
4 Future Work

Our work on polarization estimation is not yet completed. For the packet radio application of interest here, it is necessary to estimate the polarizations of two uncorrelated packets that arrive *from the same angle*. When one terminal transmits two packets in the same slots, every other terminal within range will receive both packets from the same direction. However, the estimators described in [27, 28, 29, 30] do not handle the case of two noncoherent signals with different polarization from the same direction. Hence, this problem will be the first goal for the coming year.

In addition, we plan to determine the throughput and delay characteristics for a network based on angle estimation techniques. We will consider and compare two cases: with and without the use of polarization diversity.

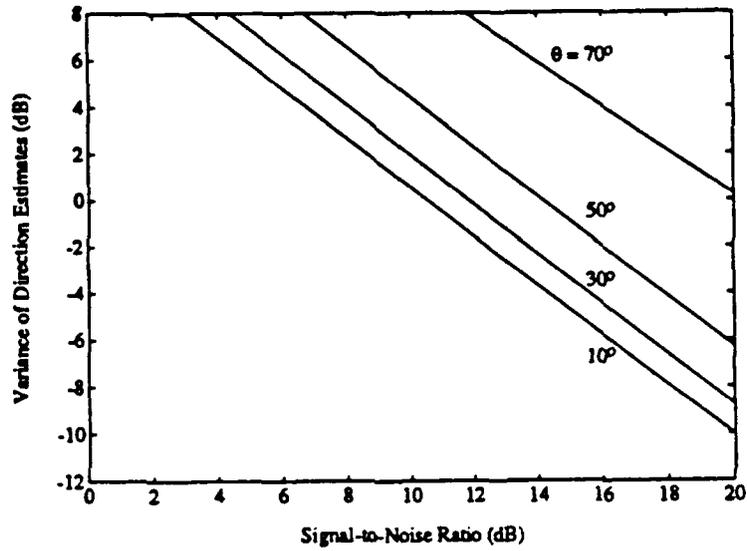


(a) Variance of direction estimates.

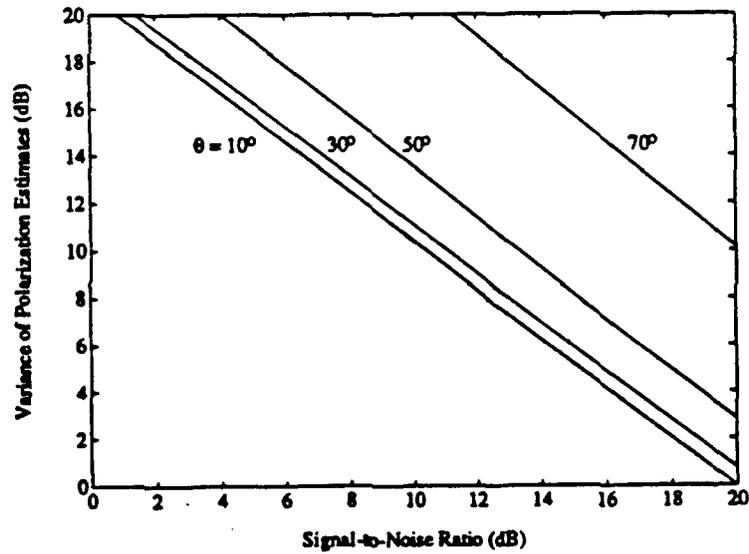


(b) Variance of polarization estimates.

Figure 11: Variance of estimates vs. β for a linearly polarized signal ($\phi = 0^\circ$, SNR=20 dB, 31 snapshots).

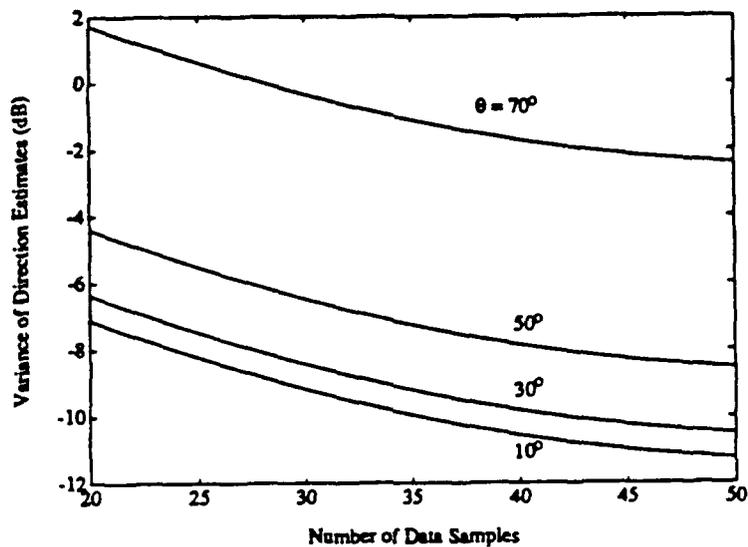


(a) Variance of direction estimates.

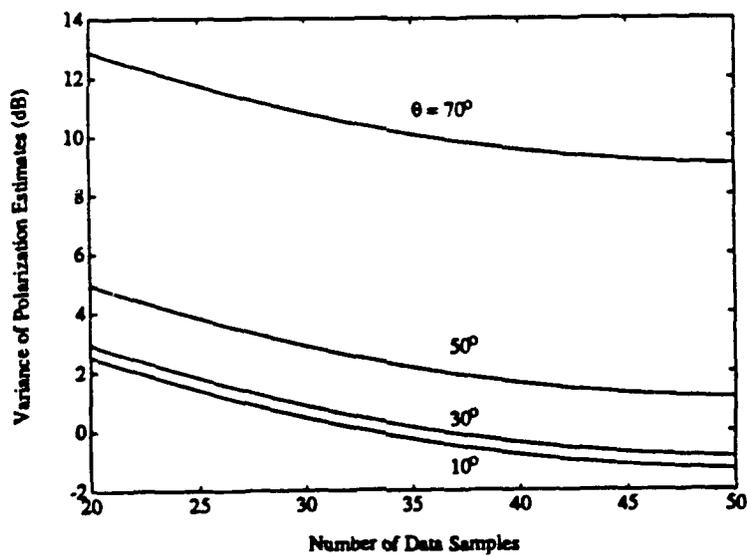


(b) Variance of polarization estimates.

Figure 12: Variance of estimates vs. SNR for a circularly polarized signal ($\phi = 90^\circ$, 31 snapshots).



(a) Variance of direction estimates.



(b) Variance of polarization estimates.

Figure 13: Variance of estimates vs. the number of snapshots for a circularly polarized signal ($\phi = 90^\circ$, SNR=20 dB).

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5 Array Studies - JSEP Publications

Published:

1. C.A. Olen and R.T. Compton, Jr., "A Numerical Pattern Synthesis Algorithm for Arrays," *IEEE Transactions on Antennas and Propagation*, AP-38(10), pp. 1666-1676, October 1990.
2. J.W. Ward and R.T. Compton, Jr., "Sidelobe Level Performance of Adaptive Sidelobe Canceller Arrays with Element Reuse," *IEEE Transactions on Antennas and Propagation*, AP-38(10), pp. 1684-1693, October 1990.
3. J. Li and R. T. Compton, Jr., "Angle and Polarization Estimation using ESPRIT with a Polarization Sensitive Array," *IEEE Transactions on Antennas and Propagation*, AP-39(9), pp. 1376-1383, September 1991.

Accepted:

1. J. Li and R. T. Compton, Jr., "Angle Estimation using a Polarization Sensitive Array," to appear in *IEEE Transactions on Antennas and Propagation*, AP-39(10), October 1991.
2. J. Ward and R. T. Compton, Jr., "Improving the Performance of a Slotted ALOHA Packet Radio Networks with an Adaptive Arrays," To appear in *IEEE Transactions on Communications*, February 1992.
3. J. Ward and R. T. Compton, Jr., "High Throughput Slotted ALOHA Packet Radio Networks with Adaptive Arrays," To appear in *IEEE Transactions on Communications*.

Submitted:

1. J. Li and R. T. Compton, Jr., "Angle and Polarization Estimation in a Coherent Signal Environment," Submitted to *IEEE Transactions on Aerospace and Electronic Systems*.
2. J. Li and R. T. Compton, Jr., "Two-Dimensional Angle and Polarization Estimation using the ESPRIT Algorithm," Submitted to *IEEE Transactions on Antennas and Propagation*.
3. J. Li and R. T. Compton, Jr. "Maximum Likelihood Estimation of the Arrival Direction of a Signal with Known Waveform," Submitted to *IEEE Transactions on Signal Processing*.
4. J. Li and R. T. Compton, Jr., "Maximum Likelihood Angle Estimation for a Signal with known Waveform in the Presence of Interfering Signals," Submitted to *IEEE Transactions on Signal Processing*.

5. J. Li and R. T. Compton, Jr., "Maximum Likelihood Angle Estimation for Signals with known Waveforms," Submitted to *IEEE Transactions on Signal Processing*.

In Preparation:

1. J. Ward and R. T. Compton, Jr., "High Throughput Unslotted ALOHA Packet Radio with an Adaptive Array," In preparation.