# 1989 URSI
# RADIO SCIENCE MEETING

International Union of Radio Science

# PROGRAM AND ABSTRACTS

JUNE 26-30, 1989

San Jose, CA

# TECHNICAL PROGRAM SUMMARY

8:15 AM – 12:00 Noon

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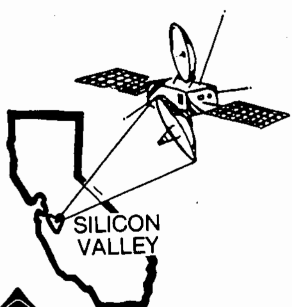
NATIONAL ACADEMIES OF SCIENCE AND ENGINEERING
NATIONAL RESEARCH COUNCIL
OF THE
UNITED STATES

1989
RADIO SCIENCE MEETING

# PROGRAM AND ABSTRACTS

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SAN JOSE, CA
JUNE 26-30, 1989

## - *A SPECIAL ACKNOWLEDGEMENT* -

**Special acknowledgments and thanks are due to the entire technical program committee; in particular, Dr. Walter Gee, Dr. Charles Hung, Dr. Peter Lam and Dr. Scott Ray for their extraordinary effort and enormous time spent in the preparation of the technical program and the digests.**

**A special thanks and recognition are also extended to the review committee members' employers and/or organizations for the use of their time, communications equipment, and facilities in support of the IEEE Antennas and Propagation Society and the URSI activities. These organizations are:**

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## Monday All Day

Joint AP-S, URSI-B Invited Poster Session 1

**Electromagnetic Theory**

*Chairs*: R. W. Ziolkowski, LLNL; C. M. Butler, Clemson Univ.

*Room*: Donner Pass *Posters Displayed*: 9:30–4:00

*Authors Available*: 2:40–4:00

# A NEW INTEGRAL REPRESENTATION OF THE MICROSTRIP GREEN'S FUNCTION FOR ELECTRICALLY LARGE COATED CYLINDERS

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The study of alternative representations of the surface Green's function for an electrically large coated circular cylinder is a problem of interest, not only for its application to the analysis of conformal microstrip antennas, but also as a canonical problem useful towards the development of asymptotic solutions valid for any smooth convex coated surface. It is well known that for an arbitrarily oriented electric dipole on the substrate, the surface fields can be expressed in terms of a Fourier series in the azimuthal $\phi$-domain and a Fourier integral on the longitudinal $(z)$ coordinate. It is also well known that due to the slow convergence of the Fourier series for electrically large cylinders, a Watson transformation allows one to "switch" to a series of double spectral integrals, whose asymptotic evaluation yields a rapidly convergent creeping wave modal representation of the fields on the surface of the coated cylinder. However, the propagation constants of these creeping wave modes must be found from the solution to a rather complicated transcendental equation involving complex orders of cylindrical functions. As an alternative to these representations for electrically large cylinders, a new representation for the Green's function is developed as follows. First, the spectral integrals resulting from the Watson transformation are expressed in terms of polar coordinates in both the spatial $(s, \alpha)$ and spectral $(r, \theta)$ domains. Second, the $\theta$-variation in the spectral integrands is accurately approximated by simple analytical functions, which allows the integrals in this variable to be evaluated in closed form. The result is the surface fields expressed in terms of Sommerfeld-type integrals in $r$. Thus, when the radius of the cylinder is very large, this representation reduces uniformly to the conventional Sommerfeld representation for the grounded dielectric slab. Numerical examples comparing the new representation with the conventional eigenfunction solution will be presented and discussed.

# A WIDE RANGE TUNABLE MW FILTER USING DOUBLE DIELECTRIC RESONATOR

Khosro Shamsaifar

Telettra España, Grafito 20, Torrejón (Madrid), SPAIN

The design of a bandpass dielectric resonator filter is presented. The filter is composed of several cylindrical cavities, each filled partially with a pair of identical dielectric resonators. In this configuration, known as double resonator, two halves of the high dielectric constant disk or plate, act as one resonator. Each cavity also contains a dielectric support as well as a tuning screw. The mutual coupling between two cavities is obtained through a small iris in their common wall.

Tuning of the resonant frequency is obtained by varying the separation between the two dielectric resonators in each cavity. It is shown that this structure provides a better tuning system compared to metal or dielectric screws, in the sense that it allows an over 20% tuning capability, while produces almost no degradation in the unloaded Q. A computer program is developed that provides the electromagnetic field distributions, as well as the stored energy, in different sections of the cavity (dielectric resonator, dielectric support, tuning screw, etc.). It is based on the variational method and determines the resonant frequency of the dielectric resonator with better that 1 percent accuracy for the $TE_{01\delta}$ mode.

The use of several cavities coupled through small irises, as has been suggested by Telettra, has the advantage, over direct coupling between the dielectric resonators placed in a waveguide below cutoff, of improving the out-of-band spurious response. Also, it has the great practical advantage of obtaining different bandwidths by changing the diameter of the irises instead of changing the distance between adjacent dielectric resonators. In fact, for a reasonably wide range of resonant frequencies, the same metallic housing can be used and only the dimensions of the dielectic resonator may be modified to obtain different frequency bands.

Duplexers containing receive-transmit bandpass filters have been designed with this structure with the advantage of using the same metallic housing for both receive and transmit filters. Also, because of a wide range of tuning capacity, in many practical applications, identical dielectic resonators can be used for both filters.

# ON THE SPHEROIDAL VECTOR WAVE FUNCTION EXPANSIONS OF ELECTROMAGNETIC FIELD

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In literature, for obtaining solutions to electromagnetic scattering and radiation problems involving spheroids the E- and H- fields are expanded as series of multipoles in terms of basically two types of quasi orthogonal spheroidal vector wave functions. These are Mie type of vector wave functins $[\vec{M}^{r(i)}_{mn}(h,\xi,\eta,\phi) = \nabla\phi^{(i)}_{mn}(h,\xi,\eta,\phi) \times \vec{r}$, $\vec{N}^{r(i)}_{mn}(h,\xi,\eta,\phi) = \frac{1}{k}\nabla\times\vec{M}^{r(i)}_{mn}(h,\xi,\eta,\phi)$, $\phi^{(i)}_{mn}(h,\xi,\eta,\phi) = S_{mn}(h,\eta)\, R^{(i)}_{mn}(h,\xi)\, e^{jm\phi}$, $i=1, 4(\text{or } 3)]$ and the Cartesian type of vector wave functions $[\vec{M}^{x,y,z(i)}_{mn}(h,\xi,\eta,\phi) = \nabla\phi^{(i)}_{mn}(h,\xi,\eta,\phi) \times (x,y,z)$, $\vec{N}^{x,y,z(i)}_{mn}(h,\xi,\eta,\phi) = \frac{1}{k}\nabla\times\vec{M}^{x,y,z(i)}_{mn}(h,\xi,\eta,\phi)$; $i = 1, 4(\text{or } 3)]$.

For Mie type expansion there is no flexibility in the choice of vector functions whereas for Cartesian type expansion there are many choices of the complete set of vector eigen functions in terms of which E- and H- fields can be expanded. In this respect the Cartesian vector functins have great advantage over Mie vector functions. As for example a field can be expanded by means of only M-vectors in Cartesian expansion instead of by means of both M- and N-vectors as required by Mie expansion.

In this paper, criterian of selecting suitable sets of Cartesian spheroidal vector basis functions for field expansions is developed in order to obtain the optimum simplicity of analytical development of the solutions for electromagnetic scattering and radition problems and the computational efficiency for obtaining the numerical results. Also, in far field the expansions of Cartesian spheroidal vector functins are obtained in terms of much simpler spherical vector functions.

# COUPLING TO AN INFINITE HORIZONTAL WIRE ABOVE A LOSSY HALF-SPACE: AN EXAMINATION OF LIMITING CASES

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The coupling to and scattering from infinite horizontal wires located above a lossy interface by external sources will be discussed. This problem is of importance to radio interference and the induction of currents onto power lines due to EMP or lightning. The excitation of the conductor by the conventional vertical electric dipole (VED) or vertical magnetic dipole (VMD) sources located in the upper half-space will be examined. Any desired source can then be modeled as a sum of these elementary TM and TE components. The current induced on the conductor, due to the VED for example, can be determined in terms of the standard transform technique (J.R. Wait, AEU, vol. 31, pp. 489-493, 1977) as

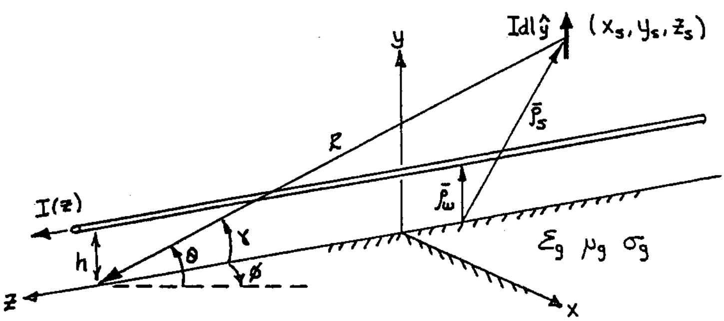
$$I(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} G_{zz}^{e}(k_z,\bar{\rho}_w,\bar{\rho}_w)^{-1} G_{zy}^{e}(k_z,\bar{\rho}_w,\bar{\rho}_s) I_{dl}\, e^{+jk_z(z-z_s)} dk_z \tag{1}$$

where $\overline{\overline{G}}^e(k_z,\bar{\rho},\bar{\rho}')$ is the Green's function taking into account the lossy interface. Various approximate methods can be employed in limiting situations to simplify the evaluation of (1)

$$I(z) \approx +j \lim_{k_z \to k_z^p}\left[\frac{(k_z - k_z^p)}{G_{zz}^{e}(k_z,\bar{\rho}_w,\bar{\rho}_w)}\right] G_{zy}^{e}(k_z^p,\bar{\rho}_w,\bar{\rho}_s) I_{dl}\, e^{+jk_z^p|z-z_s|} \tag{2}$$

$$I(z) \approx G_{zz}^{e}(k_0\cos\gamma,\bar{\rho}_w,\bar{\rho}_w)^{-1}\sin\theta\cos\gamma\left[e^{-jk_0 h\sin\theta} - \Gamma_E e^{+jk_0 h\sin\theta}\right]\frac{+jZ_0 k_0}{4\pi} I_{dl}\frac{e^{+jk_0 R}}{R} \tag{3}$$

where $\Gamma_E$ is the TM Fresnel reflection coefficient. In one extreme (2), when the source is electrically near to the conductor, the discrete mode contribution can be used to determine the current. In the other extreme (3), when the source is electrically far from the conductor, the geometrical optics approximation can be used. The validity of these approximations, which are often used in many practical applications, will be examined by comparing to (1).



# THE ELECTROMAGNETIC BACKSCATTER FROM AN OPEN ENDED CYLINDER WITH A COMPLEX TERMINATION

J.J. Boonzaaier* and J.A.G. Malherbe
Department of Electronics and Computer Engineering
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Most researchers have modeled the jet engine at the end of the circular cylindrical inlet by a planar termination such as a planar electric conductor, a planar impedance surface and planar blade configurations. This paper discusses the computation of the electromagnetic backscatter of an open ended circular cylinder with a termination consisting of a radial and longitudinal blade configuration and a coaxial centre rod to respectively describe the engine blades and the axle of the engine more accurately.

The termination is described by means of three different waveguides. A circular waveguide describes the intake, a coaxial waveguide describes the centre rod or axle of the engine and coaxial-sector waveguides describe the blades of the engine. The modal coefficients of the waveguide modes excited by the plane wave incident upon the inlet of the circular cylinder are determined from the approximate magnetic current present in the aperture. Once the coupling of the plane wave into the circular cylinder is known, the radiation of these modes from the inlet is determined via reciprocity. The fields reflected from the termination is determined by means of the modal analysis procedure. Higher order mode coupling between the different waveguides is taken into account. Calculated results for various configurations will be presented.

# TIME-DOMAIN TE-TM DECOMPOSITION OF ELECTROMAGNETIC SOURCES

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Theory for the decomposition of electromagnetic sources with arbitrary time dependence into parts radiating TE or TM fields with respect to a given constant direction in space is developed. The theory is a generalization of that given earlier for time-harmonic sources, consisting of three different decomposition methods, which for a point source can be expressed in terms of point sources, line sources and plane sources, respectively. For time-harmonic original sources, the previously derived decomposition expressions are readily obtained as special cases.

It is well known that the electromagnetic fields in free space can be split into two parts one of which is transversely electric (TE) and the other transversely magnetic (TM) with respect to a given fixed direction in space. This decomposition has been described for time-harmonic fields as well as for fields with general time dependence in well-known books by Jones or Felsen and Marcuvitz. For planar or cylindrical boundary or interface geometries, the original vector electromagnetic problem can be split into two uncoupled scalar problems corresponding to a decomposition of the source into two parts radiating TE and TM polarized incident fields. Such a decomposition was recently done for time-harmonic problems by this author [1].

In the present paper, we consider electromagnetic source decomposition for general time dependence. The results of the theory are very similar to those of the previous one, but the derivation is given a less ambiguous form. It is seen that the three decompositions given in [1] in terms of point, line and plane sources, have natural generalizations for nonsinusoidal sources. The delta function source decomposition theory gives a simple possibility to check the compatibility of the present and the previous theories, which is done at the end of the present study.

It may look too simple to limit the medium to be the 'free space', i.e., homogeneous and without any boundaries. However, problems with boundaries and interfaces between different media can be handled by considering the 'incident fields' radiating from the decomposed sources in free space and letting them interact with the boundaries and interfaces of the problem.

## REFERENCE

[1] I.V. Lindell, "TE-TM Decomposition of Electromagnetic Sources", *IEEE Trans. Antennas Propagat.*, vol. 36, no.10, Oct. 1988.

# WAVE FUNCTIONS OF THE OGIVAL CYLINDER

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## Abstract

A set of solutions is described for the scalar wave equation in bipolar coordinates which may be used to solve the problem of scattering from ogival cylinders. The wave equation is not separable in this coordinate system, and special methods are required to obtain solutions.

The solutions are obtained in a manner similar to the derivation of the toroidal wave functions by Weston (J. Math. Phys., 39, 64-71, 1960). Specifically, the solutions are obtained using the physical interpretations of Weston's wave functions by Williams (Park Math. Labs., Sci. Rep. No. 2, 1966), in which the solutions are interpreted as linear superpositions of cylindrical wave sources uniformly distributed over the poles (singularities) of the coordinate system.

A set of four solutions, even and odd in the two coordinate variables, is derived for the ogival cylinder wave functions. All four are shown to satisfy the Sommerfeld radiation condition, and to possess branch-type singularities on the surface of an infinitessimally-thin ogival cylinder.

The solutions obtained are not orthogonal functions, which also requires special methods in applying them to scattering problems. These analytical solutions may be used, among other things, to derive the amplitudes and phase factors of creeping wave modes launched by the edges of an ogival cylinder.

# Well Posedness of the Resistive Boundary Value Problem

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## Abstract

In recent years attention has focused on problems involving resistive and conductive "boundary conditions" which generalize the well-known impedance condition. However no rigorous theory of well-posedness of such problems has appeared. We provide such a theory in the present paper where we consider the existence and uniqueness of classical solutions of the Helmholtz equation in the interior and exterior regions delimited by a bounded $C^2$ - surface in $\mathbf{R}^3$. The fields are coupled by either resistive or conductive conditions on the surface which prescribe the jumps of the field or of its normal derivative across the surface. Boundary integral equations are used to establish existence and continuous dependence of the solutions with respect to data is discussed.

# RAY-MODE PARAMETRIZATION OF WAVE SCATTERING NEAR RESONANCES OF AN APERTURE-COUPLED ENCLOSURE WITH INTERIOR LOADING

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Aperture-coupled enclosures with low-loss interiors give rise to prominent features in the plane wave scattering that can be tied to the internal resonances. When the interior is loaded in such a manner as to generate layers or shells, the interior wave phenomena can be modeled in terms of guided modes, whereas the exterior wave phenomena can be described in terms of ray fields, with coupling between these effected by the aperture. This ray-mode parametrization has been applied elsewhere [Felsen and Vecchi, to be submitted to IEEE Transactions on Antennas and Propagation] to a perfectly conducting thin smooth convex cylinder, which is perforated by a narrow-axial slit that grants access to an interior loaded with a perfectly conducting smooth convex boundary. The space between the two boundaries is taken to be small, thereby simulating along the peripheral coordinate a quasi-TEM mode waveguide whose cross section changes slowly and whose deviation from symmetry near the slit is small. The presentation here deals with the detailed behavior near an internal resonance which poses the most difficult problem. The procedure involves a multiple parameter perturbation analysis structured around the resonances of the closed actual cavity and the slitted symmetric cavity. This analysis predicts a splitting of resonances when a symmetric configuration is perturbed by asymmetry. The predictions are tested on numerical reference data generated by R. Ziolkowski (private communication) for circular concentric and eccentric boundaries, and are shown to account correctly for the resonant spike locations in the bistatic scattering cross section. The behavior of the complete scattered field is based on the perturbed resonant eigenvectors and their aspect dependent projections onto the incident and scattered waves. Qualitative observations are made on the basis of these analytical results; detailed comparisons will follow after numerical evaluation has been completed.

# SCATTERING OF ELECTROMAGNETIC WAVES BY HIGH TEMPERATURE SUPERCONDUCTORS

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The purpose of this study is to investigate how a high temperature superconductor will interact with and scatter an incident EM wave.

High temperature superconductors in cylindrical bar form (longest one with diameter 0.66 cm and length 16.5 cm), loop form (diameter 0.5 cm and periphery 20 cm) and thin film form imbedded in liquid Nitrogen were illuminated by nanosecond EM pulses. The experiments were conducted in a ground-plane time-domain scattering range where nanosecond EM pulses generated by a pulse generator (Picosecond Pulse Labs 1000B-01) were radiated by a large monocone transmitting antenna. The scattered fields (impulse responses) from the superconductors were measured by a long-wire receiving antenna.

The scattered field from a superconductor consisted mainly of an oscillatory resonant waveform with a particular resonant frequency and a damping coefficient. The scattered fields from a superconductor in the normal conducting (before cooled) and the superconducting (after cooled) stages were recorded by a sampling oscilloscope (Tektronix 7854 Scope). The scattered field from an aluminum conductor of the same geometry imbedded in liquid Nitrogen was also measured for comparison.

Priliminary results show that the scattered field from a bar superconductor in its superconducting stage seemed to be enhanced about 5 to 10% from that in its normal conducting stage. This enhancement in scattered field appeared to be more pronounced for a loop superconductor. Many other results will be reported in the meeting.

# TIME-DOMAIN ELECTROMAGNETIC PENETRATION THROUGH NARROW SLOTS IN CONDUCTING SCREENS AND COUPLING TO A THIN WIRE ON THE SHADOW SIDE

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Electromagnetic field penetration through arbitrarily shaped narrow slots in a planar conducting surface and coupling to a thin wire located on the shadow side of the slotted surface are determined in the time domain by integral equation methods. Coupled integral equations are derived and solved numerically for the slot electric field and the current on the wire, from which the field that penetrates the slotted surface is subsequently determined. Results obtained compare favorably (via FFT) with those obtained by frequency domain analysis (E. K. Reed et al. 1989 National Radio Science Meeting, Meeting Digest, p. 111, Boulder, CO, 1989).

The time-domain equation is solved by a scheme incorporating finite difference approximations for the time and space derivatives in the integro-differential equation. This time-domain scheme obviates the need for large matrix inversion and the solution is progressively acquired by "marching in time." From knowledge of the slot's equivalent magnetic current and the wire's electric current, obtained as the solution of the coupled integral equations, the field which penetrates the slotted surface is calculated at various locations for several cases of plane-wave excitation.

Narrow slots were chemically etched in thin brass sheets and an apparatus was fabricated to measure shadow-side electric field and current at the base of a coupled monopole. The experimentation was conducted at the Lawrence Livermore National Laboratory on a frequency-domain test range employing a monocone source over a large ground plane. Electric field was measured at various shadow-side locations for several combinations of excitation and slot shape. Also, electric current at the base of a coupled monopole was measured for several monopole locations, lengths, and orientations. Data were collected for narrow slots having strait, annular, and rectangular geometry in the range 0.5 to 10.5 GHz. Good agreement exists between the experimental and theoretical results.

# ELECTROMAGNETIC CHIRALITY: PAST, PRESENT AND FUTURE

**D. L. Jaggard and N. Engheta**
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**University of Pennsylvania**
**Philadelphia, PA 19104**

In this talk, a tutorial of the fundamentals of *electromagnetic chirality*, ongoing activities at the University of Pennsylvania and potential applications in this area will be given.

Electromagnetic chirality is found in materials characterized by the constitutive relations

$$\mathbf{D} = \varepsilon \mathbf{E} + i\xi_c \mathbf{B}$$

$$\mathbf{H} = \mathbf{B}/\mu + i\xi_c \mathbf{E}$$

where, for the time harmonic case, $\varepsilon, \mu$ are the permittivity and permeability of the medium and $\xi_c$ is the chirality admittance. This admittance is introduced to take into account the handedness properties of the material and its absolute value is the measure of material chirality. We present similarities and differences of such media with conventional isotropic materials. We review the fundamentals of wave propagation, guiding and radiation in chiral media. These phenomena are governed by the chiral Helmholtz equation

$$\nabla \times \nabla \times \mathbf{E} - 2\omega\mu\xi_c \nabla \times \mathbf{E} - k^2 \mathbf{E} = i\omega\mu[\mathbf{J} - i\xi_c \mathbf{J_m}] - \nabla \times \mathbf{J_m}$$

where **E** is the electric field vector, **J** is the electric current density and $\mathbf{J_m}$ is the magnetic current density inside the chiral medium. Analogous equations can be found for the other field vectors **D**, **B** and **H**.

Present research includes work in propagation, guiding and radiation of sources in simple and complex chiral structures. Applications of these materials to novel structures will be addressed.

# TRANSIENTS IN A FRACTAL SLAB

**D. L. Jaggard† and Y. Kim***

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*Fractals* have provided a new geometry for the description of certain types of wildly irregular or ramified structures which are ill-defined by traditional Euclidean descriptions. This new geometry is based on the pioneering work of Mandelbrot [*The Fractal Geometry of Nature,* Freeman (1983)] and it applies to self-similar and self-affine structures, whether random or deterministic. That is, fractal geometries have dilation symmetry such that they appear identical or similar, in the mean, at many different resolution scales.

An archetypical problem in fractals has been the measurement of a rough curve such as the length or perimeter of a coastline using a yardstick of length $\varepsilon$. Empirically this length $L(\varepsilon)$ can be expressed as

$$L(\varepsilon) = C\,\varepsilon^{1-D}$$

where $C$ is an appropriate constant and $\varepsilon$ is the yardstick or resolution scale. Here $D$ is a roughness parameter whose value is bounded by unity and two. This parameter is called the *fractal dimension*. For smooth curves, the fractal dimension approaches its lower bound while for area-filling curves it approaches its upper bound. Hence, the fractal dimension $D$ can be obtained by measuring a perimeter using a variable length yardstick.

In this paper, the interaction of waves with fractal structures is formulated in terms of a plane wave impulse incident on a layered dielectric structure in which the refractive index is described by an appropriately chosen *bandlimited Weierstrass function* [Jaggard, D. L., and Kim, Y., *J. Opt. Soc. Am.* 4, 1055-1062 (1987)]. Although past work has involved the use of the incident wavelength as the appropriate interrogating yardstick, here we use the incident pulse width as an effective resolution scale $\varepsilon$. Based on the reflected pulse, the refractive index profile is reconstructed and the fractal dimensions of the slab are found from remote measurements. We will discuss the reconstruction process, give several examples and explain the physical processes involved for wave interactions with bandlimited fractals.

# GENERATING LOCALIZED PACKETS OF WAVE ENERGY†

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Exact solutions of the scalar wave and Maxwell's equations that describe localized transmission of wave energy will be reviewed. These acoustic (ADEPT) and electromagnetic (EDEPT) directed energy pulse train solutions can be optimized so that they are localized near the direction of propagation and their original amplitude is recovered out to extremely large distances from their initial location. Pulses with these very desirable localized transmission characteristics have a number of potential applications in the areas of directed energy weapons, secure communications, and remote sensing.

The ADEPT and EDEPT solutions are unique because of their intrinsic space-time nature. It will be shown that reasonable fascimiles of these ADEPT and EDEPT solutions can be generated by a finite, planar array of radiating elements by specifying both their spatial and temporal distributions. This is simulated with a Huygens' reconstruction utilizing the causal, time-retarded Green's function. The driving functions for the array elements are determined by the exact solutions. Trading simplicity of the source distribution for a more complex one, it will be shown that this localized transmission effect can be made to extend into the far-field of the array. Results from a recent acoustic experiment that tests the feasibility of launching an ADEPT solution from such an array of transducers will also be presented.

Because an ADEPT or EDEPT pulse naturally occupies a volume of space, it is believed that planar arrays may be a very inefficient sources of these pulse and that nonplanar array/sources may be better suited to launch them. Recent investigations into optimizing the array driving functions and the array configuration will also be reviewed.

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† This work was performed by the Lawrence Livermore National Laboratory under the auspices of the U. S. Department of Energy under contract No. W-7405-ENG-48.

# COULOMB GAUGE ANALYSIS OF A SCATTERER OF ARBITRARY SHAPE IN THE PRESENCE OF A WEDGE

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The Coulomb gauge is used by physicists to investigate the quantum electrodynamics of molecular level phenomena such as electron-photon and coupled field interactions. Recently it has been shown (IEEE Trans. MTT, Sept. 1988, pp 1328-33) that the Coulomb gauge can be applied to solve, in general, boundary value problems which arise in classical Maxwellian field theory—previous successful solutions required the existence of a divergenceless current which implies no free charge. The Coulomb gauge was shown to yield decoupled scalar and vector potential equations similar to those obtained with the standard Lorentz gauge. The Coulomb gauge vector and scalar potential differential equations are different from their Lorentz gauge counterparts in two significant ways: (a) the vector potential equation has a solenoidal (divergenceless) forcing function and (b) the scalar potential satisfies Poisson's equation (as opposed to the Lorentz gauge Helmholtz equation). The solenoidal nature of the Coulomb gauge vector potential has further been shown (1988 URSI Meeting, Program and Abstracts, pg 153) to result in vector potential dyadic Green's functions which contain more numerous and more slowly convergent series terms than the Lorentz gauge vector potential. On the other hand the Coulomb gauge scalar potential has for certain scattering configurations a closed form solution, a property not shared by the Lorentz gauge scalar potential.

In this paper we present the results of a Coulomb gauge mixed potential integral equation (MPIE) investigation for an arbitrary shaped scatterer in the presence of a perfect conducting wedge (wedge angle $\geq$ 180°). Both the current distribution on the arbitrary shaped scatterer and the current distribution numerical computation time are compared with a similar analysis employing the Lorentz gauge. Computation time results will also be presented for our recently refined Coulomb and Lorentz gauge analysis of an arbitrary scatterer in the presence of a perfect conducting circular cylinder.

In conclusion we will present a list of the remaining scattering configurations for which a Coulomb gauge rather than a Lorentz gauge analysis is expected to be computationally advantageous.

EXCITATION AND PROPAGATION OF TRANSIENT FIELDS OVER A WIRE MESH IN THE AIR-EARTH INTERFACE

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Propagation of transient electromagnetic fields over a wire mesh in the air-earth interface is an important aspect of the electromagnetic theory of EMP environment simulators. In this paper we consider the two-dimensional problem in which a magnetic line source just above the interface excites the electromagnetic field. An equivalent sheet-impedance dyadic operator is used to describe the mesh in the frequency range where the individual meshes are electrically small. For the field polarization of interest, the mesh properties depend on the relative permittivity of the ground as well as the mesh and wire sizes.

Evaluating the radiated field with standard asymptotic techniques, one finds that the total field can be described in terms of a space wave, which dominates the total field away from the interface, and a surface wave, which dominates the total field near the interface. The angular range in which each of these field contributions is dominant depends on the frequency and on the properties of the mesh and the ground. In examining the effect of the mesh on the propagation of transient fields, we observe pulse dispersion which depends on observation range and angle and which increases as the observer approaches the interface.

Representative analytical and numerical results are presented to illustrate the impact of the mesh and the underlying ground on the amplitude and shape of a signal which becomes a double-exponential pulse in the limit as the mesh becomes a solid, perfectly conducting surface.

# DOUBLE SLIT DIFFRACTION OF A LOCALIZED WAVE PACKET

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and

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According to the formal interpretation of quantum mechanics, complementary concepts, such as those of particle and wave properties of matter, are considered as two manifestations of reality that can not be observed simultaneously; they can only reveal themselves in different situations. For example, the corposcular nature of light is revealed in the photoelectric and Compton effects. On the other hand, the wave nature of light discloses itself in interference experiments, e.g., Young's double slit experiment.

In a typical setting for a double slit experiment, light is shone on a screen containing two narrow slits and is observed on a photographic plate placed behind the screen. The wave nature of light is directly observed since waves going through either slit interfere constructively or destructively upon reaching the photographic plate, thus forming interference fringes. On the other hand, the localized and compact nature of particles makes the explanation of the interference pattern difficult. The situation is more vexing in the case of diffraction of very low intensity light beams. In such an experiment, single photons go through the screen one at a time and always end up on one of the light fringes. A single photon with transverse dimensions much smaller than the width of the slits seems to interfere with itself. This raises a crucial question: how can a compact light particle, passing through one of the slits, feel the existence of the other one and interfere with itself?

It is our aim to provide an interpretation of the double slit diffraction problem which is radically different from the quantum mechanical probabilistic one. Specifically, we shall show the existence of an exact solution to Maxwell's equations which can accommodate both the wave and corpuscular aspects of light. Such a solution, known as a Focus Wave Mode, can interfere with itself upon diffraction with the slits on the screen and results in a causal interpretation of Young's experiment.

## Monday AM

URSI-B Session 4

### Scattering and Diffraction: Lossy & Coated Bodies

*Chairs*: T. B. A. Senior, University of Michigan; J. M. Putnam, McDonnell-Douglas

*Room*: Pine *Time*: 8:15–11:40

# SCATTERING CROSS SECTION OF COMPOSITE CONDUCTING AND LOSSY DIELECTRIC BODIES

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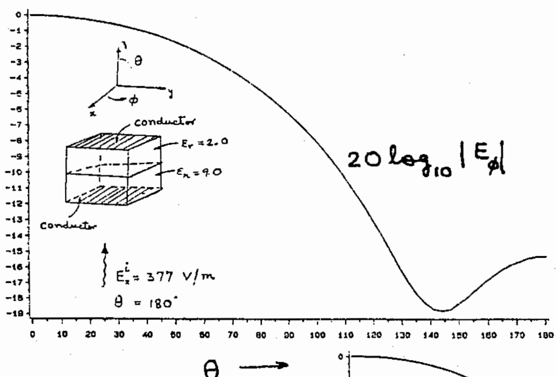
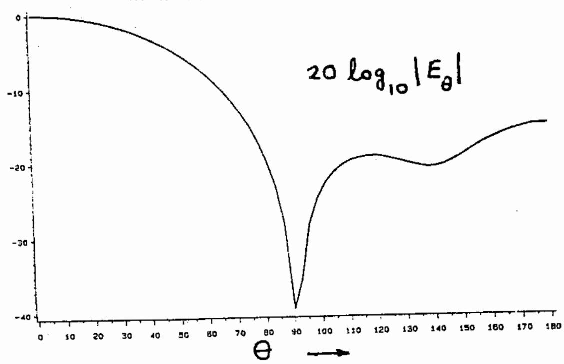
**ABSTRACT:** The objective of this paper is to describe an E-field equation for the computation of radar cross section of finite composite conducting and lossy inhomogeneous dielectric bodies. The equivalence principle are used to replace all conducting bodies by an equivalent surface electric current and the dielectric is replaced by an equivalent volume polarization current. The respective boundary conditions on the dielectric and conductor is utilized to solve for the electric current on the entire structure. Also the augmented conjugate gradient method is presented for the solution of extremely large systems of equations that arise in the present problem. Finally, typical results are presented to illustrate the potential of this method.



# DIFFRACTION BY A PARTIALLY COATED PEC HALF-PLANE

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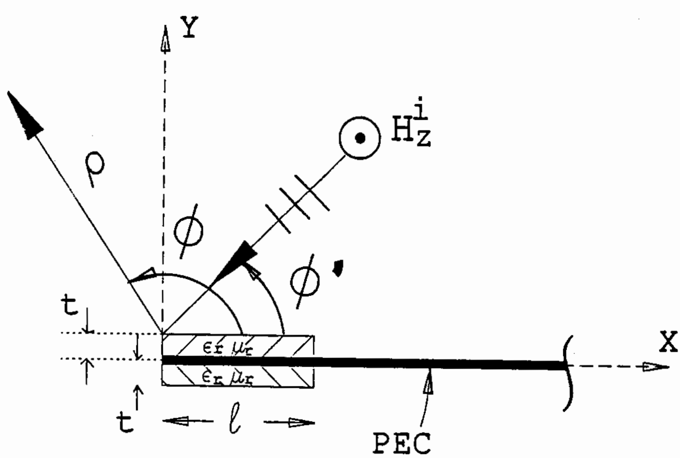
Columbus, Ohio 43212

The high frequency diffraction (TE case) by a partially dielectric-coated, perfect electric conducting (PEC) half-plane is considered. The coating is of finite length and is the same on both sides of the half-plane. This problem requires the solution of two canonical problems which are solved via the Wiener-Hopf method. The coating is assumed to be thin and it is modelled by a Generalized Impedance Boundary Condition of O(t), where t is the thickness of the coating on each face of the PEC half-plane (R.G. Rojas, Electronic Letters, Vol. 24, pp. 1093-1094, August 1988). The interaction between the edges of the coating, i.e., surface wave diffraction, doubly and triply diffracted fields, is also considered. The doubly and triply diffracted fields are obtained via the Spectral Theory of Diffraction. The backscattered and bistatic echo width is computed with the solutions developed here and it is compared with an independent moment method solution. The agreement between the two solutions is excellent.

The solutions developed here can be extended to treat thin coatings with variable permittivity and permeability. A procedure that can be followed to solve this type of problem will be discussed.




Partially Coated PEC Half-plane.

# BOUNDARY CONDITIONS FOR SCATTERERS COATED BY THICK ANISOTROPIC LAYERS

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C. Long Yu
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When a metallic body is coated by a thin lossy layer of material, its scattering properties can be described, under certain restrictions, in terms of an impedance boundary condition at the outer surface (i.e., layer-air interface) of the scatterer. This approximation becomes less accurate as the thickness of the layer increases and/or its losses diminish.

The purpose of the present study is the extension of the above theory to the more general case of a coating layer which (i) may be moderately thick (in terms of interior wavelength), (ii) may be lossless and (iii) may be made of anisotropic material. The goal is to describe the scattering properties of the coated object in terms of equivalent boundary conditions at the layer-air interface.

For scatterers whose surface has principal radii of curvature that are everywhere large respect to the free-space wavelength, the field components inside the coating layer may be expressed in terms of products of slowly-varying functions of position times trigonometric functions of a normalized distance from the metal surface. The boundary conditions at the metal-coating interface are satisfied exactly, and a perturbation scheme allows us to find the slowly-varying amplitude functions at the coating-air interface. The ensuing results are verified by comparison with canonical solutions of scattering by coated spheres.

# USING PRONY'S METHOD TO SOLVE THE PROBLEM OF SCATTERING FROM THICK, PERIODIC STRUCTURES COMPRISED OF LOSSY PLATES

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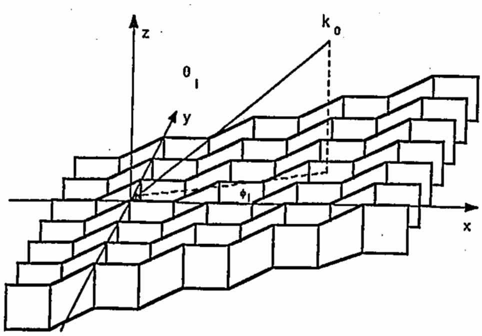
The straightforward application of the method of moments to the problem of scattering by a thick slab comprised of periodically placed lossy plates, shown in the figure below, requires a large number of unknowns to model the current along the depth of the structure. This is obviously undesirable because of the difficulty in solving large matrix equations and because the impedance matrix in periodic problems is costly to fill. It would be advantageous to be able to solve the thick problem by extrapolating the solution from a tractable thin problem. If the structure is invariant in its thickness dimension, an extrapolation procedure based on Prony's method can be applied.

The method consists of applying the method of moments twice to two related problems using two different types of basis functions. First, a thin slab is solved using subdomain basis functions throughout the structure. This slab needs to be thick enough so that the current away from the slab interface settles down to a steady-state behavior as a function of distance. Next, the current away from the slab interfaces is described in terms of a few simple functions using Prony's method. Finally, a thicker slab is solved by the method of moments using subdomain basis functions near the interfaces and the functions found by Prony's method in the interior. The objective is to minimize the number of basis functions needed to model the interior current by using functions which accurately describe its behavior so that slabs of arbitrary thickness can be solved without increasing the required number of basis functions. This method is applied to several examples of doubly-periodic slabs with unit cells composed of plates.




Geometry of Thick Periodic Structures Comprised of Lossy Plates

# FIELD BEHAVIOR NEAR SURFACE DISCONTINUITIES OF THE ANISOTROPIC MEDIUM

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The time-varying electromagnetic field behavior in the vicinity of wedge-like homogeneous anisotropic structures is considered. The analysis is based on the static theory involving a rigorous solution of the boundary-value problem leading to a transcendental equation explicitly dependent on the anisotropic medium parameters, as well as the wedge opening angle. This equation is solved numerically for the power to which the radial distance governing the exact behavior of the field close (compared to the wavelength) to the surface discontinuity is raised. In addition, it is shown that similar to the isotropic case, in the low-frequency limit, the effects of the electric or the magnetic anisotropies on the electromagnetic fields in such regions may be analyzed independently. The presented approach is an extension of the method already utilized for the study of field singularities characteristic to isotropic dielectric or permeable wedges, and in fact, the treatment of anisotropic wedge geometries is shown to reduce exactly to the corresponding results valid for the isotropic case. The undertaken theoretical methodology is also shown to be readily extendable to a region composed of multiple angular sub-sections each having different material properties, including perfect conductors. For such geometries the boundary-value problem is solved by defining appropriate static scalar potentials and enforcing the required boundary conditions. Applications of the conducted studies to electromagnetic scattering situations from anisotropic material bodies having surface discontinuities in the form of sharp corners or bends are discussed in relation to improving the convergence rates of numerical algorithms. Also included are potential applications of the theory in the high-power millimeter-wave integrated circuit technology.

# APPLICATION OF WATSON'S TRANSFORMATION TO SCATTERING FROM A CONDUCTING CYLINDER COATED WITH AN ANISOTROPIC DIELECTRIC

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Washington State University

Recently, the exact series solution for scattering of a plane wave by a perfectly conducting cylinder coated with an anisotropic dielectric has been published (H. Massoudi, N. J. Damaskos and P. L. E. Uslenghi, "Scattering by a Composite and Anisotropic Circular Cylinder Structure: Exact Solution, Electromagnetics, Vol. 8, pp. 71-83, 1988). One of the interesting results is the appearance of complex order Bessel and Hankel functions in the series when the dielectric is lossy. However, as with other series solutions for cylinders, this solution does not converge rapidly for electrically large cylinders. To remedy this, we have transformed the solution via the Watson transformation to a series which converges rapidly at high frequencies.

Massoudi et al's results are first reformulated and presented in a more conventional form. Then the new high frequency series which has been derived is compared to the known result for the isotropic coating case. Results are given for both shadow and illuminated regions with the geometric optics term evaluated in the illuminated region. In addition, computer programs have been used to study the location of the complex pole locations of the residue series determined by the Watson technique. Pole location and trajectory is examined for various degrees of anisotropy and loss of permittivity and permeability for both the TE and TM cases.

# SCATTERING BY A CIRCULAR CONDUCTING CYLINDER COATED BY AN INHOMOGENEOUS DIELECTRIC SHELL

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A boundary value solution to the scattering of an E-polarized plane wave incident at any angle on an infinitely long circular conducting cylinder coated with a layer of inhomogeneous dielectric shell is presented. The cylindrical shell is assumed to have an inhomogeneous dielectric profile in both the radial and azimuthal directions of a circular cylindrical coordinate system. The validity of the solution is verified by comparing the numerical results of specific cases with those obtained by using the method of moments. Different types of inhomogeneities are considered in order to minimize or maximize the back scattering cross section which offers many interesting possibilities for applications in radar and antennas.

# CREEPING WAVES FOR THE DIELECTRIC/FERRITE COATED SPHERES

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It is well known that the backscattering function for a conducting sphere may be broken up into an optic term and a creeping wave term. The creeping wave contributions are further broken up into terms representing E waves and H waves. In general only the first E wave, $E_1$, is significant, and the multiply-encircled creeping waves can be ingored. However, a similar analysis for a coated conducting sphere shows that

1. as the frequency increases, the order of dominance for the creeping waves is $E_1, H_1, E_2, H_2, ...$ and so on.
2. for a lossless coating, the mutiply-encircled creeping waves have to be taken into account to reveal the resonance effect.
3. for a lossy ferrite coating, the backscattering can be significantly reduced.

A typical numerical result for the backscattering of a coated sphere is shown in the figure below. This result shows excellent agreement with the exact solution. More numerical results and dicussions on the dominance of the creeping waves associated with the coated sphere will be given in the presentation.

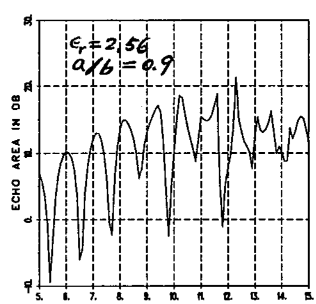


Figure 1: Backscattering by a coated sphere

# COMPLEX EIGENFREQUENCIES OF DISPERSIVE, ANISOTROPIC DIELECTRIC SPHERES AND COATED CONDUCTING SPHERES

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## ABSTRACT

The complex electromagnetic eigenfrequencies for dielectric and coated conducting objects are a function of electrical size and dielectric properties. These eigenfrequencies are important in understanding the transient electromagnetic response of dielectric and coated objects and in the optical response of physically small particles, as in the case of aerosols. The dielectric sphere and coated conducting sphere have provided a base for the analysis of more complex objects because of the analytic form of the electromagnetic scattering amplitude for spherical geometry. The computation of eigenfrequencies for non-spherical solid and coated conducting objects based on circumferentially propagating surface waves requires a complete and thorough understanding of the spherical geometry case, and the effects of dispersion and dielectric anisotropy.

We present here numerical results detailing the effects of frequency dependent dispersive dielectric constants, modeled as either arising from Debye type dipolar relaxation or atomic resonance phenomena, on the complex eigenfrequencies of a solid or coated conducting sphere. By generalizing the Mie series for dielectrics with uniaxial anisotropy such that the dielectric constant can be characterized by a radial component, $\epsilon_n$, and a tangential component, $\epsilon_t$ , the electromagnetic eigenfrequencies for these special cases will be considered.

It will be shown that the dielectric loss in the sphere or coating will shift the complex eigenfrequencies further away from the real axis, this being consistent with a creeping wave interpretation in which dielectric absorption losses are added to existing radiative losses. The uniaxial dielectric anisotropy case will be shown to effect the positions of TE series complex resonance poles but leave the TM poles in the same positions as for the isotropic dielectric case.

## Monday AM

URSI-B Session 5

### Microstrip Antennas I

*Chairs*: M. Randall, NCAR; J. H. Cloete, University of Stellenbosch

*Room*: Cedar *Time*: 8:15–11:40

# BROADBAND ANALYSIS OF A SINGLE POST-FED CIRCULAR PATCH ANTENNA

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Boeing Advanced Systems Company
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This paper examines the receiving and scattering characteristics of a single circular patch antenna. The patch is located on a layer of dielectric, situated on a ground plane, and is connected to a load impedance at the ground plane through a feed pin. The structure is then illuminated by an incident plane wave. The receiving characteristics are obtained over a frequency range of 3 to 1 or more, so that off-resonance behavior and the effect of higher order resonances on the antenna characteristics are important, and need to be accurately determined.

The receiving patch case is decomposed into scattering and transmitting cases which are solved separately, and reconstituted to give the receiving case. Accurate solutions of these cases over a wide frequency bandwidth are pursued, including full effects of the feed pin. The solution is approached through a Green's dyadic formulation for sources and induced fields both in the dielectric region and on the dielectric-cover interface.

Galerkin's method is used to solve for the currents on the patch and feed pin surfaces. The current on the patch surface is expanded as a summation over a set of smooth continuous currents along with a singular current distribution which models the current diverging from the feed pin onto the patch. The smooth currents are separated into radial and azimuthal components which vary in the azimuthal direction sinusoidally, and in the radial direction as Tchebychev polynomials modified by an appropriate edge factor. The form of the singular current distribution is chosen so that the spatial integrations over the patch may be obtained in closed form. All spectral integrations are obtained numericaly via real-line integration.

Numerical solutions for received power and input impedance are obtained.

# ANALYSIS OF TWO-PORT ELECTROMAGNETICALLY COUPLED MICROSTRIP ANTENNAS

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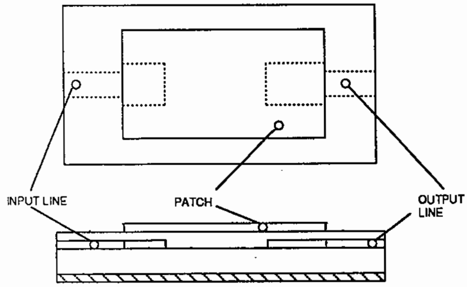
Department of Electrical and Computer Engineering
University of Colorado
Boulder, Colorado

Single port electromagnetically coupled microstrip patches have been discussed extensively in the literature. Two-port patches are useful for the design of series-fed arrays. In this paper, a general analytical technique has been developed for two-port, electromagnetically coupled, rectangular, microstrip antenna configurations like that shown below. In this technique, constant cross sectional portions of the structure consisting of the patch over the input and output lines are treated as multi-conductor transmission lines. Analysis begins by calculating the corresponding two-conductor capacitance matrix. When the feedline is much narrower than the radiating patch, the appropriate microstrip and stripline formulas can be applied to yield an accurate estimate for the capacitance matrix. The c- and $\pi$-eigenmode parameters for the coupled lines are found using this capacitance matrix. The corresponding four-port Y-parameters are then determined. Finally, the resulting four-ports are appropriately connected and cascaded to form a quantitative model of the overall structure. Results of the approach are compared to experimental findings for a typical design.



# MULTIPORT NETWORK MODELING OF ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCHES

David Hunter and K.C. Gupta*
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University of Colorado
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The multiport network modeling approach for analysis and CAD of microstrip patches has been employed successfully for microstrip-fed and probe-fed patches [Benalla and Gupta, IEEE Trans. Antennas Propagation, vol. AP-36, October 1988]. The present paper is an extension of this approach. It investigates the electromagnetically coupled patch with a microstrip feed line located on a thinner substrate underneath the patch.

The feed structure is modeled by equivalent magnetic current elements at the edges of the microstrip line. Fields underneath and at the edges of the radiating patch are evaluated as a summation of the fields produced by the individual magnetic current elements. A three-dimensional analysis of a planar resonator excited by a magnetic current element has been developed for this purpose. The Z-matrix of the patch can be determined from the field distribution. This Z-matrix is then used in the multiport network model.

The proposed model presents a convenient approach for CAD of electormagnetically coupled patches. Details of the analysis, modeling procedure and results, both theoretical and experimental, will be reported at the meeting.

# PROBE EXCITATION OF A CENTER-FED CIRCULAR MICROSTRIP ANTENNA EMPLOYING A STRATIFIED MEDIUM FORMULATION

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Massachusetts Institute of Technology, Cambridge, MA 02139

+Schlumberger-Doll Research
Old Quarry Road, Ridgefield, CT 06877-4108

Extensive work has been published on radiation by a microstrip patch excited by a probe. Most of the published work did not rigorously model the correct current distribution on the probe. In the case of electrically thin substrates, the probe current is usually approximated as being uniform along the probe. This leads to acceptable numerical results for the computation of the radiation pattern by the patch and for the mutual impedance between the probe and the patch. However, this approximation is not sufficiently accurate to solve for the current distribution on the patch nor for the computation of the self impedance across the terminals of the probe. Furthermore, this approximation is not appropriate in the case of electrically thick substrates.

In this paper we rigorously analyze the radiation problem of a circular patch which is center fed by a coaxial-line driven probe over a ground plane and situated in an arbitrary layered medium. The current distribution on both the patch and the probe is rigorously formulated using a planar stratified medium approach. A set of three coupled integral equations is derived which governs the axial current distribution on the probe, the radial current distribution on the patch and the azimuthal magnetic current sheet across the aperture of the driving coaxial line. This set of equations is then solved using the method of moments. The resulting matrix equation is obtained in terms of Sommerfeld-type integrals that take into account the effect of the layered medium. These integrals are efficiently computed by a simple deformation in the complex wavenumber domain. The probe current distribution, input impedance and radiation pattern are presented and compared to the case of a uniform probe current distribution.

# PROBE EXCITATION OF A CENTER-FED CIRCULAR MICROSTRIP ANTENNA EMPLOYING THE WEBER TRANSFORM

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Massachusetts Institute of Technology, Cambridge, MA 02139

The analysis of microstrip antennas with electrically thick substrates find many applications pertaining to millimeter wave systems and in achieving wide bandwidth. Most of the published work on the input impedance and other parameters of a probe-fed microstrip antenna employ an approximation to the probe feed where it is replaced by a uniform current ribbon of equivalent dimensions. This approximation fails to give sufficiently accurate results for the input impedance of the probe especially for thick substrates. Recently there has been some progress in this area by Davidovitz and Lo (M. Davidovitz and Y.T. Lo, *IEEE Trans. Antennas Propagt.*, vol. AP-34, no. 7, July 1986) where they solved the current distribution on the metallic probe in a closed magnetic wall cavity. They accounted for the radiation losses by lumping it artificially into an effective loss tangent.

In this paper we rigorously analyze the radiation problem of a circular patch which is center fed by a coaxial-line driven probe over a ground plane in an arbitrary layered medium. We formulate the problem in terms of a Weber transform which allows one to develop the Green's function of the layered medium with the probe and the microstrip patch as part of the medium. Using the Weber transform, automatically enforces the boundary conditions on the probe and the patch. This allows one to cast the problem as the solution of a set of two coupled integral equations governing the tangential component of the electric field across the aperture of the coaxial line feed and that across the interface where the patch lies. This set is then solved using the method of moments. The current distribution on both the probe and the patch is then computed from the component of the magnetic field tangential to their surfaces. Furthermore, from the computed electric field across the aperture of the coaxial line feed, one obtains the reflection coefficient for the TEM mode which allows one to compute the input impedance across the terminals of the probe. The probe current distribution, input impedance and radiation pattern are presented and the obtained results are compared with those using an independent approach presented in a companion paper (S.M. Ali, T.M. Habashy, and J.A. Kong).

# A MODIFIED ONE-DIMENSIONAL METHOD FOR SOLVING MICROSTRIP BEND AND DISCONTINUITY PROBLEMS

Doris I. Wu* and David C. Chang
Dept. of Electrical and Computer Engineering
University of Colorado, Boulder, CO 80309

In analyzing finite microstrip structures, a full two-dimensional current integral equation formulation combined with the method of moments approach generally yields the most accurate results. Although this approach is versatile, it requires a long computational time, particularly when dealing with microstrip lines having nonsimple discontinuities such as an interdigital capacitor or a coupled T-junction. Because both transverse and longitudinal currents are needed for these types of discontinuity, the computational time for these structures can become impractically long.

To reduce the computational time, we examine the use of a modified 1D current representation for microstrip lines in which we model a 2D current distribution only in the vicinity of a discontinuity. Using an L-shaped strip as an example, in this representation we treat the strip as two overlapping single strips and assume that the current in each single strip can be approximated by a 1D current in the longitudinal direction. Using rectangular pulses as the expansion functions, we divide each strip into a set of rectangular cells. The portion of each strip in the overlapping region is further divided into smaller size cells to give us a finer characterization of the junction region. The composite current representation for the L-shaped strip consists of a 2D current expansion in the junction region and a 1D current in each leg of the strip away from the junction. To show the adequacy of this modified 1D current, we will compare this approximation to the full 2D current approach in which both longitudinal and transverse currents are used throughout the strip. As will be illustrated, the reduction in the computational time for this modified scheme can prove to be very useful in analyzing microstrip lines with nonsimple discontinuities.

# MODELLING A MICROSTRIP RESONATOR RADIATING INTO LOSSY MEDIA BY TWO DIMENSIONAL SPECTRAL DOMAIN APPROACH.

J. PRIBETICH, P. KENNIS, P. PRIBETICH

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The realization of printed circuits applicator used in microwave hyperthermia is generally based on empirical formulas and experiments. Since few years, theoretical efforts have been developped in order to get tools for the modelization of that kind of electromagnetic sensors. The rectangular patch microstrip applicator seems to be one of the best solutions in the integration of active and passive functions for that kind of electronic system. In another hand, that element constitue a basical element for the realization of arrays in order to focuse the electromagnetic energy in a determined area. Recent modelization [1] has proved that with a simple transmission line model, it is possible to get in a first approximation the main electromagnetic parameters of that structure. At this step, the problem is to determine the range of validity of that simple model. To do so and in order to improve the modelization, we propose a more rigourous study of that kind of resonator in contact with the human tissues ( figure 1) based on a double Spectral Domain Approach (S.D.A.).[2]

To modelize that structure, we consider a microstrip resonator exited by a thin microstrip line with several layers over the strip with complex relative permittivities. The purpose is to obtain the complex resonant frequencies in order to get both the resonant frequency and the Q factor.

## NUMERICAL RESULTS

In a brevity's sake, we do not detail each step of the numerical analysis of that two dimensional method. Our numerical analysis has been compared to experimental results (table 1) and to the one dimensionnal transmission model [1].

The originality of this communication is that previous simple modelization does not obtain the resonant frequencies of that kind of applicators.(that' s to say the resonant frequency and the Q factor ). This analysis, furthermore, takes into account the layered nature of the human body. In another hand, this full wave analysis can be extended to anisotropic media which is more realistic.

At the Conference, in June, we will present the main step of that more rigourous numerical analysis in order to obtain the resonant frequency and the Q factor. In a design purpose, design chart will be presented showing the influence of the geometrical and physical parameters using that method and comparison with the simple method would be presented in order to determine the limit of validity of previous simple method.

## REFERENCES

[1] J. PRIBETICH, R. LEDEE, P. KENNIS, P. PRIBETICH, M. CHIVE
*" Modelling a microstrip antenna with dielectric protective layer for lossy medium"*
Electronics Letters Vol.24, n°23 , 10 th November 1988, pp 1464-1465

[2] Tatsuo ITOH
*" Analysis of Microstrip Resonator"*
I.E.E.E Trans. on M.T.T. Vol. MTT-22, n°11, November 1974, pp 946-952

TABLE 1

| | | |
|---|---|---|
| Experiment | $f_{ex}$ = 935 MHz | $Q_{ex}$ = 9 |
| One Dimensional Modelization | $f_{th1}$ = 915 MHz | |
| Two Dimensional Modelization | $f_{th2}$ = 920 MHz | $Q_{th}$ = 17 |

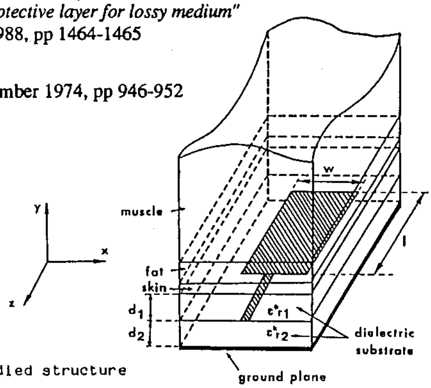


Figure 1 : Schematic diagram of studied structure

# ANALYSIS OF PROPAGATION CHARACTERISTICS OF DOUBLE MICROSTRIP COPLANAR LINES LAID ON SEMICONDUCTOR SUBSTRATE.

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One way to analyse a double gate travelling wave field effect transistor is to determine the fundamental modes (even and odd) of the passive transmission line and to use these results for the lumped electric scheme of the double gate lumped FET .

For such structures when propagation effects are investigated, different problems must be taken into account: that is to say metallic losses, bulk losses in the semiconductor substrate, and coupling phenomena between the differents electrodes. This last point is particularly important for the double gated FET due to the complex geometry of the structure.

The purpose of this communication is to precise, in a first step, the importance of these last two points when realistic geometry is taken into account. In this mind we analyse the propagation characteristics of a double microstrip coplanar line laid on a semiconductor substrate (figure 1) by using the spectral domain approach . In this case , the choice of the basis functions is not so simple as for the classical microstrip line due to coupling and interaction between the neighboured slots. In order to take into account these interactions we must use even and odd basis functions (with respect to each slot). A comparison between theory and experiment (figure2) points out the validity of these numerical considerations.
After this classical verification we can present the effects of the coupling phenomena , more particulerly when the ratio between the strip and the slot is high. In this case the figure 3 shows the necessity to include coupling function in the analysis.
For the conference we propose to present this analysis and the main theoretical and experimental results.

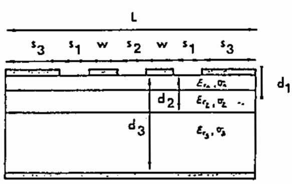


FIG.1 cross section of the studied structure.

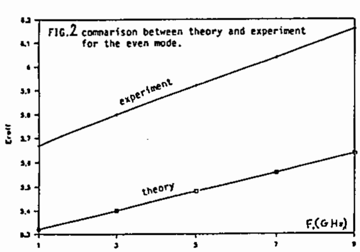


FIG.2 comparison between theory and experiment for the even mode.

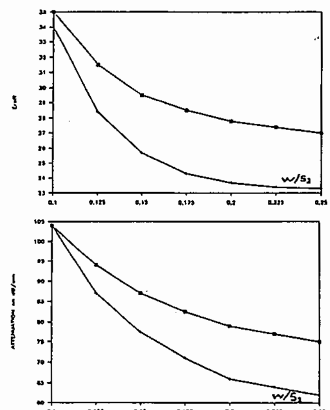


FIG.3 influence of the coupling on the propagation parameters.

+ basis functions with coupling

o basis functions without coupling

$d1 = 0.1 \mu m$ $d2 = 0.2 \mu m$ $d3 = 100 \mu m$ $S3 = 300 \mu m$ $S1 = 20 \mu m$ $W = 5 \mu m$

$\varepsilon_{r1} = \varepsilon_{r2} = \varepsilon_{r3} = 13.0$ $\sigma_1 = 0$ $\sigma_2 = 100$ $\sigma_3 = 1.e-7$

# CAD OF ANY MICROSTRIP ANTENNA FOR ANY MODE OF EXCITATION

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ABSTRACT

Three simple theories are developed to determine the radiation characteristics of any microstrip antenna for any mode of excitation. This includes the radiation resistance, the various type of Q-factor, efficiency, gain, bandwidth and directivity. The theories correlate the antenna parameters with the patch dimensions and relate them directly to the required specifications. Moreover, they give the antenna designer some kind of freedom to select the best antenna. Simply, these are:

Theory 1: The open-ring microstrip antenna is proposed to be a standard patch microstrip antenna. This is because a large number of different shaped antenna can be obtained by changing the gap angle and the annular width. This includes the special cases of quarter, half, three-quarters and ideal-gap open-ring (closed-ring with a cross cut) antennas with their limiting case such as their annular's reduction to a circular. The well knwon disc and rectangular patches can also be obtained.

Theory 2: The Gain-Bandwidth product is Merit Figure since the gain is proportional to the input impedance at resonance and bandwidth is inversely proportional to the total antenna Q-factor. The figure tells us the best substrate thickness for good antenna performance. It can also be used to extract meaningful comparison about the radiation characteristics of different structures.

Theory 3: Once the 'Figure of Merit' of any microstrip antenna is determined, the corresponding antenna radiation characteristics can be calculated using different techniques and by utilizing the 'Figure of Merit' of the available standard antenna. This includes the case of the same structure for different modes of excitation.

Details of these theories and the results would be discussed.

## Thursday PM

Joint AP-S, URSI-F Session 6

**Inverse Scattering and Imaging**

*Chairs*: W.-M. Boerner, U. of Illinois, Chicago; W. X. Zhang, Southeast U., Nanjing

*Room*: San Simeon *Time*: 1:15–5:00

# An Iterative Solution for Two-Dimensional Electromagnetic Inverse Scattering Problem

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**Abstract.** A new method, based on an iterative procedure, for solving two-dimensional inverse scattering problem is presented. This method employs an equivalent Neumann series solution in each iteration step. The moment method is used in solving the forward problem. The outline of the method can be discribed in the following steps. (1) Solve for the first order profile solution by using the Born approximation. (2) Solve the scattering problem for the field in the object and at the observation points for the last reconstructed profile. (3) Put the field in the object obtained in step (2) into the integral equation to recover the next order profile solution. (4) Repeat the step (2) and compare the field obtained by the reconstructed profile and the measured data which in our case is the simulated field for the exact profile at the observation points. If the difference is less than five percent of the scattered field, the iteration terminates. Otherwise, repeat the cycle untile the solution is convergent. In step (1) and step (3), the regularization procedure is employed to circumvent the inherent instability of the inverse problem.

The purpose of the algorithm is to provide a general method to solve the two-dimensional imaging problem when the Born and the Rytov approximations break down. Numerical simulations were calculated for several cases where the conditions for the first order Born approximation were not satisfied. The results show that in both high and low frequency cases, good reconstructed profiles can be obtained for smoothly varying permittivity profiles. Limited number of measurement around the object at a single frequency with four plane incident waves from different directions are used. The method proposed in this paper could be easily applied to the three-dimensional inverse scattering problem, if computational resource is available.

# THE APPLICABILITY OF INVERSE SCATTERING FOR IMPERFECT OPTICAL WAVEGUIDES

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An inverse scattering problem is concerned with reconstructions of unknown properties of scattering medium on the basis of scattered data. In this paper, we examine the applicability of an inversion theory to determine the imperfect boundaries of an optical waveguide. Since optical waveguides possess finite size in transverse direction, only eigenmodes are allowed to propagate in waveguides. These eigenmodes propagate independent of each other if a waveguide has perfect boundaries. However, couplings between eigenmodes of a waveguide occur if the boundaries of the waveguide are imperfect. It is this coupling that contains informations on the boundaries of an optical wavegude. We note that there exists an analogy between fiber-axis-distortions and boundary imperfections. Hence, this technique may be a powerful tool to estimate fiber-axis-distortions inside communication cables.

The frequency range of an incident wave is chosen such that only two modes can propagate in the waveguide. If only the lowest TE mode is excited using a differential exitation technique, the other mode will be generated from a coupling process owing to imperfect boundaries. The coupling strength is obtained for various frequencies of an incident wave. The coupling strength in terms of $\Delta\beta$ is utilized to reconstruct the imperfect boundaries of the waveguide. Here, $\Delta\beta$ is the differnce between longitudinal wavenumber of the two modes. The applicability and limitations of this inversion scheme will be presented with several examples.

# ACTIVE MICROWAVE IMAGING : A MODEL-BASED APPROACH

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## ABSTRACT

The development of tomographic processes for X-rays, ultrasonics and nuclear magnetic resonance has evolved to a high degree of sophistication, however, active microwave imaging is just beginning to be realized as a viable approach in certain applications as non destructive testing.
Recently, work by one of the authors has been accomplished applying active microwave imaging to biomedical applications (Ch. Pichot et al., IEEE Trans. Ant. Prop. AP-33, 416-425, 1985) and extended to the geophysical area for the detection and identification of buried inhomogeneities using electromagnetic waves (L. Chommeloux et al., IEEE Trans. Microwave.Theory.Tech. MTT-34, 1064-1076, 1986 and W. Tabbara et al., Inverse Problems 4, 305-331, 1988). Such detection and identification of buried inhomogeneities using electromagnetic waves are areas of current importance for geophysical or civil engineering applications, e.g., detectors of pipes and cables or metallic rods in opaque material. The problem with which we are concerned here is 2D. The imaging approach is to reconstruct some information about the object by measuring the scattered field using a linear sensor probe array and solving the diffraction tomographic problem. In fact, this approach is a solution to the inverse problem, that is, given the measured field, find the corresponding object cross-sectional image.
In the frame of a collaboration with *Laboratoire Central des Ponts et Chaussées* (French Public Works Research Laboratory, French Ministry of Transportation) a microwave camera has been constructed for civil engineering applications and specifically for metallic rods detection in reinforced concrete using reflection mode imaging. The algorithms are developed for quasi-real time processing.
A model-based approach to improve the spatial resolution of buried objects using the active microwave imaging system (microwave camera) is discussed. First, we generate the model, by numerically solving an integral equation representing the scattered field of the object. Next, using this model, we develop an optimal spatial filter to process the measured field by solving the dicrete multichannel Wiener-Hopf equations. Finally, inverse problem is solved using an imaging algorithm based on diffraction tomography using Fourier transforms. We then analyze the performance of the processor. Experimental results indicate a robust performance of the approach.

# INTERPRETATION OF THE DEPOLARIZING EFFECTS IN VECTOR (POLARIZATION) DIFFRACTION TOMOGRAPHY

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The major difficulty of evaluating possible practical applications of vector diffraction tomography is that experimental data are still sparse, and that data generated involve usually either the BORN or RYTOV scalar wave approximations. In order to test the depolaring effects in electromagnetic wave diffraction tomography and especially for the inverse problem of image formation, oblique incidence on a circular cylindrical scatterer is investigated. It is shown that reconstruction of the exact fields at oblique incidence deteriorates rapidly as the angle of incidence deviates further from normal incidence. And it is demonstrated how the entire copolarized (HH and VV) and cross-polarized (HV and VH) components must be carefully integrated into the image reconstruction process in order to obtain a complete image according to the "span" - invariant. By analyzing the obvious but simple model of a cylindrical conducting and/or dielectric scatterer at oblique incidence, the role of wave depolarizing effects in image formation in vector diffraction tomography is clearly interpreted.

## FREQUENCY RESPONSE OF A DIPOLE IN CONDUCTING MEDIA

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Bilkent University, Ankara, Turkey

Quasi-static electromagnetic fields produced by electric and magnetic dipoles are investigated in terms of the frequency dependence of the amplitude of field components at selected distances from the sources. For cases when the displacement current can be neglected, numerical results reveal that the intensity of some of the field components exhibit a maximum at a given frequency. For a vertical magnetic dipole located at the sea floor interface, the amplitude of the horizontal component of the magnetic field is maximized at the frequency for which the skin depth of the sea water is roughly one-third of the distance from the source. For some of the other field components, this maximizing frequency is found to be a sensitive function of the conductivity of the sea-floor. Again at this same frequency the lateral wave component of the entire field that exists due to the presence of the sea floor boundary becomes dominant. Some of the practical applications are discussed.

## Monday AM

URSI-H Session 7

### Active Space-Based Experiments and Plasma Sheaths

*Chairs*: P. Bernhardt, Naval Research Lab; P. Kellogg, University of Minnesota

*Room*: Carmel *Time*: 8:15–11:40

| | | |
|---|---|---|
| 8:20 | **Electromagnetic Instabilities of a Finite-Radius Electron Beam in a Uniform Background Plasma**<br>C. S. Lin,* H. K. Wong, Southwest Research Institute | 48 |
| 8:40 | **Electron Beam Radiation/Propagation Experiments**<br>D. E. Donatelli,* Rome Air Development Center | 49 |
| 9:00 | **Induced Surface Charge and Electrostatic Wave Fields from the Motion of the Electrodynamic Tether**<br>D. J. Donohue,* K. J. Harker, P. M. Banks, Stanford University | 50 |
| 9:20 | **Neutral Gas Emissions During an Electron Beam Mother-Daughter Sounding Rocket Experiment**<br>B. E. Gilchrist,* P. M. Banks, T. Neubert, P. R. Williamson, R. I. Bush, Stanford University, N. B. Myers, W. J. Raitt, Utah State University, S. Sasaki, Inst. for Space & Astro. Science, Tokyo | 51 |
| 9:40 | **Measurements of Radio Frequency Emission from the Exhaust Plume of the Space Shuttle Main Engine: Instrumentation, Methodology, and Analysis**<br>S. T. Wu,* NASA - Stennis Space Center | 52 |
| 10:00 | **The Sheath Structure Around a Negatively Charged Rocket Payload**<br>T. Neubert,* Stanford University, M. J. Mandell, S-CUBED, B. E. Gilchrist, P. M. Banks, P. R. Williamson, Stanford University, W. J. Raitt, Utah State University, S. Sasaki, Inst. for Space & Astro. Science, Tokyo, I. Katz, S-CUBED | 53 |
| 10:20 | **Coffee Break** | |
| 10:40 | **Reflection Coefficient of an Inhomogeneous Plasma Layer for Plane Wave at Arbitrary Angles of Incidence**<br>R. W. Lawrence,* C. R. Cockrell, NASA - Langley Research Center | 54 |
| 11:00 | **Interaction of Aperture Antennas with Spacecraft Plasma Sheaths in Cylindical Geometry**<br>S. H. Choi,* Vigyan Research Associates, L. D. Staton, NASA - Langley Research Center | 55 |
| 11:20 | **Electron Plasma Waves Excited by a Loaded Antenna**<br>Y. Morita,* S. Egashira, Saga University | 56 |

# ELECTROMAGNETIC INSTABILITIES OF A FINITE-RADIUS ELECTRON BEAM IN A UNIFORM BACKGROUND PLASMA

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Southwest Research Institute
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During electron beam injection experiments in the ionosphere, electric and magnetic waves are frequently observed with wave frequencies from the ion cyclotron frequency to the electron plasma frequency. To study these complex phenomena, the electromagnetic dispersion equations of a finite-radius electron beam interacting with a cold uniform background plasma are solved. The main goal of the study is to determine the dependence of the growth rates of various wave modes, including ion cyclotron, lower hybrid, whistler, electron beam, and electron plasma waves as a function of the beam parameters. The propagation velocity and the spatial growth length will be estimated for these wave modes. In addition, the instability effects of a pulsed electron beam on electromagnetic wave radiation will be discussed.

# Electron Beam Radiation/Propagation Experiments

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Two experiments are planned to verify that VLF waves generated by a modulated electron beam propagate through the ionosphere and are detectable on the ground. These experiments and the issues associated with them will be discussed. The issues fall into two categories: those concerned with radiation excitation, proagation, and transmission; and those affecting beam emission and propagation.

In the first category, theoretical studies show that a modulated electron beam will radiate at the modulation frequency and its harmonics (K.J. Harker and P.M. Banks, Radio Sci. 19, 454-470, 1983). If the modulation is sinusoidal, the radiated power will be concentrated at the modulation frequency (J. Lavergnat, T. Lehner, and G. Matthieussent, Phys. Fluids 27, 1632-1639, 1984). The propagation path through the ionosphere has been mapped using ray-tracing calculations, and from this the transmitted power is estimated. Previous experiments have verified this theory in the near-field, but not in the far-field. The first of the planned experiments will be a simple proof-of-concept using a sounding rocket and space and ground-based receivers. The second will be a more extensive test with a low-orbiting satellite, two space receivers on sub-satellites, and a network of ground receivers.

The second category of issues arises because of the constraints placed on the beam by the issues in the first category. The power transferred to waves is proportional to the initial beam power and the length of the beam. In order to achieve the resonance condition for maximum power transfer, high current-low energy beams are needed. The emission and propagation of such beams may be disrupted by space-charge effects and beam-plasma interactions (R.M. Winglee and P.L. Pritchett, J. Geophys. Res. 93, 5823-5844, 1988). Methods for counteracting these effects, including beam and spacecraft neutralization, are being studied and will be tested as part of the experiments.

# INDUCED SURFACE CHARGE AND ELECTROSTATIC WAVE FIELDS FROM THE MOTION OF THE ELECTRODYNAMIC TETHER

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Recent efforts have been made to calculate a self-consistent solution for the induced charge and currents on the surface of a conducting tether moving through the ionospheric plasma. We have developed a theory which describes a coupled system of charge, currents and radiation fields satisfying all of the electromagnetic boundary conditions at the interface between conductor and plasma. In this paper we describe an approximation to the above theory in which the velocity of the conductor is assumed to be small and therefore retained only to lowest order. In this quasi-static ($v/c<<1$) or MHD ($\mathbf{k}\cdot\mathbf{v}=\omega<\Omega_i$) limit the induced currents and electromagnetic effects can be shown to be higher order effects which may be neglected to lowest order. The problem then reduces to solving for a surface distribution of charge which is self-consistent with the induced $(\mathbf{v}\mathbf{x}\mathbf{B})\cdot\mathbf{L}$ potential. The charge can be calculated by a discretized integral equation technique with an appropriate choice of Green's function. Detailed numerical results from this calculation will be presented with a first order approximation of the surrounding electrostatic wave fields.

# NEUTRAL GAS EMISSIONS DURING AN ELECTRON BEAM MOTHER-DAUGHTER SOUNDING ROCKET EXPERIMENT

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The CHARGE-2 sounding rocket experiment utilized electron beam injections with 1 keV energy and up to 40 mA current to generate substantial vehicle charging on its main, mother payload. Charging potentials reached approximately 50% of initial beam energy during many beam emissions. In addition, a daughter payload was ejected to a distance of 426 m away from the mother, although the two payloads were electrically connected through an insulated, conducting tether. The daughter was utilized both as a remote contact to the plasma and as a remote VLF/HF observation platform. Because the two payloads were electrically connected, the daughter payload remained close in potential to mother.

A nitrogen gas thruster system, firing every 36.5 s, was utilized on the daughter to maintain separation velocity. During concurrent thruster and electron beam emissions, substantial enhancement to return current collection at the daughter and reduction of vehicle potential at the mother was observed. On one occasion, when a +450 V high voltage bias system was also connected in series between the two payloads through the tether, the mother potential was actually observed to be driven negative. Further, the VLF and HF spectrum was substantially altered during thruster, electron beam emissions.

These observations can be interpreted in terms of an electrical discharge in the region near the daughter payload, enhancing current collection from the ionosphere and reducing vehicle charging. Further, the plasma heating and turbulence normally present around electron beam injections in a space plasma can be disregarded as a contributor to the observed discharge since the daughter was located well away from the electron beam injection. The discharge only requires accelerated ionospheric electrons both to start and maintain the process in and around the neutral gas injections.

This presentation will provide new information from the HF and VLF spectrums and other data sets associated with the observed electrical discharge. It will be emphasized that similar conditions may also be present during the upcoming shuttle tethered satellite mission, TSS-1.

# Measurements of Radio Frequency Emission from the Exhaust Plume of Space shuttle Main Engine: Instrumentation, Methodology, and Analysis

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## ABSTRACT

Several baseline radio frequency emission measurements (using max-hold, and later remotely controlled sweep-frequency techniques) were conducted from May 3 to August 29, 1988. In addition to establishing a baseline, these initial operations provided the necessary checkout period required to identify inherent problems with the equipment and techniques used, and also allowed the personnel to become familiar with the systems operation. Using a max-hold techniques with the Tektronix 2756P Spectrum Analyzer, and by comparing the recorded spectral waveforms before, during, and after the test firing, it was found that the exhaust plume radiated electromagnetic energy in several spectral regions: 20 to 100, 140 to 160, 400 to 420, and 460 to 470 MHz. The maximum amplitude differences were more than 20 dBm from the regular noise level. However, since the max-hold technique was used, no real-time amplitude variations on the dynamics of spectral signatures were recorded. On August 29 measurement, two Tektronix spectrum analyzers were used to measure radio-frequency emission: Model 2756P with max-hold, remote site control techniques, and Model 2756P with run time display of spectral waveforms using a video camcorder to record real time amplitude variations or the dynamics of spectral signatures from the scope. The video recording failed due to low battery power, but the off-site system did record a very prominent RF radiation (more than 28 dBm difference) in the spectral range of 20 to 40 MHz. The encouraging results obtained on August 29 indicated the need for additional measurements with spectral bandwidth set at 4 to 44 MHz. The tape recorded the dynamics of spectral signatures from the scope, and the recorder images were sequentially "frame-grabbed". Analysis of the frame-grabbed images indicate that there are significant amplitude variations in spectral frequency both in 29 to 31 MHz and 34 MHz spectral bands.

# THE SHEATH STRUCTURE AROUND A NEGATIVELY CHARGED ROCKET PAYLOAD

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The sheath structure around a rocket payload charged up to 460 V negative is investigated experimentally and by computer simulations. Our experimental results come from the CHARGE-2 sounding rocket campaign in which the payload was split into two separate sections connected with a conducting, insulated tether. The two platforms (Mother and Daughter) drifted apart in a direction perpendicular to the ambient magnetic field, reaching a maximum separation distance of 426 m. Periodically, a high voltage bias was applied between the Mother chassis and the tether driving the Mother negative relative to the tether and the Daughter. The voltage was sweapt from 0 V to 460 V. The tethered Mother/ Daughter then functioned as a double probe, the negative probe (Mother) reaching large negative potentials relative to the ambient plasma potential, while the positive probe (Daughter) stayed close to the ambient potential. A floating probe array was mounted on the Mother, measuring the Mother potential relative to the plasma at radial distances of 25, 50, 75, and 100 cm. As the Mother is biased increasingly negative, the ion-rich sheath surrounding the Mother is expanding outwards. This expansion is reflected in the floating probe measurements. Observations of the tether current as function of bias potential and of the sheath expansion seen by the floating probes are presented and compared with NASCAP/LEO computer simulations.

# REFLECTION COEFFICIENT OF AN INHOMOGENEOUS PLASMA LAYER FOR PLANE WAVE AT ARBITRARY ANGLES OF INCIDENCE

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The study of electromagnetic propagation within a plasma and its usefulness in plasma diagnostics are well known. The reflection of a plane wave from an inhomogeneous plasma and the determination of electron density from group delay measurements have been studied in detail in the area of ionosphere sounding research (Budden, Radio Waves in the Ionosphere, Cambridge Press, 1961). There is interest in developing the capability of determining the electron density as a function of distance from the vehicle skin in a low-loss plasma sheath for a reentry spacecraft. This requires the development of a model to predict the admittance of, or the coupling between two apertures on a ground plane in the presence of a plasma with gradient of permittivity normal to the ground plane.

Since it is desired that the above model apply to the near-field case, the reflection coefficient must be determined for a plane wave of arbitrary polarization and angle of incidence. Numerical solutions for perpendicular polarization can be found without too much difficulty. In fact, for this polarization closed form solutions exist for some profile shapes. Difficulties arise in the solution for the parallel polarization case. Many of these difficulties stem from the fact that the differential equation obtained for the tangential magnetic field shown below has a regular singularity at $\epsilon(z)=0$; i.e.,

$$\frac{\partial^2 H}{\partial z^2} - \frac{1}{\epsilon_r(z)} \frac{\partial \epsilon_r(z)}{\partial z} \frac{\partial H}{\partial z} + k_0^2\left(\epsilon_r(z) - \sin^2\theta_i\right) H = 0$$

where $\epsilon_r(z)$ is the effective relative permittivity of the plasma medium.

Here, no closed form solutions seem to be available for other than normal incidence. Further, the singularity clearly creates difficulties when numerically solving the above equation for the low loss case. The addition of loss to the plasma will move the singularity away from the real axis reducing the numerical problem. However, for the low loss case other methods should be investigated.

This presentation will include the development of the above coupling models. The discussion will include the analysis of the propagation and reflection of a plane wave in an inhomogeneous plasma. A method to circumvent the difficulties in numerically solving the wave equation for parallel polarization through the singularity will be presented. Finally, results of the above model will be discussed.

# INTERACTION OF APERTURE ANTENNAS WITH SPACECRAFT PLASMA SHEATHS IN CYLINDRICAL GEOMETRY

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The Aeroassist Flight Experiment (AFE), scheduled for launch by NASA in the early 1990's, will study the physics of the aerobraking maneuver. This maneuver, an aid for orbital transfer from high to low earth orbits, involves upper atmospheric flight under conditions that generate a relatively dense plasma sheath in the forebody region of the vehicle. Among the sensors planned for the AFE are a set of microwave and millimeter-wave sensors that will measure the stand-off distances of selected critical electron den sity values. A substantial amount of rigorous analytical work, dating largely from the 1960's and 1970's, has been done for the calculation of aperture antenna admittances in the presence of such plasma sheaths. That work is almost entirely based on models having electron density gradients that are normal to the antenna aperture and its associated ground plane. The present paper discusses the reformulation of those rigorous cold-plasma approaches in a cylindrical coordinate system that allows for azimuthal as well as radial electron density variations. This new model will allow benchmark calculations for reflectometer sensors that may be located in places on the AFE vehicle that have a "tilted" plasma layer above the antenna and its ground plane.

This paper discusses this new analytical model and its application to inhomogeneous electron density profiles that have been computed by workers in the Computation Fluid Dynamics community for the AFE experiment. Numerical solutions to the equations will be discussed, and those results will be compared to antenna performance predictions based on less rigorous methods.

# ELECTRON PLASMA WAVES EXCITED BY A LOADED ANTENNA

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In plasma wave experiments, it is important to excite or to receive plasma waves efficiently. The disk shaped antenna have been used so far as a typical radiating and receiving antenna for plasma waves. It is clarified, however, that the disk antenna shows ineffectiveness for the excitation of electron plasma wave(S.Ohnuki, et al., J. Appl. Phy. 49, 1, 138-145, 1978) when the ratio of $r/\lambda_D$ is large, where r is the radius of the disk and $\lambda_D$ is the Debye length. In order to improve this defect, we use a thin wire ring antenna, i.e. a circular monopole loop antenna for the radiation of electron plasma waves. A thin wire antenna may not perturb the plasma compared with the disk antenna, and it has been shown that a two-element ring antenna has a good radiating characteristics for electron plasma waves(Y.Morita, et al., Tran. Inst. Electron. Commun. Engrs. Japan, J61-b, 420-421, 1978).

In this report, we study a coil loaded two-element ring antenna including a feeder in a warm plasma as a boundary-value problem. The element 1 and element 2 are connected respectively to the inner and outer conductor of a coaxial feeder. The lumped load is attached to the feeding point of element 2. It constitutes asymmetrically driven antenna. Then the undesirable current flows the outer surface of the feeder. In order to facilitate the analysis, the antenna system is decomposed into the zero phase component and the normal phase component. A lumped load is replaced by a equivalent slice generator. The basic equation that govern this system is Maxwell's equations and the linerlized hydrodynamic equations for warm electrons and cold ions. However, Landau damping is considered to estimate the effects of the feeder, because it is inherent for plasma waves and the Landau damping rate is approximately constant versus frequency, which has been demonstrated experimentally (H.Delfler & T.C.Simonen, Phy. Rev. Lett. 17, 172-175, 1966). The integral equations for the current are derived for the both cases, applying a electrically boundary condition at the antenna surface. Using the moment method, the current distributions and the input inpedances are calculated for various loads. The current distributions of element 1 and element 2 are triangular in shape and opposite in phase, when the element spacing is 5mm and antenna dimensions are 15.5mm in radius and 0.5mm in wire radius. The real part of the input impedance increases slightly as the inductive load increases. Whereas the imaginary part decreases roughly proportional to the increasing of the load. The wave potential for electron plasma waves launched from the loaded two-element ring antenna becomes large by a factor of about 4-6 compared with the case of the unloaded one-element ring antenna, which is substantiated experimentally.

## Monday AM

URSI-B Session 9

**Waveguides and Transmission Lines I**

*Chairs*: W. Matthews, Ford Aerospace; S. T. Peng, New York Institute of Tech.

*Room*: San Carlos *Time*: 8:15–12:00

# ABSORBING BOUNDARY CONDITION FORQUASI-STATIC ANALYSIS OF MICROWAVE TRANSMISSION LINES

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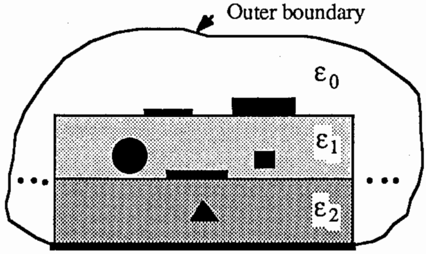
*Electromagnetic Communication Laboratory*
*University of Illinois, Urbana, Illinois 61801*

The Finite Element method (FEM) is a versatile tool for analyzing complex electromagnetic problems involving inhomogeneous dielectrics, as for instance single or coupled microstrip lines. However, when applying FEM to open geometries, one must address the difficult problem of properly truncating the region in which the differential equation is being discretized, in order to limit the number of unknowns to a manageable size without introducing too much error in the solution. Two approaches to obviating this truncation problem for a microstrip line geometry are: (i) introduction of a perfectly conducting shield that encloses the line entirely, and renders it a closed region problem; (ii) using an infinite element in the asymptotic regions. However, the introduction of a p.e.c shield can perturb the line characteristics substantially, unless the shield is moved to a distance that is large compared to the dimensions of the line, and a large number of mesh points is used in the formulation. On the other hand, the infinite element approach requires an accurate asymptotic expansion of the potential over the infinite element, followed by an integration in closed form over an infinite region.

The purpose of this paper is to show how we can use a local boundary condition on the outer boundary to truncate the FEM mesh at moderate distances from the line, without significantly affecting the line characteristics. This local condition, which is an absorbing boundary condition (ABC), specifies the normal derivative of the potential u in terms of its first and second order tangential derivatives, $u_t$ and $u_{tt}$, respectively. It takes the form $\frac{\partial u}{\partial n}=\bar{\alpha}u+\bar{\gamma}u_t+\bar{\beta}u_{tt}$, where $\alpha$, $\beta$ and $\gamma$ are specified in terms of the geometry of the outer boundary that can be arbitrary in shape and may be chosen to conform to the geometry of the transmission line structure in order to reduce the number of mesh points. The paper presents numerical results for the impedance of single lines, and self and mutual capacitances for multiple lines, derived by using the absorbing boundary condition and shows that the results compare well with the previously published values obtained by using other methods.




Multiconductor transmission line structure.

# EQUIVALENT CIRCUITS FOR MULTIPLE DISCONTINUITIES IN COAXIAL LINES

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In this paper we present a technique for deriving the equivalent circuit of a inhomogeneously-filled coaxial line with multiple discontinuities, a geometry that is encountered in many practical situations. The discontinuities may be in the form of steps in both the inner and outer conductors of the line, and may also be present in the dielectric fillings of the guide. While the isolated step discontinuity problem in a homogeneously-filled waveguide has been analyzed in the past by Whinnery and Jamieson, the multiple discontinuity case in a partially-filled guide has not been thoroughly investigated. An approximate generalization of the Whinnery and Jamieson approach yields an equivalent circuit containing discontinuity capacitances for each step that fails to adequately account for the higher-order mode interaction inevitably present in the multiple discontinuity case, particularly when the separation is small. Furthermore, these capacitances are frequency-invariant and do not adequately model the problem at high frequencies. The purpose of this paper is to present an analysis that attempts to correct both of these deficiencies.

To illustrate the application of the method, the double discontinuity problem in a coaxial line is investigated using the mode-matching method, followed by the the extraction of a frequency-dependent equivalent circuit that is helpful in designing various coaxial transition systems. As a first step, the propagating as well as evanescent modes that can exist in various regions of the homogeneously or inhomogeneously-filled coaxial guide are derived by solving transcendental determinantal equations. A system of coupled integral equations is derived next for the unknown aperture field distributions at the two discontinuity planes, and solved via the method of moments. Measurable quantities such as the scattering parameters for the discontinuity regions are then computed. The numerical convergence of the procedure is verified by increasing both the number of modes retained in the interaction region and the basis functions used in the representation of the aperture fields. Plots of the aperture fields, distribution of higher-order modal coefficients, return loss, and the transmission coefficient are obtained for a range of frequencies, using the distance between the two discontinuities as a parameter. Normalized modal coefficients are examined to ensure that sufficient number of modes have been retained in the field expansions. Conservation of power criterion is also imposed as an additional check of the accuracy of the computed results. Finally, the equivalent circuit derived from the present approach is compared to that obtained from the modified Whinnery and Jamieson method and the differences are pointed out.

# COMPUTATION OF THE IMPEDANCE PROPERTIES OF SLOTS IN RECTANGULAR WAVEGUIDE INHOMOGENEOUSLY LOADED WITH A DIELECTRIC SLAB

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Essential in the design of slotted waveguide arrays is a quantitative knowledge of the properties of the individual slots, either in the form of scattering coefficients or as equivalent network parameters. The present paper describes the computation of such results for transverse and longitudinal slots in the broadwall of rectangular waveguide that is inhomogeneously loaded with a centrally placed dielectric slab.

The dyadic Green's functions of the electric and magnetic type, for magnetic current sources, has been derived by the authors for such inhomogeneously loaded rectangular waveguide. This result has been used to extend the integral equation formulation for slots in homogeneous rectangular waveguide (R.W.Lyon & A.J.Sangster, IEE Proc. Pt.H, Aug.1981) to the present inhomogeneous case. These integral equations have been solved for the slot properties using the method of moments technique. The numerical formulation has been checked by setting the relative permittivity of the central slab to unity, in which case reduction to the conventional homogeneous waveguide situation occurs, yielding results identical to those published elsewhere.

The results of a parametric study of the properties of slots in the inhomogeneously loaded waveguide is described. These show the dependance of slot equivalent network properties (and hence their scattering parameters) on : the slab permittivity and thickness; whether the slots straddle a dielectric region only, an air region only, or a region partly dielectric and partly air; and the waveguide dimensions (eg. the effect of reduced height). The said behaviour is compared to that for slots in conventional homogeneous waveguide.

# RESONANT MODES IN CYLINDRICAL CAVITIES LOADED WITH GYROTROPIC MEDIA

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Finite Integration Technique (T. Weiland, URSI Int. Symp. on EM Theory, 537-542, Budapest 1986) has been employed to formulate an algebraic eigenvalue problem whose eigenvalues are the resonant frequencies for rotationally symmetric cavities inhomogeneously loaded with anisotropic and non-reciprocal (i.e. gyrotropic) media such as microwave ferrite. Two different eigenvalue formulations result, one for the modes with no field variation with the angle of azimuth (modal index m=0) and one for the modes with sine/cosine field variation with the angle of azimuth (m>0).

A mixed field formulation employing $\phi$-directed electric and magnetic field components of m=0 modes, leads to a real quadratic eigenvalue problem. The eigenvalue problem shows that pure TE or TM modes can not exist in gyrotropic cavities, that is even the modes with m=0 are hybrid. Pure TE or TM modes can exist, however, in the case of "uniaxial" media, characterized by permittivity/permeability with zero off-diagonal tensor elements.

Magnetic field formulation has been employed for m>0 modes in cavities with magnetic gyrotropy (tensor permeability), leading to a complex generalized eigenvalue problem. This formulation shows that the "degenerate" modes (R.F. Harrington, Time-Harmonic Electromagnetic Fields, 213-215, McGraw-Hill, 1961) can not exist in gyrotropic cavities.

The abscence of pure TE/TM and the "degenerate" hybrid modes is caused, in the case of the magnetic gyrotropy, by the cross-coupling of magnetic field components perpendicular to the direction of the bias (d.c.) magnetic field. In technically important case of axially magnetized ferrite, the coupling is between $\phi$-directed and r-directed magnetic field components.

# A NUMERICAL SOLUTION FOR LOSSY, STRIPLINE TYPE, TRANSMISSION LINES

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An abundance of material has been presented on the topic of numerical solutions of waveguide and transmission line problems. However, the vast majority of papers either ignore loss or treat it as a perturbation. In addition, much of the work has assumed the validity of a TEM or quasi-TEM form of solution. This paper presents a numerical based computer routine which relaxes these restrictions.

The considered geometry is a stripline type transmission line in which a center conductor is surrounded by a dielectric region, and finally by a sufficiently thick outer conductor which totally encloses the inner structure. Except for the above restrictions, the cross sectional geometry is arbitrary. The conductors and dielectric are allowed to have a finite conductivity and loss tangent respectively. The material properties are assumed to be homogeneous, isotropic, and non-magnetic in the current research.

With the use of the Fourier transform along the longitudinal direction, the full-field problem is reduced to two dimensions. Via the equivalence principle, a set of integral equations is obtained for the electric and magnetic fields in terms of equivalent sources along the two boundries between the dielectric and the conductors. By matching both electric and magnetic tangential field components at the boundries, a set of eight coupled integral equations are obtained. These equations may be solved by the method of moments. To obtain the propagation constant of the lossy guiding structure, the resultant matrix must be forced to have a null determinant for the proper propagation constant. In a measurement situation, the propagation would be determined and the material parameters may be estimated by again enforcing a null matrix determinant. The important feature of this work is the inclusion of the loss mechanisms for both the conductors and the dielectric without requiring a low-loss assumption.

# ACCURATE SOLUTION OF HOMOGENEOUS WAVEGUIDES WITH ARBITRARY SECTION.

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Several methods have been developed (J.B. Davies, Proc. IEE, 33-37, 1972) for the analysis of general cross-section homogeneous waveguides: Schelkunoff methods, which is the objective of this paper; full numerical methods like finite differences or finite elements; Transverse Resonance Methods, etc.

In this paper, the importance of an accurate solution of the eigenvalue problem will be shown and a comparative study of the results obtained by means of two usual techniques employed for the analysis of arbitrary hollow waveguides, based on Schelkunoff formulation, will be presented. Both of them give a complete description of fields in terms of expansion series of cilyndrical functions.

The boundary conditions can be imposed in two different ways: a) in a finite number of discrete points of the waveguide closed contour (point-matching method) (R.H.T. Bates, IEEE Tr. MTT, 185-187, 1967); b) on the whole contour by means of functional integral equations (integral adjust) (E. Kuhn, Proc. 15ª EMC, 715-720, 1985).

Significant characteristics of both methods can be summarized as follows: 1) point-matching adjust: less complex to formulate, it doesn't need to solve numerical integrals and it requires less CPU time. 2) Integral adjust : a quicker convergence is achieved (only five terms in the summatory are enough to give a good accuracy of wavenumbers and a good description of the E.M. field), and no generation of systematic errors due to points election.

The truncated circle waveguide has been analysed by means of both methods and a comparison between them is stablished. Quantitative results of wavenumbers and field plots of the fundamental and higher order modes will be presented.

# IMPROVED EQUIVALENT CURRENTS FOR A PLANAR CURVED EDGE

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Equivalent edge currents (MEC) and/or their counterpart in terms of incremental length diffraction coefficients (ILDC), provide an effective tool for the high-frequency description of the far-field scattering from edges at any aspects of illumination and observation.

In applying this technique to calculate the RCS ($\sigma$ ) of a perfectly conducting circular disc, it was found that the use of the equivalent edge currents of a locally tangent half plane yields numerical results that are not completely satisfactory, even if higher order interactions are included. This suggests that an additional contribution may arise due to the curvature of the edge. Also this suggests that in treating the scattering by a planar curved edge, the use of improved equivalent edge currents of a locally tangent disc is more appropriate.

In this paper, high frequency expression of the equivalent edge currents are presented for the canonical problem of a locally tangent disc with radius a. The solution is obtained via a perturbative method, by introducing into the expression of the scattered field, in addition to the contribution from the locally tangent half plane, a term which depends on the radius a of curvature. A Sommerfeld spectral integral formulation for this additional term is obtained by solving an inhomogeneous Helmholtz equation. An explicit expression of the spectrum is determined for distances from the edge $r<a$. Next the above expression is used to find the surface currents on both faces. Then, their radiation integral along the ray path and the Sommerfeld spectral integral are recognized as a Laplace Transform pair. Thus, the spectrum directly furnishes the expressions for improved equivalent currents, after evaluating it at a point that depends on both the ray path and the observation directions.

It is found that in the axial direction the present solution yields an additional term into the asymptotic expression for $\sigma/\sigma_{po}$. It is noted that this provide a significant contribution in addition to those that may be obtained by a conventional application of the solution for the half plane. Also, numerical results for $\sigma/\sigma_{po}$ are found in a very good agreement with the exact solution up to $ka = 2$.

It is worth pointing out that outside the caustic region, the stationary point contributions to the radiation integral of the equivalent currents along the edge provide a useful correction to a conventional GTD description of the scattering phenomenon. Consequently, it is suggested that the expression for the field on the Keller cone given by these improved equivalent edge currents, may be usefully employed when applying GTD to the case of planar curved edge.

# NONSTANDARD VARIATIONAL ANALYSIS OF WAVEGUIDES WITH IMPEDANCE BOUNDARIES

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In this paper, the nonstandard variational method previously applied to real problems (I. V. Lindell, IEEE Trans. Microwave Theory Tech., vol MTT- 30, no. 8, pp. 1194-1204, Aug.1982., and M. I. Oksanen, I. V. Lindell, to be published in IEEE Trans. Microwave Theory Tech. in Jan. 1989) is extended here to problems with complex-valued functionals arising in waveguide and resonator analysis involving impedance boundaries. We consider a straight waveguide of radius $a$ with an impedance boundary. The propagating wave can be expressed in terms of the Hertzian potentials which satisfy the scalar Helmholtz equations. The boundary of the guide is given by the boundary condition of the Leontovich type. The variational method can then be constructed by identifying Hertzian potentials as the unknown trial fields, the Helmholtz and Leontovitch equations excluding the fields as the operators of the problem and defined on the cross section and at the boundary of the guide, respectively. By using a symmetric inner product the operators can be proved to be self adjoint with respect to these inner products, and the resulting functionals are stationary formulae in the vicinity of the correct solution, the eigenvalue of the problem. In the nonstandard variational method, this eigenvalue can be chosen here as the propagation constant, the boundary impedance, or the cutoff wavenumber. Various choices lead to different stationary functionals. The analysis includes hybrid HE and EH modes and TE and TM modes, whose mutual functional relationships are inferred, also.

To exemplify the method, cutoff wavenumbers of the basic hybrid mode in a waveguide with a resistive boundary are calculated, and propagation constant and attenuation in a waveguide with a resistive or a complex boundary are prescribed for TE or TM modes. Finally, stationary functionals for a two-dimensional resonator with complex boundaries are given. Numerical results for the resonator cover set of cutoff curves drawn in a complex impedance plane. In all examples, elementary polynomial complex functions are used with one or two optimizable parameters. Thus the method is essentially simpler than the exact analysis involving Bessel functions with complex arguments. The accuracy of the present method is studied by comparing the results with the exact eigenvalue solutions. Variational method is seen to predict eigenvalues within errors ranging from 0.1 % to few % in the regions of interest.

# OPEN DIELECTRIC WAVEGUIDE T-BRANCH SOLVED FROM THE RIGOROUS BOUNDARY VALUE POINT OF VIEW

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The widespread use of dielectric waveguide Y- and T-branches of open type have stimulated many theoretical studies. In contrast to Y-branch, T-branch has not yet been discussed precisely from the point of view of the boundary value problem, even if it is two dimensional, because it is impossible to solve its boundary value problem with mathematical completeness. This paper challenges for the first time to obtain the rigorous solution of T-branch from the boundary value point of view, and clarifies its virtual branching characteristics as precise as possible.

The mathematical difficulties in the analysis of T-branch are clear when the power splitting of the input surface wave mode from the vertical line of T is considered.(Hereafter, this line along the z-axis is referred to as the input guide, while the horizontal line along the y-axis is referred to as the output guides.)

For solving such a problem, it is inevitable to express the possible field on the discontinuous boundaries with the mathematical completeness, in order to apply the mode matching method to the given boundary conditions. As for the input guide, it is well-suited to express the complete field on it in terms of the elementary fields of both the surface wave modes and the radiation wave on a dielectric slab at any plane transverse to the z-axis which is parallel to the dielectric slab side-walls (x-y planes) of the output guides. If following this expression, it no longer makes sense to express the field on the output guides in terms of the elementary fields defined at a plane transverse to the y-axis.

Instead, the field on the output guide and its surroundings should be expressed only by the radiation wave defined on an infinite x-y plane transverse to the z-axis, because the discontinuous boundaries to be considered here are the specific two planes among those x-y planes. However, the field mentioned above never exhibits the net power flow along the y-axis because of the perfect standing-wave type expression of radiation wave. Looking this result from the point of view of the excitation condition, we may understand that the problem under consideration is same with that the nominal input surface wave modes (the incoming wave component of the standing-wave) are considered from the output guides, in addition to the virtual input surface wave mode.

Since the virtual branching characteristics are obtained when the effect of such nominal input modes is canceled, we therefore show in this paper a possible method to cancel it by considering one more excitation problem in which the surface wave mode is incident from both of the output guides, while the input guide is considered as the semi-infinitely extended dielectric layers. In such an analytical process, the microwave network approach based on the non-unitary branch matrix is effectively used.

The precise analysis reported here can be very important when T-branch with very low-loss due to radiation is synthesized in millimeter-wave and optical frequency regions.

# REFLECTION OF MODES NEAR CUTOFF AT THE EDGES OF A LINEARLY TAPERED WAVEGUIDE

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In a linearly tapered waveguide, the fields corresponding to different modes propagating toward the apex of the waveguide will be reflected back from different positions in the guide. From a ray optical consideration, the reflection of an nth mode occurs at a distance $\rho_{cn} = n\pi/k\phi_o$ from the apex, where k is the free space wavenumber, $\phi_o$ is the angular span of the tapered waveguide, and $\rho_{cn}$ is the radius of the modal ray caustic circle of the nth mode. Within the waveguide at a distance less than $\rho_{cn}$ from the apex, the fields of the nth mode become evanescent. If the tapered waveguide does not extend to the apex, but is truncated at a distance $\rho_o$ from the apex, those modal fields whose $\rho_{cn} >> \rho_o$ will still experience a total reflection, while those with $\rho_{cn} << \rho_o$ will leak energy into the exterior region and also be partially reflected into different modes. The modal reflection of the latter can be evaluated using a technique which combines the geometrical theory of diffraction with the equivalent current method since the fields of those modes at $\rho_o$ ( $\rho_o >> \rho_{cn}$ ) can be expressed nicely in terms of a set of modal ray fields. However, that technique is not directly applicable to calculating the reflection of a waveguide mode with $\rho_{cn} \approx \rho_o$ , because its modal field, which lies within a cutoff transition region, can not be expressed as a sum of simple ray optical fields. In this paper, we present a method for evaluating the reflection of modes near cutoff (i.e., with $\rho_{cn} \approx \rho_o$ ) from the edges of a linearly tapered waveguide. The near cutoff modes are expressed as integrals of plane wave spectra. The geometrical theory of diffraction is employed to find the diffracted field of each plane wave spectrum at the aperture of the waveguide. A knowledge of the aperture field then enables one to find the reflected modes. The result of this method may also serve as a reference for those of other high frequency techniques.

## Monday AM

### URSI-B Session 10

### Antenna Elements I

*Chairs*: O. G. Villard Jr., SRI International; L. Botha, CSIR

*Room*: San Juan *Time*: 8:15–11:40

# EFFECTIVE HEIGHT OF A SMALL ANTENNA

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The optimum design of an electrically small receiving antenna that meets certain allocated space requirements necessitates the determination of its input impedance and effective height. It is well known (Schelkunoff and Friis, *Antennas: Theory and Practice*, Ch. 10, J. Wiley & Sons, 1952) that these antenna parameters are related to the electrostatic charge distribution on the antenna. An analytical expression for the input reactance of electrically short monopoles has been derived by Casey and Bansal (*Electron. Lett.*, **24**, 1021-1022, 1988). Numerical results for the charge distribution, capacitance, and effective height of cones both with and without a top load have also been reported by Wilton (AFOSR-TR-76-1078, 1976). In this paper, the definition of effective height is extended to the case of a conducting body of revolution above a ground plane. A method of moments algorithm is presented that computes the electrostatic charge distribution along a body of revolution and is applied to determine the effective height of an arbitrary monopole antenna. Results are presented for monopoles of various geometries both with and without a top load.

# DESIGN OF SMALL-COMPARED-WITH-THE-WAVELENGTH UNIDIRECTIONAL ANTENNAS

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## ABSTRACT

The traditional view of small antennas is that, owing to their size, their directive patterns cannot be other than very simple. An example is the conventional loop, which (when signals having arbitrary polarization are assumed) is characterized by two point nulls 180 degrees apart. Point nulls have little usefulness when the antenna must reject signals having several components at different arrival angles, as is the case of sky-wave transmissions at HF. It is desirable to have a null which is elongated in one dimension so that it can reject more than one signal component at a time, assuming these to be in a common plane, which is normally the case. Such a pattern turns out to be obtainable with a shielded vertical loop and a direction-ambiguity-resolving whip antenna, provided that both the whip and the station direction lie in the plane of the loop, and suitable precautions are taken. A null in these circumstances has a maximum depth at the horizon and reasonable depth even at 45 degrees elevation. As a result, this configuration permits good rejection of fading sky-wave signals by an amount which can be in excess of 20 dB. A particularly simple and foolproof configuration, called the "coplanar twin loop," is described. Although three controls are needed, two are straightforward and only one requires significant adjustment. Very low impedance levels, which are desirable in indoor reception, can be achieved.

# Radiation Properties of Printed Circular Loop Antennas

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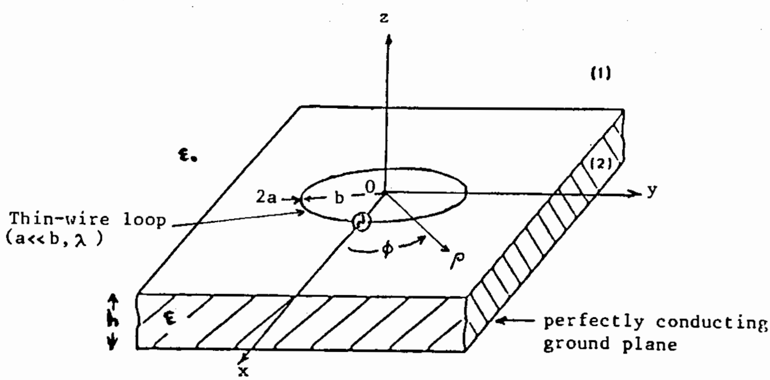
The radiation characteristics of a printed circular loop antenna are studied. The Figure shows a circular wire-loop antenna printed over a grounded dielectric substrate of dielectric permittivity $\epsilon = \epsilon_r \epsilon_0$. The ground conductor is assumed to be perfect. A full-wave analysis is presented. The vector and scalar potentials are first determined as Sommerfeld integrals in the complex plane of the radial component $k_\rho$ of the wave vector. Then, the fields are derived from Maxwell equations. The far-fields are obtained by asymptotic techniques. The effects of the substrate thickness, dielectric permittivity (possibly complex) on the radiation pattern are to be studied, particularly on the directivity and antenna quality factor.



# THE BEHAVIOUR OF FOLDED DIPOLE ANTENNAS ON CONDUCTING MASTS

Louis Botha[1*] and Derek A. McNamara[2]

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Arrays of vertically stacked, or azimuthally distributed, folded dipole antennas mounted on conducting masts are widely used for communications purposes. While some antenna design handbooks make brief reference to such configurations (R.C.Johnson & H.Jasik, Antenna Engineering Handbook, McGraw-Hill, 1984), quantitative information does not appear to be readily available in the literature. Most of the references are those which date back some years now (G.S.Carter, Proc. IRE, 1943), and which only contain the rather restricted information available before digital computers made comprehensive parametric studies feasible.

In the present paper the results of a parametric study of the above-mentioned problem, using a moment method analysis approach, are presented in the form of a set of performance curves. The directivity and impedance properties of individual folded dipole antennas mounted at various radial distances ($R/\lambda$) from the centre of masts of different diameters ($D/\lambda$) is considered. Hereafter similar data is given for arrays of vertically stacked folded dipoles. Finally, arrays of N azimuthally distributed folded dipoles are discussed, clearly showing the directivity and omni-directionality properties for different N, $R/\lambda$ and $D/\lambda$ combinations.

An attempt is also made to present the data in the convenient form of parametric graphs and synoptic charts (C.W.Trueman, T.J.Pavlasek and S.J.Kubina, IEEE Trans., EMC-19, 365-370, 1977) particularly useful to designers.

# RECEIVING AND SCATTERING PROPERTIES OF AN IMAGED MONOPOLE BENEATH A LOSSY SHEET

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In an effort to reduce the backscattered field, aircraft antennas may be covered with a layer of lossy material. It is found that the scattered field is reduced dramatically, while the power received by the antenna, while also reduced, is maintained at an acceptable level.

In this paper, the simple structure of a thin cylindrical monopole antenna above an inifinite conducting groundplane, and below a thin infinite sheet of lossy material, will be considered. By analyzing both the scattering and transmitting cases, and using superposition, the field in the backscatter direction and the power received by the antenna are calculated, in the presence of plane wave illumination.

A transform domain approach is used to solve for the currents on the antenna. A Green's function, consisting of Sommerfeld type integrals, is established to determine the vertical field produced by a vertical current source in the layered environment. The currents on the antenna are then found by solving a Hallen type integral equation.

# IMPROVED BANDWIDTH CAVITY BACKED SLOTS

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It is well known that the addition of a cavity behind a slot radiator in an infinite groundplane will greatly reduce the useful bandwidth of the slot. The reason for this reduction in bandwidth is easily demonstrated on a Smith chart where one observes that as the frequency is changed, the admittance of the cavity changes in the same manner as the admittance of the slot. Thus when the two are added together, the total change in admittance is quite rapid. Such is not the case when a dipole is placed in front of a groundplane. For the dipole case, the addition of the groundplane improves the overall bandwidth because the dipole admittance moves in a direction opposite that of the groundplane, thus the two effects tend to cancel one another and the admittance changes very little. A common technique for increasing the bandwidth of the slot, is to reduce the cavity admittance by introducing loss in the cavity, which reduces the overall efficiency of the antenna.

This paper will demonstrate a method for improving the bandwidth of the cavity backed slot through the addition of parasitic elements near the slot radiator. It will be shown that the admittance introduced by these elements can be made to counteract the admittance introduced by the cavity, and thus the bandwidth of the slot radiator can be improved without the addition of lossy material. The design of the complete antenna, consisting of radiating slot, cavity, and parasitic elements is easily accomplished on a Smith chart and will be demonstrated.

# HYBRID ANALYSIS FOR RADIATION FROM SLOT ANTENNAS ON COATED SURFACES

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A current-based hybrid analysis is developed for slot antennas on electrically large coated surfaces that satisfy the impedance boundary condition (IBC). As in the hybrid analysis for perfectly conducting radiators (L. N. Medgyesi-Mitschang and D.-S. Wang, JINA '88), a complex radiator is decomposed into parts solved by the combination of the method of moments (MM) techniques and the asymptotic methods. The MM representation is used for the surface currents around the slot antennas and the Ansatz currents derived from the asymptotic methods are used for the induced currents on the remaining surface. For coated surfaces, the slot antennas under the coating are replaced in the present analysis by equivalent magnetic current sources exterior to the coating.

This investigation discusses the effectiveness of the present hybrid analysis by examining the problem of radiation from an electrically large body excited by circumferential slot antennas. The Ansatz currents for the induced currents are derived from the asymptotic expansion of the Mie solutions for the radiation from coated spheres excited by a circumferential slot. This investigation also discusses the choice of the integral equation formulations used and the efficient coupling between the MM and the Ansatz-current regions. Ansatz currents for arbitrarily smooth surfaces are subsequently derived to extend the hybrid analysis to arbitrarily shaped 3-D radiators. The numerical results from the hybrid analysis are compared to those from the entirely MM-based solutions.

# L-BAND SHAPED BEAM ANTENNAS

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There is considerable interest in shaped broadbeam, circularly polarized antennas for low and medium altitude orbiting satellites at L-band frequencies. This paper describes two types of compact antennas: (1) quadrifiar helix; and (2) shaped reflector.

Quadrifiar helix antennas can achieve conically shaped radiation pattern. We will discuss various helix parameters which have effects on the radiation patterns and axial ratios. When the pitch of a helix increases, the radiation peak moves toward low elevation angle. In shaped reflector antenna, the reflector shaping has been evolved using Geometrical Optics approach on only amplitude basis to results in a reforcement of a signals at required angle. The shaped reflector section is approximately 2$\lambda$ diameter for the RADARSAT L-band antennas.

# ENERGY POWER RELATIONSHIPS IN BICONICAL RADIATORS

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A recently completed numerical analysis of biconical transmitting antennas permits calculation of average and reactive power versus distance from the terminals. Knowledge of reactive power and the conservation of energy permit us to calculate the magnitude and phase of the reactive energy per unit length. Then a Gaussian surface centered on the terminals permits calculation of the radiative Q, for any radius.

Since Q(r) is proportional to the ratio of external reactive energy to output power and since energy is necessarily positive, it follows that $Q(r_1)<Q(r_2)$ if $r_1>r_2$. Therefore the terminal value, Q(0), necessarily exceeds that measured at the terminus of the antenna arms, Q(a).

Chu (L.J.Chu, J Appl Phys, 19, 1663, 1948) used a linear electric multipolar expansion technique to discuss the frequency dependence of electrically small, spherical radiators, using Q(a). He concluded that, as the size to wavelength ratio decreased, the needed surface currents increased so precipitously as to obviate a practical device. Since ideal biconical transmitters support only linear electric multipolar sources, within the limits of roundoff error, we are able to directly verify Chu's conclusions.

Detailed tabular power-energy results will be given for several conical angles at several arm lengths: electrically short antennas, the first resonance, and electrically long antennas. Plots of reactive power and energy versus radius from $r=0$ through $r=\infty$ will be shown.

## Monday PM

### Joint AP-S, URSI-B Session 13
### Numerical Methods: Wire Antennas

*Chairs*: A. F. Peterson, U. of Illinois–Urbana; F. X. Canning, Rockwell
*Room*: Oak    *Time*: 1:15–5:00

# Electromagnetic Scattering by a Straight Thin Wire

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**Abstract**

The travelling wave energy which multiply diffracts on a straight thin wire is represented as a sum of terms which can be individually examined in the time domain, each with a distinct physical meaning. These analytic expressions can be extended to lossy wires with a simple approximate modification using the propagation velocity on the wire as derived from the Sommerfeld wave on a straight lossy wire. Both the perfectly conducting and lossy wire solutions are compared to Moment Method results.

# CONCERNING THE RELIABLE COMPUTATION OF NEAR-FIELD DEPENDANT OBSERVABLES FOR WIRE ANTENNAS

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In many instances the primary aim of an electromagnetic analysis of wire antennas is to obtain the values of a few important quantities or *observables* with a rather high accuracy. These include antenna input impedance, efficiency and inter-antenna coupling. Their reliable computation is of vital importance since design decisions are made on the basis of the values of such observables. In spite of this, while much work is at present underway on the extension of the electrical size of problems for which computation of far-zone radiation is feasible, there appears to be relatively little activity on the investigation of improving the reliability of the computation of the above near-field dependant quantities.

In view of the importance of the precise values of such observables, one should be willing, if necessary, to expend a modest amount of computational effort on any such calculation. Indeed, it is often remarked by practicing antenna designers that if one cannot compute these observables with sufficient reliability that decisions may be based on them, then <u>any</u> attempt at their computation at all is of doubtful value, and puts into question the real use of computational electromagnetics in antenna engineering practice.

The present paper will highlight some of the weaknesses of existing general purpose moment method thin-wire codes in computing near-field observables for even geometrically simple antennas. This will be followed by a discussion of improved source models for use with thin-wire antenna analysis, and results will be presented and compared to those obtained by the more conventional ones used in existing general purpose computer codes. This will be followed by a discussion of the use of alternative expressions for the computation of certain observables instead of the direct use of the segment current vector obtruded as the moment method solution.

# A MULTIRADIUS, RECIPROCAL IMPLEMENTATION OF THE THIN-WIRE MOMENT METHOD

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Presented is an implementation of the moment method for electromagnetic analysis of multiradius thin-wire structures, including multiwire, multiradius junctions. It is an extension of the authors' uniradius bridge-current modification of J.H. Richmond's uniradius thin-wire theory. The method features an exactly symmetric mutual impedance matrix ensuring reciprocity between sources, it is unconstrained with respect to both the length ratio and the radius ratio of adjoining segments, and it permits the self-consistent inclusion of coaxial-cable sections in the configuration under analysis. The method is validated (a) through comparison with simplified theory and an alternative moment-method analysis on both an electrically small rectangular loop and a short coaxial cage transmission line, (b) through comparison with transmission-line theory for a two-wire line and a coaxial cable, (c) through comparison with measurements on a folded monopole antenna, a sleeve monopole antenna, and a log-periodic dipole antenna, and (d) through comparison with the uniradius bridge-current moment method and transmission-line theory for a bazooka-balun-fed dipole antenna.

The method is a filamentary-current approximation to the concept of tubular expansion and testing dipolar currents. As such, it can handle the case of thin coaxial tubular conductors. This enables one to analyze wire antennas or feed lines with coaxial stubs by modelling the stubs explicitly, rather than resorting to a transmission-line theory approach. The filamentary current approximation of course requires much less computer time than the exact surface current treatment.

The method has some applications where it is a significant improvement over other popular moment methods such as those in the NEC and MININEC computer programs. One improvement is the unique ability to handle thin coaxial tubular conductors, as described above. Another is the ability to accurately handle close-spaced parallel wires carrying a transmission-line mode. Some examples of this will be given, and comparisons will be made between this method, NEC and MININEC in order to identify the areas in which there is an improvement.

# ANALYSIS OF A WIRE ANTENNAS OVER THE EARTH BY MEANS OF THE MODIFIED DIAKOPTIC THEORY

Robert G. Kaires and Chalmers M. Butler
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The modified diakoptic theory is applied to the problem of a thin-wire antenna near the air-earth interface. Zero-order and first-order currents are obtained by solving a simple integral equation for current on short segments of the antenna, with the approximate current on each segment computed as if it were isolated from all other segments of the diakopted antenna. These zero-order and first-order currents are then used to construct the open-port currents needed in a variational expression for the elements of the open-port impedance matrix. The open-port currents and the open-port impedance matrix account for the presence of the air-earth interface via Green's functions incorporating Sommerfeld integrals. In computing the open-port impedance elements by means of the above-mentioned variational expression, one finds it computationally convenient to represent a given open-port current both as a linear combination of pulses and a linear combination of triangles. Numerical results (open-port impedances and final wire currents) are presented for selected wire antennas. For comparison, corresponding quantities are obtained from a MoM solution techniques applied to the antenna. Excellent agreement is observed for all cases considered. It is pointed out that, in the modified diakoptic theory, wire currents are obtained by solving a system of linear equations which is far smaller than is necessary in the MoM technique applied to the same problem.

# ANALYSIS OF MULTIPLE-JUNCTION WIRE ANTENNAS BY THE MODIFIED DIAKOPTIC THEORY

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A systematic method, based on the modified diakoptic theory, is presented for analyzing multiple-junction wire antenna structures, comprising both straight and curved wire segments. The theory is an extension of that developed for straight-wire antennas and incorporates both the exact kernel and the reduced kernel as is done in typical moment method techniques. Criteria for selecting port locations are discussed, and particular attention is devoted to characterizing the junctions for obtaining the zero-order and first-order currents used in the modified diakoptic theory. These zero-order and first- order currents are used to synthesize approximate open-port currents on the structure. Then, as is done in the straight-wire diakoptic analysis, the open-port impedance matrix employed in the diakoptic theory is determined from these approximate open-port currents in a variational expression. Numerical results (open-port impedances and final currents) obtained from this method for arbitrarily curved wires with junctions are compared with results obtained from a MoM solution for the entire wire structure. Excellent agreement is observed for all cases considered. As has been shown for the modified diakoptic theory applied to straight-wire antennas, the open-port impedance matrix of the diakoptic theory is of far lower rank than is the MoM impedance matrix for a given structure. Hence, results are obtained by the diakoptic theory by solving a lower-rank system of linear equations than is needed in the MoM technique applied to the same structure. This suggests three potential advantages of the modified diakoptic theory over the traditional moment method applied to the wire antenna. A given problem can be solved more accurately, a more complex problem can be solved, or a larger (more wire [length/wavelength]) problem can be solved.

# On the Excitation of a Wire Antenna by a Coaxial Aperture

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**Abstract**

The excitation of wire transmitting antennas by magnetic frill and ring currents is considered. Using piecewise sinusoidal test functions, closed form expressions for the elements of the voltage matrix (the reactions) are obtained for the linear antenna. Given in terms of exponential integrals and trigonometric functions these expressions facilitate the calculation and comparison of the two reactions; furthermore they determine conditions where the terminals may be adequately modeled by the more simple delta function generator.

For wire antennas of arbitrary shape, the Dyadic Green's function in vector wave function form is used to derive new, simple expressions for the near field of the magnetic frill and ring currents. These results are useful in calculating the reactions in this more general case.

## Monday PM

Joint AP-S, URSI-B Session 15

### Numerical Methods

*Chairs*: T. K. Sarkar, Syracuse U.; J. R. Mosig, EPFL

*Room*: Pine *Time*: 1:15–3:40

1:20 **Spectra of Integral Operators and Convergence of Iterative Solutions to Electromagnetic Scattering Problems** AP-S
M. Bleszynski,* Rockwell Science Center, T. Jaroszewicz, Univ. of California, Los Angeles

1:40 **A High-Frequency Iterative Method using the Combined Integral Equation** AP-S
R. B. Marks,* Delft Univ. of Tech.

2:00 **Analysis of Finite Structures using the CG-FFT Method and Discretizing Green's Function in the Spectral Domain** AP-S
E. Gago, M. F. Catedra,* Universidad Politecnica de Madrid

2:20 **Application of a Conjugate Gradient Method to the Synthesis of Planar Arrays** AP-S
T. J. Peters,* Aerospace Corp.

2:40 **Coffee Break**

3:00 **Geometrical Transformation of Bodies of Arbitrary Cross-Section for Numerical Computation** AP-S
H. Moheb,* L. Shafai, University of Manitoba

3:20 **The Application of the Lanczos Method of Minimized Iterations to Electromagnetic Scattering Problems** 90
R. G. Riechers,* Mission Reseach Corp.

# THE APPLICATION OF THE LANCZOS METHOD OF MINIMIZED ITERATIONS TO ELECTROMAGNETIC SCATTERING PROBLEMS

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The solution of electromagnetic scattering problems formulated as Fredholm integral equations is accomplished by reduction of the integral equation to a linear system of equations using the Method of Moments. The inherent limitation in such methods is the requirement for inverting a matrix of large order for electrically large scatterers.

The use of a method such as the Method of Successive Substitutions will yield the solution as an infinite series that can be truncated when a sufficiently good approximation to the solution becomes available. The limitation of this method is that the solution is given as a series in powers of a parameter of the problem. The convergence of the resulting series is dependent upon this parameter, and the norm of the Fredholm operator. If the method is used for solving problems of scattering by penetrable objects, this limits the usefulness of the method.

The S-Expansion solution is, for a matrix operator, a finite series; hence there are no convergence problems. The method is a member of the so-called $N$-step methods, and thus the solution can be obtained in a number of steps $\leq N$.

The S-Expansion is applied to scattering problems including; scattering by a two-dimensional dielectric strip, scattering by a thin dielectric circular cylindrical shell and scattering by a perfectly conducting square cylinder. Results will be presented that demonstrate the utility of the method for these types of scattering problem.

## Monday PM

URSI-B Session 18

## Waveguides and Transmission Lines II

*Chairs*: K. J. Webb, Univ. of Maryland; D. P. Nyquist, Michigan State University

*Room*: Carmel *Time*: 1:15–4:20

# COUPLED MICROSTRIP TRANSMISSION LINES: FULL-WAVE PERTURBATION THEORY AND EXPERIMENTAL VALIDATION

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The coupling between adjacent, parallel microstrip transmission lines in the micro/mm-wave PC/IC environment is studied both analytically and experimentally. A numerically efficient coupled-mode theory is obtained through a full-wave, EFIE-based perturbation approximation. The perturbation theory leads to propagation eigenvalue shifts associated with symmetric and antisymmetric coupling of both the principal and higher-order propagation modes. Experimental measurements are made on PC-board implementations of coupled microstrip pairs at micro/mm wavelengths to confirm the predicted coupling lengths.

A full-wave EFIE formulation for the currents on N coupled microstrip lines, located in the cover layer at the film/cover interface of a tri-layered conductor/film/cover environment, is based upon the Sommerfeld-integral representation of an appropriate electric Green's dyadic. The perturbation solution to those coupled EFIE's exploits a rapidly-convergent, modulated Chebychev series numerical solution for the isolated strip currents as the zero'th-order approximate induced current in the coupled system. Propagation eigenvalues $\zeta$ for coupled system modes satisfy

$$\bar{C}_{mm}a_m[\zeta-\zeta_{mp}^{(0)}] + \sum_{n\neq m} C_{mn}a_n = 0 \quad \ldots \text{ for } m = 1,2,\ldots,N$$

where $\zeta_{mp}^{(0)}$ is the phase constant for the p'th mode on the m'th isolated microstrip, $a_n$ is the current amplitude on the n'th strip, $\bar{C}_{mm}$ is a normalization constant, and the $C_{mn}$ are coupling coefficients involving field/current overlap integrals. For the case of two coupled lines, the propagation eigenvalues split and shift symmetrically away from their isolated limit as the microstrip become closely spaced. A simple coupled-mode theory leads to the coupling length in terms of the eigenvalue shifts.

The coupling length is measured experimentally, at micro/mm wavelengths on PC-board implementations of two coupled microstrip, to validate the perturbation-theory predictions for similar system parameters. A monopole microcoax probe is used to measure the axial electric field amplitude distribution along the coupled system. The probe is inserted through the conducting ground screen into the film and/or cover layers to measure the normal electric field there. A pattern of small holes is drilled through the PC board to implement probe insertion. A harmonic heterodyne detector assures measurement linearity. A new theoretical study of higher-order mode coupling is included.

# ON THE LIMITATION OF THE WEAK-COUPLING ASSUMPTION FOR CROSSTALK ANALYSIS IN A LOSSLESS INHOMOGENEOUS MEDIUM

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Two transmission lines are often described as being "weakly coupled" when the voltage and current induced on the receptor line do not alter the voltage and current on the source line. The equations which describe weak coupling have a simpler structure than those which characterize full coupling. Consequently, analytic solutions can be obtained for the weakly coupled equations which describe transmission lines imbedded within an inhomogeneous medium, and also lines which possess certain types of non-uniform coupling. Similar analytic solutions may not be possible for the fully coupled equations.

In this paper, the region of validity of results obtained under the weak-coupling assumption for two transmission lines with a common ground in an inhomogeneous medium is examined. This is accomplished by determining the relationship between the TEM propagation constants associated with both the fully coupled and the weakly coupled equations. All loss is neglected and the lines are assumed to be symmetric. For frequencies below a well defined cutoff, which depends on the length of the coupling region as well as the mutual and self capacitance and inductance terms, it is shown that the basic structure of the solution which describes full coupling reduces to the weak-coupling form. This cutoff frequency can often be several gigahertz; thus, the weakly coupled equations can be useful for a wide range of practical problems. Theoretical and experimental results are given in both the frequency and time domains for several trace geometries on circuit boards.

# USING CLOSED-FORM MODE SOLUTIONS AND FINITE DIFFERENCES TO ANALYZE THE POWER-HANDLING CAPABILITIES OF A RHOMBOID WAVEGUIDE

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and

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Recently, we have found that a uniform waveguide of 60-120° rhomboid (diamond shaped) cross section is a possible candidate for use in high-power microwave applications (C. E. Baum, Air Force Weapons Lab, Sensor and Simulation Notes, November 18, 1988). Assuming perfectly conducting walls, we have determined that some of the modes of this structure can be found in closed form by using the even and odd transverse electric and transverse magnetic solutions of an equilateral triangular waveguide (P. L. Overfelt, D. J. White, IEEE Trans. Microwave Theory Tech., *MTT-34*, 161-167, January 1986) and applying the Riemann-Schwarz reflection principle. Unfortunately, a complete set of modes for the rhomboid waveguide is not derived in this way. Conspicuously absent is the lowest-order mode, although the second lowest-order mode is known. Since the lowest-order mode must be known in order to predict the power-handling capabilities of the rhomboid waveguide, finite difference techniques are used to determine an approximate $TE_{10}$ eigenvalue and eigenfunction. A dimensionless efficiency factor (C. E. Baum, above) is computed, using the three lowest-order guided modes of the rhomboid guide. This factor is then compared with efficiency factors computed from other more standard waveguides, including the rectangular guide.

# POLARIZATION CHANGE IN WHISPERING-GALLERY WAVEGUIDE DUE TO TORSION AND TWIST

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Whispering-gallery waves are applied in acoustic, millimeter and infrared wavelenths with their forms of Airy-Hermite-Gaussian functions. They have a tendency to cling to a curved boundary, so this phenomenon can be regarded as successive reflections at a incident small angel $\theta$. In this paper, polarization change in helically-wound and twisted metallic waveguide is studied by geometrical optics treatment.

For toroidal metallic guide, the reflective wave will be elliptically polarized even if the incident wave is linearly polarized as metal has its complex index of refraction n+jk ( M. Born and E. Wolf, Principles of Optics, Pergamon, New York, 1970).

When the guide has the torsion t and twist with its twisted rate w, the polarization rotation comes about(X-S. Fang and Z-Q. Lin, MTT-35, 978-983, 1987).

Based on the above effects, if the incident electric field has its Jones vector $E_i = [\,E_n, E_b\,]^*$ , where n and b denote the normal and binormal directions of the Serret-Frenet frame, and * denotes transpose of a matrix , the reflective field $E_r$ can be presented as

$$E_r = \begin{bmatrix} r_n \exp(jd_n) & \\ & r_b \exp(jd_b) \end{bmatrix} \begin{bmatrix} \cos[(t+w)s] & \sin[(t+w)s] \\ -\sin[(t+w)s] & \cos[(t+w)s] \end{bmatrix} E_i, \quad (1)$$

where s denotes the propagation distance along the equator of the concave surface, $r_n$ and $r_b$ are the real parts with

$$r_n \exp(jd_n) = \{\cos\theta - T\}/\{\cos\theta + T\},$$

$$r_b \exp(jd_b) = \{(n+jk)^2 \cos^2\theta - T\}/\{(n+jk)^2 \cos^2\theta + T\}, \quad T = [(n+jk)^2 - \sin^2\theta]^{1/2}.$$

Based on (1), the polarization of eigenstates for whispering-gallery waves can be determined , and the additional attenuation due to the torsion and twist can be obtained by the factor $[1+ (t+w)^2\,]$.

# TLM ANALYSIS OF THE MODULATION OF A SIGNAL IMPRESSED ON A TIME-VARYING DIELECTRIC SLAB IN A RECTANGULAR WAVEGUIDE

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*and*
*Raj Mittra*
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The problem of scattering of a microwave signal by a dielectric slab whose characteristics vary as a function of time is not only challenging but interesting as well, as it finds some important practical applications. The time-varying nature of the dielectric medium precludes the use of the conventional Fourier transform approach applied to a cw solution, and the problem must be solved directly in the time domain. In this paper, we analyze the problem of a step-modulated microwave signal of frequency $f_1$ incident upon a dielectric slab placed in a rectangular waveguide, when the permittivity of the slab varies with time at a frequency of $f_2$. The problem is analyzed by using the method of the transmission-line modeling of 3-D electromagnetic fields, called the TLM method. The condensed-node version of the TLM method, which permits accurate modeling of material discontinuities and is very convenient for organizing the input data file describing the structure and the excitation, is employed to solve the modulation problem directly in the time domain. The temporal response is subsequently Fourier-analyzed to extract the modulation frequencies present in the spectrum of the reflected signal. It is shown that the reflected wave has the spectral content given by $f_1 + n\, f_2$, where n = .., -2 , -1,0,1,2,...., and the complex amplitudes of these intermodulation frequencies are determined. In the conventional form of the TLM method, the structure is described by various blocks whose material parameters are the same. However, in order to simulate the time-varying effects, the material block describing the dielectric slab as well as the excitation block describing the incident wave are now modified to accommodate new values at each iteration step. Numerical results are compared with those obtained previously for an infinite slab for a normally-incident plane wave using the finite difference time-domain approach, and the differences are pointed out.

# GUIDED WAVES IN AN OPTICALLY ACTIVE SLAB WAVEGUIDE

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In this paper, coupling between TE (transverse electric) and TM (transverse magnetic) modes in an optically active slab waveguide is investigated. We consider linear effects of chiral polymeric materials that possess the characteristic of optical activity intrinsically. Our starting equation is the wave equation given by

$$\nabla^2\vec{E} + \omega^2\mu_p\varepsilon\,\vec{E} + 2\omega\mu_p\xi\,\nabla\times\vec{E} = 0$$

where $\mu_p = \mu/(1-\omega^2\varepsilon\mu\alpha^2)$, $\xi = \omega\varepsilon\alpha$, and $\alpha$ is the measure of optical activity. Two eigenmodes that satisfy the above wave equation are right and left hand circularly polarized waves. However, eigenmodes for slab waveguides are TE and TM modes. This difference in eigenmodes causes fundamental difficulty in investigating wave propagation in an optically active slab waveguide. The consequences of coupling between TE and TM modes will be discussed. The results of optical experiments will be presented. The effects of this coupling on linear and nonlinear polymeric waveguides will also be addressed.

# An Exact Modal Solution for the Resonances in a Dielectric Resonator on a Grounded Substrate

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*ABSTRACT*

The applications of dielectric resonators (DRO) are currently of considerable interest in microwave integrated circuit technology. One of their most practical uses is in realizing high $Q$ tuned circuits on planar microwave circuits. Most of the work in the past on this problem has concentrated primarily on the lowest fundamental mode, the so called $TE_{01\delta}$ mode. This work investigates the general field solutions, and in particular, the *HE* modes on planar circuit configurations. These solutions are important because they will allow the design of multimode filters, and provide other flexibilities in component realizations on planar waveguiding structures.

In our approach the fields in all the regions involved in this complex geometry are expressed in terms of the two general types of cylindrical basis functions, (*TE* and *TM*) with unknown propagation factors, and coefficients. The relationships between the propagation factors in the various regions, and the coefficients of the basis functions in the various regions are established by judicious application of the electromagnetic boundary conditions at the interfaces between the various regions. These relations after some tedious manipulations lead to a system of homogeneous linear equations involving the unknown coefficients. The matrix associated with this system of equations has a null determinant around a set of discrete frequency regions indicating resonances of the DRO.

Numerical results on the general resonance characteristics of DROs on grounded substrates for various combinations of the physical, and electrical parameters will be presented. The results indicate that the exact field structures for this geometry cannot be given by a pure single mode (*TE* , *TM* or *HE*), as has been used in various approximate models earlier.

# MODAL DESIGNATIONS FOR COMPLEX AND BACKWARD-WAVE MODES IN RADIALLY INHOMOGENEOUS LOSSY WAVEGUIDES

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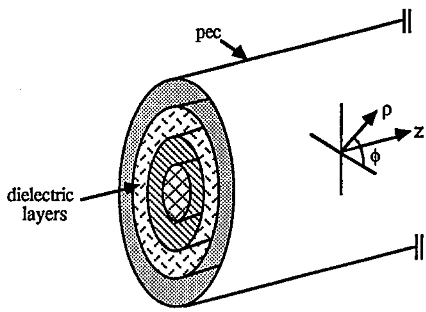
University of Illinois, Urbana IL

Dielectric-rod loaded circular waveguides have been investigated extensively in the past with many notable contributions from Clarricoats, Waldron and others. Recent applications for multiple dielectrics in layered circular waveguides have prompted the analysis, presented in this paper, for a circular waveguide containing any number of concentrically layered, and perhaps lossy, dielectrics.

The mode designations for these waveguides become blurred somewhat from those in a homogeneous waveguide since both $E_z$ and $H_z$ field components exit for all nonazimuthally symmetric modes. To the authors' knowledge, no consistent method for mode designations in these waveguides has been established. Here a designation is presented based on Snitzer's method (*J. Opt. Soc. Amer.*, pp. 491-498, May 1961) of comparing $E_z$ and $H_z$ field expansion coefficients in the innermost dielectric coupled with a mode tracing concept from Waldron (*Theory of Wave Guides and Cavities*, 1967). Using these methods, it will be shown that a new designation for backward-wave modes is needed. This new designation is more consistent with other properties of the wave such as the sign of the net power flow down the guide in addition to continuity in the axial wavenumber trace as some dielectric parameter is gradually modified, such as the dielectrics' radii. These designations will be further reinforced when the complex modes (which are known to always accompany the existence of propagating backward-wave modes in an axial wavenumber trace) are examined with dielectric losses present.

Finally, from these designations the concept of a cut-off frequency for a mode is examined when propagating backward-wave mode regions exist in the axial wavenumber traces. The frequency for which the group velocity vanishes and not necessarily when the phase velocity vanishes may perhaps be a more plausible notion for cut-off in these loaded waveguide arrangements.



## Monday PM

URSI-F Session 20

**Surface Scattering and Clutter**

*Chairs*: D. E. Barrick, CODAR Ocean Sensors Ltd.; C. Eftimiu, McDonnell-Douglas

*Room*: San Carlos *Time*: 1:15–4:00

1:20 **An Alternate Integral Equation for Scattering from Randomly Rough Conducting Surfaces** 102
G. S. Brown,* Virginia Polytechnic Institute

1:40 **Electromagnetic Scattering by a Dielectric Rough Surface in First-Order Wiener-Hermite Approximation** 103
C. Eftimiu, McDonnell-Douglas, C. W. Pan,* University of Wisconsin-Milwaukee

2:00 **Optimization of the Incoherent Power Scattered from a Rough Surface Using Polarization Diversity** 104
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H. R. Raemer,* A. K. Bhattacharyya, D. Hsu, Northeastern University

# AN ALTERNATE INTEGRAL EQUATION FOR SCATTERING FROM RANDOMLY ROUGH CONDUCTING SURFACES

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There is a great deal of work being done these days in solving the problem of scattering by rough surfaces via numerical means. This kind of approach is based on the facts that existing asymptotic results have been pushed about as far as they can go, and time on very powerful computers is becoming more readily available. Most of the numerical work is being directed toward the two dimensionally rough surface (a corduroy surface having a randomly varying period and height). While this work is yielding many very interesting results, there is still a very pressing need to extend the analyses to three dimensions. For example, the question of polarization conversion by scattering from a rough surface can only be answered by dealing with the three dimensional problem. Unfortunately, the transition from two to three dimensional roughness is very difficult for a pure numerical approach, and will probably take some time to accomplish.

Given this degree of difficulty with the pure numerical approach, the only obvious alternate approach is to attempt to develop another formulation which has an approximate solution that is more robust than the others. Such is the intent of this research.

The starting point is the Magnetic Field Integral Equation for the current induced on a perfectly conducting roughened planar surface. This equation is Fourier transformed to obtain an integral equation for the far zone scattered field. The method of smoothing is then applied to this equation,i.e., the field is split into an average value and a zero mean fluctuating part. Taking the fluctuating part of the resulting equation generates an integral equation for the fluctuating field which is exactly what is needed for interest in off-normal-incidence backscattering. The fluctuating field depends upon the average scattered field (which is also not known) but not in a sensitive manner. The main point of this development is the new Born term that is generated by this approach. This term contains both the Rice perturbation limit and the Kirchhoff form. More importantly, however, is the presence of term involving multiple scattering by means of the average propagator on the surface. This term is unique to surface scatter in that it does not appear in continuous or discrete random media propagation problems. A discussion of the importance of this term will be given.

# ELECTROMAGNETIC SCATTERING BY A DIELECTRIC ROUGH SURFACE IN FIRST-ORDER WIENER-HERMITE APPROXIMATION

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We study the scattering of plane electromagnetic waves by a rough surface, $z = \zeta(x,y)$, separating free space from a dielectric (possibly lossy) medium, using Wiener-Hermite expansions to first order for currents and fields. The surface is viewed as a realization of a stochastic process with $\langle\zeta\rangle=0$.

The Wiener-Hermite functionals $He_n(\zeta)$ possess the important property that $\langle He_m \cdot He_n\rangle=0$ if $m \neq n$, so that they provide orthogonal expansions of currents and fields. As a consequence, even when the expansions are carried out only up to first order, the coherent and incoherent responses contain contributions from all orders of multiple scattering.

The results obtained by this approach are compared to those obtained by other methods.

# OPTIMIZATION OF THE INCOHERENT POWER SCATTERED FROM A ROUGH SURFACE USING POLARIZATION DIVERSITY

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In a previous publication (R. J. Papa, J. F. Lennon and R. L. Taylor, IEEE Trans. on Antennas and Prop., AP-34,10, 1229-1237, 1986), a technique was presented to optimize the bistatic observation of rough surface scattering for the case of a given incident polarization, by using polarization diversity in the receiver. The optimal performance is obtained by varying the co-polar and cross-polar relations as a function of incident and scattering geometries. The algorithm for optimum reception was obtained on the basis of an expression for the normalized cross section $\sigma^0$ derived under the assumptions of Physical Optics (PO) (radius of curvature of surface irregularities large compared to a wavelength). In this paper, we assume the surface has two scales of roughness; a large scale describable by PO, and a small scale describable by the perturbation method (G.T. Ruck, D. E. Barrick, W. D. Stuart, C. K. Krichbaum, Radar Cross Section Handbook, Vol. 2, Plenum Press, 1970).

With the further assumption that the large scale slopes are small, it is possible to write

$$\sigma^0 = \sigma^0_{LS} + \sigma^0_{SS}$$

where $\sigma^0_{LS}$ is the cross section derived from PO and $\sigma^0_{SS}$ is the cross section derived from perturbation theory. The receiver power $I_R$ is a function of receiver polarization angle $\psi$ and the expressions for $\sigma^0_{LS}$ and $\sigma^0_{SS}$. By differentiating $I_R$ with respect to $\psi$ and setting $\frac{\partial I_R}{\partial \psi} = 0$, one can obtain an explicit expression for the optimum receiver polarization angle. Graphs are presented of the relative received power as a function of receiver polarization angle for different geometries, dielectric constants, and surface roughness parameters. This optimization represents a much more complex condition than the previous result. In the previous single scale of roughness PO model, the algorithm for the optimum receiver polarization angle included only the complex dielectric constant of the surface and the angles of incidence and scattering; it was independent of the surface roughness. Now, in the two scales of roughness model, the optimum receiver polarization angle is a function of both degrees of roughness and also depends explicitly on the wavelength.

# Removal of Phase-Modulation Contamination from Second-Order HF Radar Sea Echo for Wave Measurements from a Moving Offshore Oil Platform

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CODAR Ocean Sensors Ltd., Mountain View, CA 94039

## ABSTRACT

CODAR, a high-frequency (HF) compact radar system was operated continuously over several weeks aboard the semi-submersible oil platform, the Treasure Saga, for the purposes of waveheight directional measurement and comparison. During North Sea winter storm conditions, the system operated at two different frequencies depending on sea state. Wave data are extracted from the second-order backscatter Doppler spectrum produced by hydrodynamic and electromagnetic nonlinearities. Because the floating oil rig itself moves in response to long waves, these motions introduce significant phase modulation on the signal that shows up in precisely the same region of the Doppler spectrum as the normal second-order signal used for extracting wave parameters. A technique is developed and successfully demonstrated that eliminates this convolutional contamination of the echo, employing separate accelerometer measurements of the platform's lateral motions. With this contamination thereby removed, the extracted CODAR waveheight, mean direction, and period are compared with data from a Norwegian directional wave buoy; in seas with storm significant waveheights that exceeded 9 m, the two height measurements agreed to within 20 cm, and mean direction to 15° rms.

# A BISTATIC SCATTERING MODEL FOR CONDUCTING RANDOMLY ROUGH SURFACES

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Beginning with the standard Kirchoff model and the small perturbation model, there has been a continuing interest in the problem of rough surface scattering. In this paper, we are concerned with noncoherent scattering by three-dimensional randomly rough surfaces. We begin with the evaluation of surface current induced by a plane electromagnetic wave on a rough conducting surface. The Magnetic Field Integral Equation (MFIE) for the surface current is solved iteratively. The surface current obtained appears to be more exact than either the Kirchhoff or the small perurbation model. We next formulate the far-zone scattered fields by the Stratten-Chu equation, and subsequently compute bistatic scattering coefficients for vertical, horizontal and cross-polarizations, employing the more accurate surface current. The results are as follows:

$$\sigma^o_{HH} = (kl)^2 e^{-k^2\sigma^2(\cos\theta+\cos\theta_s)^2} \left[\frac{\cos\varphi_s-\sin\theta\sin\theta_s+\cos\theta\cos\theta_s\cos\varphi_s}{\cos\theta+\cos\theta_s}\right]^2$$
$$\sum_{n=1}^{\infty} \frac{\left[k^2\sigma^2(\cos\theta+\cos\theta_s)^2\right]^n}{n!n} e^{-\frac{(kl)^2}{4n}\left[(\sin\theta-\sin\theta_s\cos\varphi_s)^2+\sin^2\theta_s\sin^2\varphi_s\right]}$$
$$+2(kl)^2\frac{\cos\varphi_s-\sin\theta\sin\theta_s+\cos\theta_s\cos\theta\cos\varphi_s}{(\cos\theta_s+\cos\theta)\cos\theta_s}(\sin\theta\sin\theta_s-\sin^2\theta)$$
$$e^{-k^2\sigma^2(\cos^2\theta_s+\cos^2\theta+\cos\theta_s\cos\theta)}$$
$$\sum_{n=1}^{\infty} \frac{\left[k^2\sigma^2(\cos^2\theta_s+\cos\theta\cos\theta_s)\right]^n}{n!n} e^{-\frac{(kl)^2}{4n}\left[(\sin\theta-\sin\theta_s\cos\varphi_s)^2+\sin^2\theta_s\sin^2\varphi_s\right]}$$
$$+\frac{(kl)^2}{\cos^2\theta_s}e^{-k^2\sigma^2(\cos^2\theta_s+\cos^2\theta)}$$
$$\Big\{\sec^2\theta_s\big[\sin^2\theta_s\cos\theta\cos\varphi_s+\sin^2\varphi_s\sin^2\theta_s\cos\varphi_s(\cos\theta_s-\cos\theta)$$
$$+\cos\varphi_s\cos\theta_s\sin^2\theta_s\sin^2\varphi_s-\cos^3\varphi_s\cos\theta\sin^2\theta_s\big]^2$$
$$\sum_{n=1}^{\infty}\frac{(k^2\sigma^2\cos^2\theta_s)^n}{n!n}e^{-\frac{(kl)^2}{4n}\left[(\sin\theta-\sin\theta_s cos\varphi_s)^2+\sin^2\theta_s\sin^2\varphi_s\right]}$$
$$+\sin^2\theta(\sin\theta_s-cos\varphi_s\sin\theta)^2\sum_{n=1}^{\infty}\frac{(k^2\sigma^2\cos^2\theta_s)^n}{n!n}$$
$$e^{-\frac{(kl)^2}{4n}\left[(\sin\theta_s\cos\varphi_s-\sin\theta)^2+\sin^2\theta_s\sin^2\varphi_s\right]}\Big\}$$

These coefficients, in the high frequency cases, analytically reduce, irrespective of the incident or scattered angle, to the Kirchoff result. In the low frequency region, the bistatic scattering expressions reduce to the small perturbution results only in the specular and backscattering directions. Finally, the results obtained by this approach are compared with the modified Wiener-Hermite results, both bistatic and backscattering, as well as laboratory measurments. Reasonably good agreement is observed.

# WIDEBAND TEMPORAL CLUTTER STATISTICS OF DECIDUOUS TREES FOR SMALL RANGE RESOLUTION CELLS AND LOW GRAZING ANGLES

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In the last decade several investigators have published the mean, median and 84 percentile values of the clutter cross sections of various types of terrain at low grazing angles. An abundance of uncalibrated data exists for various sea states at different grazing angles. Spotty data exists for terrain with various types of cover. The need for a complete statistical characterization of the distributions of measured cross sections and the necessity for the description of the calibration techniques have been emphasized in recent years. Experimentalists tend to rely on the calculated cross section of calibrated targets, and reported data for co-and cross-polarized cross sections of various types of clutter.

In this paper we report results using corner reflectors, instead of standard spheres, as calibration targets for obtaining co-and cross-polarized cross sections of trees at low grazing angles. Spheres could not be used because, ideally, there is no cross-polarized energy scattered monostatically. An alternative calibration method using a transponder with variable polarization, as opposed to a passive calibrating target, seems ideal for use in bistatic, variable polarization cross section measurements.

Comparisons of the measured results to Rayleigh, Weibull, and log-normal cumulative probability distributions indicate that the log-normal distribution most closely approximates the behavior of deciduous trees in small resolution cells.

## ABSTRACT

"Simulation Studies of Radar Clutter and Multipath Returns"


Harold R. Raemer, Asoke Bhattacharyya and Dong Hsu
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Boston MA 02115



The authors have developed a very versatile and modular program to simulate a wide range of radar clutter and multipath scenarios. Some problems in the modelling of ground surface scattering for implementation in that program were discussed in a paper presented at the 1988 AP-S/URSI symposium (H. Raemer et al; "Some Practical Considerations in Modelling of Ground Surface Scattering for Computer Simulation Purposes).

Among the topics studied with the aid of the simulation program are: comparison of the use of purely analytical and empirical scattering models for natural terrain and discrete scattering objects; the effects of variation of antenna beamwidth and sidelobe levels on the clutter return; effects of shadowing at low grazing angles; comparison of results using a flat-earth approximation with those including the effect of earth curvature (i.e. at what ranges and radar altitudes does earth curvature play a significant role in the clutter return); the effect of certain parameter variations on the distribution of return power between different polarizations (both linear and elliptical polarization) and effects of "multiple bounce" contributions on the total clutter return.

In the present paper, some results obtained during the past year using some of the above capabilities of this program are presented and discussed. Although many of these results are quite scenario-dependent, it is sometimes possible to draw general conclusions that are applicable to a wide range of radar-clutter geometries.

## Monday PM

URSI-B Session 22

### Scattering and Diffraction: Integral Equation Methods

*Chairs*: D. R. Wilton, Univ. of Houston; K. A. Michalski, Texas A&M University
*Room*: San Martin *Time*: 1:15–4:00

# APPLICATION OF THE MAGNETIC FIELD AND COMBINED FIELD INTEGRAL EQUATIONS TO PROBLEMS OF ELECTROMAGNETIC SCATTERING BY ARBITRARILY SHAPED BODIES

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The numerical solution of electromagnetic scattering problems involving arbitrarily shaped bodies has been previously investigated using an electric field integral equation (EFIE) formulation and a triangular patch model for the body (Rao, Wilton, & Glisson, IEEE T-AP, 30, 409-418, 1982). The EFIE formulation, however, is known to fail for closed bodies at a discrete set of frequencies corresponding to the resonances of a conducting cavity having the same surface. One approach to the elimination of this internal resonance problem which has been implemented for the triangular patch model (Correia & Barbosa, AP-S Symp. Dig., 898-901, June 1988) is the augmented integral equation (AIE) formulation. A second approach to the elimination of the internal resonance problem is the use of a combined field integral equation (CFIE) formulation. The CFIE formulation has the advantages over the AIE formulation that it requires no additional storage for the moment matrix over the EFIE as the AIE does and the size of the moment matrix is not dependent on whether some portions of the structure are thin conducting sheets.

The CFIE formulation is obtained by simply adding the magnetic field integral equation (MFIE) to the EFIE. This addition may be performed over the entire body surface for closed bodies, or over only part of the body if some portions of the body are thin conductors. The MFIE formulation has been previously implemented by Rao for the triangular patch model (Ph.D. Thesis, Univ. of Miss, 1980), where it was found that the approximations to the Galerkin solution procedure used with the EFIE did not yield satisfactory results with the MFIE.

In this work comparisons of the accuracy and computation times for the full Galerkin solution procedure for the MFIE and alternative approximations to the Galerkin procedure are presented. The CFIE formulation for the triangular patch model is then developed and demonstrated to eliminate the internal resonance problem.

# SCATTERING FROM PERFECTLY CONDUCTING AND DIELECTRIC BODIES OF ARBITRARY SHAPE: SURFACE FORMULATION

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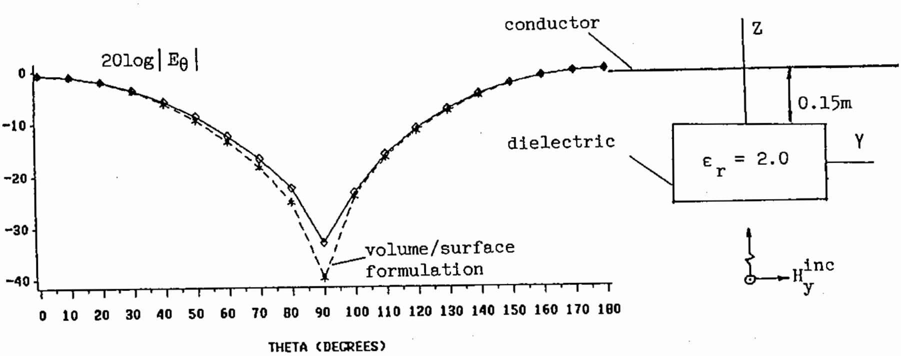
Electromagnetic field scattered from a composite system consisting of perfectly conducting and dielectric bodies of arbitrary shape is computed. The surface equivalence principle is used to replace the conductors by electric surface currents and the dielectric bodies are represented by equivalent electric and magnetic surface currents. A set of coupled integral equations involving the surface currents is obtained by enforcing the boundary conditions on the tangential components of the fields. The tangential components of the total electric field are set to zero on the conducting surfaces, and the continuity of the tangential components of both total electric field and total magnetic field are enforced on the dielectric surfaces. The surfaces are approximated by triangular patches . The figure below shows the normalized far scattered field pattern (in the XZ plane) for a system consisting of a dielectric slab (0.4mx0.4mx0.2m) with dielectric constant 2.0, and a perfectly conducting plate of size 0.75mx0.75m . The plate is in the z=0.25m plane, and the system is illuminated by an x-polarized, z-travelling plane wave with the wavelength equal to 1m. The results computed from a volume/surface formulation are also shown for comparison.



# AN $E_Z$-$H_Z$ FORMULATION FOR OBLIQUE SCATTERING FROM INHOMOGENEOUS DIELECTRIC AND MAGNETIC CYLINDERS

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A new formulation is developed for scattering from penetrable, inhomogeneous cylinders illuminated by an obliquely incident plane wave, in terms of coupled integral equations for the longitudinal electric and magnetic fields. Previous formulations have employed a square-cell discretization of the integral equations and have required as many as six field components as unknowns per cell. The present approach utilizes triangular cells with unknowns limited to the $E_Z$ and $H_Z$ field components at the corners of each cell. The triangular-cell discretization permits a more accurate model of the inhomogeneous cross section than possible with a square cell model, and with far fewer unknowns. If illuminated by a normally-incident excitation, the method reduces to the electric-field integral equation (EFIE) approach of Al-Bundak ("Electromagnetic scattering of arbitrarily shaped inhomogeneous cylinders whose cross-sections are modeled by triangular patches," MS Thesis, University of Mississippi, 1983) for TM incidence and the magnetic field integral equation (MFIE) approach of Peterson and Klock ("An improved MFIE formulation for TE-wave scattering from lossy, inhomogeneous dielectric cylinders," *IEEE Trans. Antennas Propagation*, Jan. 1988) for TE incidence. For an obliquely incident excitation, the response of the scatterer is a combination of TM and TE polarizations, and the formulation involves both the EFIE and MFIE. These equations are discretized throughout the cross-sectional volume of the scatterer using a piecewise linear representation for $E_Z$ and $H_Z$ and point-matching.

Results will be presented for cylinders that are a combination of dielectric and magnetic materials. Extensions to treat conducting strips or cylinders embedded in the penetrable scatterer will be described.

# ELECTROMAGNETIC DIFFRACTION BY AN APERTURE BETWEEN TWO PERFECTLY CONDUCTING HALF PLANES AND LOADED WITH A DIELECTRIC CYLINDER

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## ABSTRACT

A rigorous field analysis of the problem of diffraction by a loaded aperture formed of two perfectly conducting half planes and excited by an electric or magnetic line current is given in this paper. The aperture is loaded with a dielectric cylinder whose axis coincides with the extension of the two half planes. The two media outside the dielectric cylinder which are separated by the two half planes are, in general, dielectric materials. All dielectric media are considered to be linear, homogeneous and isotropic materials. The edges of the two half planes are parallel to the axis of the cylinder, however their surfaces can be in two different planes. The field components in the three regions are expressed in terms of cylindrical harmonic functions with unknown expansion coefficients. For each type of excitation, an infinite set of equations is obtained after applying the appropriate boundary conditions. The infinite set of equations is then truncated to allow for a numerical solution for the expansion coefficients. The electromagnetic field components are subsequently determined and compared whenever available with previous published data. The analysis is then specialized to solve for other geometries such as a slit, a slit loaded with a dielectric cylinder, a conducting wedge with a cylindrically dented edge as well as to a corner reflector loaded with a dielectric or conducting cylinder at the apex. Plane wave excitation is also considered as a special case of the line source illumination. Sample numerical results for the slit, loaded slit, dented wedge and loaded corner reflector problems are presented.

# FIELD AMPLITUDE DISTRIBUTIONS FOR HYBRID MODE SURFACE WAVES PROPAGATING ALONG AN INFINITELY LONG DIELECTRIC CYLINDER

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*Department of Electrical Engineering*
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The characterization of hybrid mode surface waves which propagate along dielectric circular cylinders is an important aspect in the design of rod antennas and fibre optic structures. Additionally, it has important implications in the design of dielectric supports for loop antennas and in certain areas of bioelectromagnetics.

This paper considers the amplitudes of the field components of hybrid mode surface waves on an infinitely long dielectric circular cylinder. The surface waves are excited by a $\cos n\phi\ \delta(z)$ electric current distribution which is located coaxially at the air-dielectric interface, as illustrated in Figure 1. Residue theory is employed to obtain analytical expressions for the surface wave field components. In the development of these expressions, Elsasser's eigenvalue equation appears:

$$\left[\frac{\varepsilon_r J_m'(p)}{pJ_m(p)} + \frac{K_m'(q)}{qK_m(q)}\right]\left[\frac{J_m'(p)}{pJ_m(p)} + \frac{K_m'(q)}{qK_m(q)}\right] = \left[\frac{m\lambda}{k_o}\left\{\frac{p^2+q^2}{p^2q^2}\right\}\right]^2$$

where $p=\sqrt{k_i^2-\lambda^2}\ a$ and $q=\sqrt{\lambda^2-k_o^2}\ a$

The field expressions for the surface wave modes are obtained by computing the residues of the corresponding integrands at the various eigenvalues. Therefore:

$$\begin{Bmatrix} E_{z,surface} \\ H_{z,surface} \end{Bmatrix} = -j2\pi \sum_{m=-\infty}^{\infty} e^{-jm\phi} \begin{Bmatrix} N_e(\lambda) \\ N_h(\lambda) \end{Bmatrix} \times \frac{1}{D'(\lambda)}\Big|_{\lambda_p}$$

where $N_e(\lambda)$, $N_h(\lambda)$ are the numerators of the appropriate integrands and $D'(\lambda)$ is the derivative of the common denominator.

Of special interest are what the authors refer to as "second index higher order" surface wave modes. For surface waves described as $HE_{nm}$ or $EH_{nm}$, the *SIHO* modes occur when $m > 1$. A comparison of relative field amplitudes for a number of *SIHO* modes is presented. In conclusion, some numerical results are presented which illustrate surface wave amplitude and propagation constant dependance upon various physical parameters.

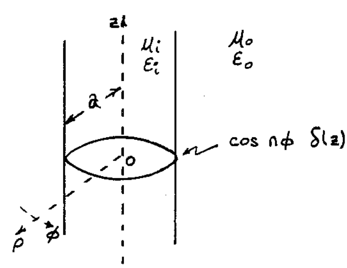


*Figure 1*

# SCATTERING BY A LOSSY DIELECTRIC CYLINDER BURIED BELOW THE PLANAR INTERFACE BETWEEN TWO SEMI-INFINITE HALF-SPACES

Chalmers M. Butler and Xiao-Bang Xu
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In this paper is presented an analysis for determining the scattering by a lossy dielectric cylinder buried below a planar interface separating two semi-infinite, homogeneous half-spaces of different electromagnetic properties. The lossy dielectric cylinder of general cross section is of infinite extent and the excitation is taken to be transverse magnetic (TM) or transverse electric (TE) to the cylinder axis. Coupled integral equations are formulated with equivalent sources for the external and internal regions as unknowns. For TM excitation, the coupled integral equations are formulated in terms of the equivalent electric surface currents, while for TE excitation, they are derived in terms of the equivalent magnetic surface currents. Integral equation Green's functions, which account for the presence of the interface by means of Sommerfeld intergrals, are summarized, and a numerical solution technique is briefly outlined. For a few cases of interest, the equivalent current solutions and far-zone scattered fields are presented graphically as functions of various parameters of the buried cylinder and the two half-spaces.

# OBLIQUE INCIDENCE SCATTERING FROM A FINITE CIRCULAR CYLINDER

*F. Coşkun and H. Raemer*

*Department of Electrical and Computer Engineering and*

*Center for Electromagnetics Research*

*Northeastern University*

*Boston, MA 02115*

Our objective is to determine the scattered fields from a finite length, perfectly conducting, circular cylinder which is illuminated by a plane wave at oblique incidence.

The first step of our solution to this problem is to expand Hertz vectors into cylindrical vector wave functions. Secondly, we apply the boundary conditions for a perfectly conducting surface and finally the Stratton-Chu integral is computed for the determination of radiation fields at a remote receiving point.

In F. Coşkun and H. Raemer, (APS-URSI, Syracuse, June 1988) same problem was addressed with a cylinder whose dimensions were assumed to be comparable or large compared to the wavelength. Numerical solutions for the backscattering were applicable to a narrow range of near-normal angles in the plane of incidence because large argument approximations were used in all computations involving Bessel Functions. In the current study, these limitations on the dimensions of the cylinder and the angle of incidence are removed. As a result, the numerical computations of the radar cross section are extended to **any** elevation angle for the incident wave.

The radar cross section for vertical and horizontal polarizations are computed and numerical results are compared to the previous work done in this area. Scattering from an infinitely long cylinder is presented to emphasize the effect of finite length on the cylinder.

## Monday PM

URSI-H Special Session 23

**Wave Generation by Particle Injection**

*Chairs*: K. J. Harker, Stanford University; D. E. Donatelli, RADC

*Room*: San Simeon *Time*: 1:15–4:40

| | | |
|---|---|---|
| 1:20 | **Space-based Electromagnetic Wave Generation Experiments using Electron Beams**<br>P. M. Banks,* Stanford University | 118 |
| 2:00 | **Low Frequency (1-10KHZ) Plasma Waves Measured During the Echo-7 Electron Beam Experiment**<br>G. P. Ginet,* Air Force Geophysics Lab, J. Ernstmeyer, Massachusetts Technological Lab, AFGL | 119 |
| 2:40 | **Coffee Break** | |
| 3:00 | **Transient High Frequency Wave Generation by the Echo-7 Electron Beam**<br>J. Ernstmeyer,* Rome Air Development Center | 120 |
| 3:20 | **ELF/VLF Waves Generated by an Electron Beam in a Large Vacuum Chamber**<br>D. E. Donatelli,* Rome Air Development Center | 121 |
| 3:40 | **VLF Wave Generation by Pulsed and DC Electron Beam Injection on Spacelab-2**<br>G. D. Reeves,* P. M. Banks, T. Neubert, R. I. Bush, K. J. Harker, D. A. Gurnett, W. J. Riatt, Stanford University | 122 |
| 4:00 | **Whistler Wave Generation by Electron Beam Injection**<br>P. L. Pritchett,* N. Omidi, H. Karimabadi, Univ. of California, Los Angeles | 123 |
| 4:20 | **Dipole Radiation Generated by Emission of an Intense Electron Beam from a Rocket at High Altitude**<br>I. Katz,* M. J. Mandell, S-CUBED, D. C. Cooke, Air Force Geophysics Lab | 124 |

# Space-based Electromagnetic Wave Generation Experiments Using Electron Beams

Peter M. Banks
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Stanford University
Stanford, CA 94305

The Stanford Space Plasmas Group has conducted a variety of space experiments with moderate energy (~ 1 to 7.5 keV), low current (0 to 300 mA) electron beam sources. The intent has been to explore the various physical processes associated with injection of d.c. and pulsed electron beams into the relatively low density plasmas of the Earth's ionosphere. Particular topics investigated have included charging of the source and its platform, internal charging of the electron beam, plasma return currents, and the possibility of generating electromagnetic radiation in the ELF and VLF radio bands. This paper presents an integrated view of the important results gained from the studies of electromagnetic wave generation. These include results from three Space Shuttle flights (STS-3, Spacelab-1, and Spacelab-2) and a rocket flight (CHARGE-2). Wave generation results show the importance of the Cerenkov process in stimulating electromagnetic waves in different portions of the ELF/VLF bands. In addition, the observed wave intensities for pulsed electron beam emissions compare well with the theoretical models of the source region. Plans for new experiments will also be presented.

# LOW FREQENCY (1-10KHZ) PLASMA WAVES MEASURED DURING THE ECHO-7 ELECTRON BEAM EXPERIMENT

**G. P. Ginet***, Air Force Geophysics Laboratory, Hanscom AFB, MA 01731
**J. Ernstmeyer**, Massachusetts Technological Lab, AFGL, Hanscom AFB MA, 01731

In February of 1988 the ECHO-7 rocket experiment was successfully carried out in the ionosphere (apogee = 292 km) near Poker Flat, Alaska. Situated on the MAIN payload was an electron accelerator which produced an electron beam in a sequence of different modes with the maximums of energy and current being 40 kev and 250 mA. The primary purpose of the experiment was to observe the portion of the beam electron population which was reflected from the southern hemisphere conjugate point and returned to the payload. Along with the particle detectors, the three free-flying daughter payloads contained several electric field detectors capable of measuring plasma wave activity in the local environment perturbed by the beam. We report on electric field wave measurements in the range of 1-10 KHZ from the Energetic Particle Payload (EPP) which reached maximum perpendicular and parrallel distances from the MAIN payload of ~380 m and ~700 m, respectively. Prominent in a Fourier transform of the temporal data is a peak at the lower-hybrid frequency which exists for all modes of beam injection. Also visible are sharp peaks at harmonics of 1 KHZ when the beam source is strongly modulated at 1 KHZ. Besides an exposition of this data as a function of time throughout the flight, we will present comparisons of our results with theories of beam generated waves.

# TRANSIENT HIGH FREQUENCY WAVE GENERATION BY THE ECHO-7 ELECTRON BEAM

J. Ernstmeyer, Electromagnetics Directorate, Rome Air Development Center Hanscom AFB, MA 01731

The MAIN payload of the Electron Echo-7 sounding rocket carried a Pierce diode electron gun, which emitted currents up to .25 amperes at accelerator potentials up to 40 kV. The EPP (Energetic Particles Payload), one of three free-flying subpayloads, included a single axis, high frequency electric dipole antenna. We present data from the EPP's on-board, 0 - 5 MHz swept frequency analyzer (SFA) applied to signals from the dipole.

In stepping through the flight program, the electron gun turned on and off quite frequently during the entire flight. Although the gun rise time was considerably less than a millisecond, the SFA reveals distinctive gun turn on signatures lasting for up to ten milliseconds. We associate these transient emissions with disequilibrium in the local return current system. We compare and contrast them with steady state emissions by the beam.

# ELF/VLF Waves Generated by an Electron Beam in a Large Vacuum Chamber

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A series of electron beam experiments were performed as part of the pre-flight tests of the BERT rocket payload in the Johnson Space Center Chamber A. During these tests, the electron gun on the main payload emitted beams with energies of 0.5, 1.0, and 2.0 keV stepped through currents of 0.1 to 20 mA. Simultaneously, the instrumented nosecone, ERNIE, separated from the main payload, measured electric field fluctuations from DC to 5.5 MHz and magnetic field fluctuations from DC to 10 kHz. Abrupt changes in wave activity occurred during the 0.5 and 1.0 keV beam emissions.

When emitted beam current is below a threshold, waves in the frequency range of 1-30 kHz are primarily electrostatic and increase in frequency and intensity with increasing beam current. However, as beam current approaches the threshold, electrostatic waves give way to broadband electromagnetic waves with a lower cut-off near the ion cyclotron frequency and peak intensity near the lower hybrid frequency. As beam current increases above the threshold, these electromagnetic waves intensify.

These changes are associated with formation of a virtual cathode. As the beam current is increased, it approaches the threshold for space-charge limited current flow from the payload to the chamber wall. When this threshold is exceeded a virtual cathode forms. The resulting changes in charge distribution and current flow induce corresponding changes in wave activity.

# VLF WAVE GENERATION BY PULSED AND DC ELECTRON BEAM INJECTION ON SPACELAB-2

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K. J. Harker, D. A. Gurnett, and W. J. Raitt
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The Spacelab-2 mission offered an unprecedented opportunity to study the production of waves produced by the injection of electron beams from the Space Shuttle Orbiter. The Stanford/Utah State vehicle charging and potential experiment package included the fast pulsed electron generator (FPEG). The FPEG was used to inject a 1 keV electron beam with currents of 50 or 100 mA. The beam was pulsed and command controlled. The pulsing frequencies investigated ranged from DC to tens of kilohertz. Various modulation schemes (sequences of pulsings at various frequencies and durations) were used to investigate important parameters affecting the production of waves. Owing to the relatively long duration of the mission compared to rocket flights, over 300 separate beam injection experiments were performed.

The resultant waves were measured with instruments on the University of Iowa plasma diagnostics package (PDP). The PDP included a wideband wave receiver which sampled AC electric and magnetic fields at frequencies up to 30 kHz. During most of the mission the PDP measured wave fields from its position in the payload bay. During one 6 hour period the PDP was released and measured wave fields out to distances of several hundred meters from the beam.

The Spacelab-2 experiments showed that electromagnetic waves were produced in the whistler mode. Both pulsed and DC beams produced broadband waves at VLF frequencies. Pulsed beams also produced narrowband waves at harmonics of the pulsing frequency. Both propagating and near-field contributions to the wave fields were measured. The propagating components showed good agreement with the predictions of theory when the mechanism of production was the Cherenkov resonance and the waves had wave normal angles less than the Gendrin angle.

The results of the Spacelab-2 mission also helped to identify some of the important capabilities and limitations of electron beam wave stimulation experiments conducted on the Shuttle Orbiter. The amplitude of radiation produced by beam injection is dependant on many parameters including frequency, duty cycle, pitch, and ambient plasma density. In addition, the dynamics of beam injection and interactions with the Orbiter and the Orbiter environment can produce significant effects on wave production.

# WHISTLER WAVE GENERATION BY ELECTRON BEAM INJECTION

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N. Omidi and H. Karimabadi (Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90024)

The generation of whistler mode radiation has been observed in connection with many electron beam experiments in both plasma chambers and in space. In the laboratory work this characteristic whistler spectrum was an unfailing indication of the beam-plasma discharge. The generation mechanism for the whistler waves, however, has not been clearly established. Farrell et al. (J. Geophys. Res., 93, 153, 1988) suggested that the electrostatic plasma waves observed in connection with the beam injection could lead to the formation of electron bunches, which could in turn produce the whistler waves via coherent Cerenkov radiation from "super particles".

We have used a two-dimensional (with all three velocity components) electromagnetic particle simulation code to investigate the production of electromagnetic waves from electron beams. The process is treated as an initial-value problem in which a dilute beam of field-aligned electrons exists initially throughout the central region of the simulation box. The beam energy is 5.7 keV, and the fractional beam density is 1/4. The return current is carried by the ambient electrons. The magnetic field strength is such that $\Omega_e/\omega_{pe} = 0.3$. Absorbing regions allow the radiation to escape from the simulation box.

We observed that the electromagnetic wave spectrum is dominated by the production of whistler waves with $\omega/\Omega_e \sim 0.4 - 0.7$. The waves are propagating near the resonance cone and have a phase velocity of order c/10. The growth of the whistler waves lags slightly behind but is closely associated with the electrostatic waves generated by the beam-plasma interaction. This interaction is observed to produce strong gyrophase bunching of the beam electrons. The role of this gyrophase bunching, as well as other possible mechanisms, in producing the whistler waves will be discussed.

# DIPOLE RADIATION GENERATED BY EMISSION OF AN INTENSE ELECTRON BEAM FROM A ROCKET AT HIGH ALTITUDE

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Recently, it has been reported by Maehlum *et al.* (*Geophys. Res. Lett.*, *15*, 725, 1988) that the electrical charging of the MAIMIK rocket was thousands of volts in excess of the energy of the emitted electron beam. The mechanism for the charging in excess of the beam energy was uncertain. During the MAIMIK experiment, the beam plasma frequency was much greater than the local ionosphere plasma frequency, and the beam limiting distance was much smaller than the space charge sheath around the rocket. Under these conditions, the rocket and electron beam interact strongly with each other, and somewhat weaker with the ionosphere due to the difference in distance and time scales.

We have simulated numerically in two dimensions the emission from a sphere of an intense electron beam with parameters similar to those of the MAIMIK experiment. Strong, persistent, electrostatic dipole oscillations are induced as part of the space charge limiting of the beam. These oscillations broaden the beam energy distribution. When the return current supplied by the ionosphere is only a small fraction of the beam current, only the high energy tail of the beam escapes the sheath. Due to the energy broadening of the beam, the spacecraft achieves potentials in excess of the initial beam energy. The earth's magnetic field constrains the beam space charge thus enhancing the broadening mechanism.

## Tuesday AM

Joint AP-S, URSI-B Session 26

### Numerical Techniques for Computer Architectures - Large & Small

*Chairs*: W. R. Stone, Stoneware Ltd.; Ch. Hafner, Swiss Federal Institute of Tech.

*Room*: Oak *Time*: 8:15–11:40

# A SURVEY OF THE VARIOUS COMPUTER ARCHITECTURES FOR SOLVING LARGE ELECTROMAGNETIC FIELD PROBLEMS

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A recent trend for the solution of large electromagnetic field problems is the use of vector and concurrent processing for solution speed-up. A general misconception about parallel computation is that the real performance improvement is simply a matter of deriving a means to use as many processors as possible. Though this is important, an equally important feature involves the optimum use of the complex memory on any parallel machine.

This paper surveys various computer architectures for the solution of large matrix equations by placing importance on the largest size of the matrix that can be solved. Two methods viz. gaussian elimination and conjugate gradient method have been used to solve the matrix equation and the cpu time compared. Though the conjugate gradient method has been known to produce fast results on a sequential computer, this may not be the case on a parallel shared memory computer such as the ALLIANT FX/80. Some of the computer architectures surveyed are the VAX 8530, IBM 3090, Multimax, Connection Machine and the ALLIANT FX/80.

Some preliminary results are given below:

ALLIANT FX/80 :

Largest Size of Matrix that can be solved - 4000x4000 (complex,double precision)

Timing:

Matrix Size - 2700x2700 (complex, double precision)

Matrix Generation - 6977 secs

Gaussian Elimination - 7358 secs

Conjugate Gradient Method - 7872 secs (1.E-08 accuracy)
4834 secs (1.E-06 accuracy)

VAX 8530 :

Time for solution using conjugate gradient method (accuracy 1.E-08) for a 1200x1200 complex, double precision matrix is 34909 secs.

# SOLUTIONS OF LARGE OR TIME CONSUMING PROBLEMS ON THE HYPERCUBE COMPUTER

*Tom Cwik**
*Jean Patterson*

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Parallel computer architectures which are under continuing development, offer one means for solving memory or CPU intensive calculations in electromagnetic problems. The analysis and design of antennas, scattering, or waveguiding structures which, in the past, required exceedingly large amounts of memory or computer time can now be considered. Various classes of parallel architectures, roughly grouped by memory location--either distributed or shared--and by grain size--either coarse or fine--are being used in computational electromagnetics. This paper considers the use of a coarse grained, distributed memory machine, the JPL/CIT Mark III Hypercube.

As a coarse grained parallel computer, the Mark III Hypercube combines upwards of 128 relatively powerful computational nodes (each roughly equivalent to a Vax 11/750) into a general purpose machine. Each node allows the access of 4MBytes of memory. Since the computational power is relatively easy to access, the Hypercube can be programmed in numerous ways. The simplest application consists of executing the identical program in each node of the Hypercube. If the problem requires less than 4 MBytes of memory, e.g. a matrix solution with matrix order 300, and many input variables which would normally be executed sequentially within a loop, each node of the Hypercube can solve the problem in parallel for each input variable thereby reducing the computation time by the number of nodes operating. A 128 node Hypercube can solve for a combination of 128 frequencies, incident angles or element dimensions in nearly the time it takes to execute the code on one node. At the opposite extreme is the solution of large problems which are memory intensive. The 512 MBytes of memory accessible in a 128 node machine allows the direct in-core solution of matrix problems of matrix order 4800 or comparable sized finite difference or finite element solutions. With the use of the distributed architecture in a large problem comes a penalty of communicating between nodes. This penalty has been found to be relatively small in the problems considered. This talk will examine various uses of the Hypercube and extremes of problem size which may be efficiently solved.

# LOW AND HIGH FREQUENCY ELECTROMAGNETIC METHODS AND CALCULATIONS ON A CONNECTION MACHINE

* Laszlo A. Takacs

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Many of the solutions to electromagnetic problems can be formulated in ways that are inherently data-parallel. When algorithms to solve such problems are implemented in parallel programming languages, the resulting algorithms and software are invariably simpler and more elegant than their serial counterparts. Also, dramatic speedups are observed for certain problems.

The aim of this paper is to demonstrate these facts by outlining a number of parallel algorithms and benchmarking their performance for several common electromagnetic problems in the frequency domain. Some of the parallel solution techniques discussed are specific to

- PTD calculations, the Physical Theory of Diffraction
- Method of Moments - generating very large matrices
- Shooting and Bouncing Rays - ray tracing issues and electromagnetic scattering from cavities

Benchmarks were generated using a Connection Machine model CM-2 using *LISP, a data-parallel extension of Common Lisp. Depending on the application, performance is found to exceed that of the CRAY X-MP.

# MASSIVELY PARALLEL RAY TRACING METHODS FOR GTD APPLICATIONS

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One of the central difficulties encountered in the application of the GTD to general electromagnetic problems is finding the pertinent ray paths in and around complicated geometries. The possible paths are defined variationally to be the stationary paths of a generalized Fermat's priciple, and in practice they can be very difficult to calculate.

The usual way to compute the ray paths is is to solve the equations which result from a specified sequence of geometric interactions with the ray. The difficulty with this procedure is that each interaction of ray with geometry introduces an additional degree of freedom into the solution, hence solving the resulting equations can quickly become intractable. Also, the ray path solutions for the various species of multiple interactions must usually be formulated seperately. Thus, the resulting software is costly to develop and difficult to thoroughly test.

In this paper, a parallel approach is described which avoids these problems. It is noted that the parallel method does have limitiations of its own which have prevented its use in the past. However, with the advent of massively parallel machines and the substantial software/algorithm simplification possible with fine-grained data-parallel architechtures, the simpler parallel approach may now be viable.

The algorithms are implemented in *LISP, a data-parallel extension of common lisp for the Connection Machine CM-2, a hypercube structure with $2^{16} = 65,536$ nodes.

# MASSIVELY PARALLEL FIELD COMPUTATIONS IN THE TIME DOMAIN


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Two massively parallel time domain methods of solving Maxwell's equations are discussed. Both methods consist of dividing the physical space into small cells, and computing via nearest-neighbor interactions the time evolution of the electromagnetic fields. The first method uses a finite volume technique, involving computing fields and integrals over surfaces and volumes of cells. The second uses a more standard finite difference method, adapted for the architecture of the Connection Machine.

To analyze scattering from realistic, detailed objects, consideration must be given to the specification of matter within the space. Representation and computation tradeoffs are discussed between the speed and simplicity of a rectilinear grid of cells and the accuracy and flexibility of a general curvilinear grid, as well as possible compromises between these two extremes.

The close link between the massively parallel architecture and the nature of time domain methods is discussed, and favorable benchmarks of the Connection Machine versus other supercomputers are presented. Results are described for a variety of objects, frequencies, and space configurations.

# NEC2 IN A MIMD COMPUTING ENVIRONMENT

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The application of moment method codes at present is restricted by, among other factors, computational limitations, in particular the solution of the set of simultaneous equations. Different formulations, such as spectral methods, have been proposed to try and increase the electromagnetic size of the problems that can be handled. However, the efficiency of these techniques depends upon exploiting specific geometrical properties to allow use of the FFT and thus save computer time. For general three-dimensional problems, which lack some form of geometrical simplicity, other methods must be investigated, both in the mathematical formulation stage and the computation stage of the problem. This paper addresses the latter, viz parallel computation.

Parallel processing holds out the promise of radically increasing the computing power available, especially to those without access to supercomputers such as the Cray series, at reasonable cost. We are investigating the use of an array of T800 transputers, a micro-processor developed by the British company INMOS, for parallelizing the well known code NEC2. This array is hosted in a PC clone and can be used to implement a Multiple Instruction, Multiple Data (MIMD) machine with local memory. The transputer is particularly suitable for use in a parallel processing environment as it has four 20 MBit/s serial links that allow fast inter-processor communication. The T800 processor is a very fast machine in its own right, utilizing the reduced instruction set concept, and our group has already reported the use of the transputer on a card slotting into a PC as a workstation. (JJ le Roux et al, Electronic Letters, pp 991-992, 4th August 1988).

In particular, we will report on the use of this MIMD system for the solution of the matrix equation using iterative algorithms. We will discuss the suitability of various well known iterative algorithms, such as the conjugate gradient method, for parallelism. Parallel processing requires some re-thinking of existing approaches; for example, the conjugate gradient algorithm in its general form is problematic for multi-processors with local memory, because of the matrix transpose operation. We will also report on certain benchmark problems used to investigate the speed-up possible using this MIMD system.

# A THREE DIMENSIONAL PC-GRAPHICS PROGRAM FOR DISPLAYING ANTENNA PATTERNS

**George M. Ruhlmann*, John C. McKeeman, and Warren L. Stutzman**
**Department of Electrical Engineering**
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**Abstract**

Visualization of three dimensional antenna patterns is difficult. The chance of misconception is high unless the pattern is displayed accurately. At Virginia Tech a program called 3D has been developed that displays three dimensional antenna patterns on IBM personal computers and compatibles. Current personal computers are capable of displaying a pattern in high resolution graphics under reasonable time constraints. The program will display any antenna pattern that is expressible in a spherical coordinate equation. The power of 3D is its ability to eliminate hidden lines regardless of pattern orientation. The use of several hidden lines algorithms minimizes the time necessary to eliminate hidden lines.

The program 3D is completely menu driven for easy use. The program supports a mouse, however a mouse is not necessary. The program supports CGA, EGA, MCGA, and VGA graphic displays. 3D will run on any IBM PC or PS/2 computer or true compatible under DOS 2.1 or higher. The program will run with 256K of RAM, but for most practical applications the program will need 640K. A math co-processor is not required but, again, for most practical applications a math co-processor is strongly recommended.

The user has the ability to rotate the pattern around any axis, zoom in or out, and select hidden line algorithms. Finally, the program supports a plotter for generating hard copies of the displayed patterns. Currently, 3D is undergoing testing in antenna classes at Virginia Tech.

## Tuesday AM

Joint AP-S, URSI-B Session 29

**EM Theory I**

*Chairs*: L. B. Felsen, Polytechnic U. of New York; G. Franceschetti, U. of Napoli

*Room*: Cedar *Time*: 8:15–12:00

| | | |
|---|---|---|
| 8:20 | **Time-Spectral Domain Green's Dyad in a Lossless Half-Space**<br>M. Yu,* C.-S. Shi, D. Lin, D. Lu, Tsinghua University | AP-S |
| 8:40 | **Image of a Current Loop over a Superconducting Sphere**<br>A. Sezginer,* Schlumberger-Doll Research, W. C. Chew, Univ. of Illinois at Urbana-Champaign | AP-S |
| 9:00 | **Planar Waveguide Model of Rotman Lens**<br>K. K. Chan,* Chan Technologies Inc. | AP-S |
| 9:20 | **Geophysical NMR: Electromagnetic Aspects**<br>A. Sezginer,* Schlumberger-Doll Research | AP-S |
| 9:40 | **Analysis of Coupling of Composite Dielectric Resonator Structure using Mode Matching Technique**<br>T. Bhattacharjee,* X. Tu, New Jersey Institute of Technology | AP-S |
| 10:00 | **Coffee Break** | |
| 10:20 | **Beamspace Domain ML Based Low Angle Radar Tracking with an Array of Antennas**<br>T.-S. Lee,* M. D. Zoltowski, Purdue University | AP-S |
| 10:40 | **Characterization of the Dispersion of a Rotman Lens**<br>V. K. Tripp,* J. E. Tehan, C. W. White, Georgia Tech. Research Institute | AP-S |
| 11:00 | **An Electromagnetic Model for Multiconductor Connectors**<br>R. G. Plumb, A. T. Adams,* R. F. Harrington, Syracuse University | AP-S |
| 11:20 | **On the Superconducting Suspension Effect**<br>A. Sezginer,* Schlumberger-Doll Research | AP-S |
| 11:40 | **Microwave Applications of Superconductors**<br>T. L. Simpson,* University of South Carolina | 134 |

# MICROWAVE APPLICATIONS OF SUPERCONDUCTORS

T. L Simpson
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Through recent advances in high-temperature superconductors, superconducting materials are now available for investigation in practical microwave components. Devices which have previously been limited by ohmic losses may now be partially or totally freed from this constraint. In addition, through the interaction of externally controlled magnetic fields and dc bias, new control mechanisms may be constructed.

A review of current research will be presented along with some experimental results from the Microwave Laboratory at the Swearingen Center in conjunction with the USC Center for Superconductivity. Small superconducting components embedded in microsrip resonators and microwave cavities are currently being investigated. Particular attention is being directed toward the microstrip radiator problem where conventionalal patch antennas have been severely limited by bandwidth and loss.

## Tuesday AM

### URSI-A Session 31
### Measurements I

*Chairs*: M. Kanda, NBS; J. F. Aurand, Sandia National Lab
*Room*: Carmel *Time*: 8:15–10:20

# A COMPACT HF RECEIVING ANTENNA FOR GROUND- AND SKY-WAVE DIRECTION FINDING AND INTERFERENCE REDUCTION WITH SUPERIOR PERFORMANCE INDOORS

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## ABSTRACT

The noteworthy features of this device include (1) making both elements of a close-spaced Adcock-type array part of a single resonant circuit to simplify tuning, prevent coupling interaction, and achieve adequate sensitivity in a small size; (2) using as array elements two partially shielded resonant foreshortened monopoles or dipoles having exceptionally low impedance for improved performance indoors, where magnetic fields are relatively less distorted than electric fields; and (3) electrically isolating the output cables from the device to minimize undesired pickup due to the array and its attached wires acting as the end of a random-length wire antenna.

The result is an easily adjusted, readily transportable bidirectional antenna suitable for direction finding or interference reduction with either ground or sky waves, and capable of performing these functions reasonably well indoors. In that case, the antenna can be located on a small turntable immediately adjacent to the receiver for ready access by the operator. Proximity of the operator's body has little effect. Over an operating frequency range which can be as large as four to one, the only tuning adjustment is one that maximizes sensitivity.

# USING A GROUND-REFLECTION FACTOR TO IMPROVE ANTENNA MEASUREMENT ACCURACY

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When performing antenna measurements on outdoor ranges, the presence of the ground usually makes it difficult to obtain accurate results. Attempts are made either to reduce the ground reflection effects and assume free-space conditions between the antennas, or to enhance the ground reflections and assume ideal mirror-image conditions. Depending on the operating frequency, antenna gains, and ground properties, these conditions may be hard to achieve.

This paper presents a simple ground-reflection factor (GRF) to account for ground-reflected waves in antenna measurements. It can be used to modify the assumed transmission loss between antennas, to modify theoretical free-space patterns, or to predict where to best locate the transmit and receive antennas on a measurement range.

The ground-reflection factor is defined at some location to be the ratio of the actual received power density to the power density that would occur at that position if only a direct free-space wave was present. It quantifies the assumed superposition of a direct wave and a single specularly-reflected wave off a flat ground surface. If the location is assumed to be in the far-field of the transmit antenna, with a small grazing angle for the reflected wave, then the GRF can be expressed as

$$GRF = |1 + R\exp(j2\pi\Delta L/\lambda)|^2,$$

where R is the complex ground reflection coefficient for linear polarization (either horizontal or vertical), $\Delta L$ is the path-length difference between the reflected wave and direct wave, and $\lambda$ is the wavelength.

Several uses of the GRF will be presented: improving the accuracy of the two-antenna method of measuring gain, determining the best distance and height for positioning the receive antenna, predicting the power density dropoff with increasing distance, and predicting the received power density pattern in the vertical plane. These will be illustrated by comparisons with actual measurements.

The approach has proven quite useful in our antenna testing by increasing the accuracy of our measurements, and it should be beneficial to others who perform antenna measurements.

# SOURCES OF ERROR IN A SPHERICAL NEAR FIELD SYSTEM

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David Florida Laboratory, Ottawa, Canada

## ABSTRACT

In order to validate and to estimate error budget for a spherical near field facility, an extensive study of possible sources of error and their effect on transformed patterns is now under way. This paper will report the results and significant conclusions of this study. The spherical near field system is novel (P. Wood et al, AMTA 1988, P. Cowles et al, ICAP 1989) in hardware and software. The sources of error under study include positioning errors, alignment errors, coordinate reference errors, sampling errors (number of samples, data acquisition speed, and sample position errors), probe errors (probe pattern, polarization and alignment), receiver drift, receiver non linearity, numerical computation and truncation errors.

The results will be presented in the form of parametric data to assist in identifying design criteria for economic spherical near field facilities.

# TARGET CLASSIFICATION USING MULTI-FREQUENCY RCS STATISTICS

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In this presentation, an algorithm is described to classify the targets into one of the N preselected body shapes. Statistics like 5, 50 and 95 percentile values of Radar Cross Section (RCS) and RCS standard deviation are used.

This method for target shape classification uses radar back-scattering data from two or more collocated radars operating at different frequencies. Results from Multi-frequency data analysis will be presented.

An auto-regressive parameter estimation model will also be described to classify target dynamics.

# STRESSED-SKIN TARGET SUPPORTS FOR RCS MEASUREMENTS

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ABSTRACT

An inflatable structure used as a target support for radar cross section measurements in an anechoic chamber provides substantial improvement over a foam column. Theoretical analysis indicates that backscatter from the support is minimized because its mass is reduced below that of a foam column and is distributed to favor incoherent scattering. Interactions between target and support are less than 1% of target RCS. A pressurized thin shell can support a heavy load with remarkable stability. Experimental observations using a high tensile strength, low permittivity material confirm these results. "Ground bounce" from rotational machinery normally located below a foam column is reduced by lining the bottom of an inflatable support with absorber.

# ALTERNATE FIXTURE SAMPLE GEOMETRIES FOR MATERIAL PARAMETER DETERMINATION

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The complex permittivity and permeability determination of material is commonly performed with measured $S_{11}$ and $S_{21}$ parameter data using coaxial or rectangular wave-guide fixtures. Ideally, the material sample completely fills the cross-section of the fixture but this can not always be practicely achieved. The presence of an air gap between the material sample and fixture constitutes an error term. This error term is especially significant if the internal electric field distribution is normal to the parallel walls forming the gap. This error term is analyzed to determine its influence on the value of the extracted constitutive parameters. Alternate material sample geometries are evaluated to minimize the effect of this error term.

Joint AP-S, URSI-B Special Session 33

**Brainstorming - New Trends**

*Chairs*: R. M. Bevensee, LLNL; D. L. Jaggard, Univ. of Pennsylvania

*Room*: San Carlos *Time*: 8:15–11:45

| | | |
|---|---|---|
| 8:20 | **Recent Advances in Radar Polarimetry Identification of New Trends in Radar Signal and Image Processing**<br>W.-M. Boerner,* University of Illinois at Chicago | 144 |
| 8:40 | **The Synaptic Antenna for Reconfigurable Array Applications-Description**<br>R. C. Dempsey,* California Microwave Inc., R. M. Bevensee, Lawrence Livermore National Laboratory | AP-S |
| 9:00 | **The Synaptic Antenna for Reconfigurable Array Applications–Behavior**<br>R. M. Bevensee,* Lawrence Livermore National Laboratory, R. C. Dempsey, California Microwave Inc. | AP-S |
| 9:20 | **Phase Space Engineering for Neurodynamic Target Identification**<br>N. H. Farhat,* H. Babri, University of Pennsylvania | AP-S |
| 9:40 | **Coffee Break** | |
| 10:00 | **Planned Major Improvements to the Arecibo Telescope**<br>T. Hagfors,* Cornell University | AP-S |
| 10:20 | **Chaos in Electromagnetic Fields**<br>R. M. Bevensee,* Lawrence Livermore National Laboratory | 145 |
| 10:40 | **Radiation from Waves Guided by Nonuniform Active Surfaces**<br>R. J. King,* Lawrence Livermore National Laboratory | AP-S |
| 11:00 | **Open Discussion of Chaos** | |

# RECENT ADVANCES IN RADAR POLARIMETRY

## IDENTIFICATION OF NEW TRENDS IN RADAR SIGNAL AND IMAGE PROCESSING

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During the past six years, basic research on the fundamentals of coherent and partially coherent radar polarimetry were carried out within the UIC-EECS/CL with applications to target detection in clutter, target and background clutter classification, target imaging, and identification. As a result of these investigations the underlying fundamental theory of polarization radar technology was revised and corrected and generalized, and the related polarimetric radar-target phenomenology, originally introduced by Dr. Edward M. Kennaugh was reformulated in a physically more transparent three-stage target versus clutter optimization procedure. Also, we have clarified existing micsonceptions about the valid use of the restricted $\rho$-formulated unitary transformation matrix presentation of the optimal polarization Null/Max theory of Kennaugh and Huynen in the monostatic cases. Simultaneously, electromagnetic vector inverse scattering theories which utilize complete relative phase scattering matrix radar data were developed which allow straightforward interpretation of polarimetric radar measurement data in terms of the characteristic geometrical and material features of isolated and distributed targets. Based on the Three-Stage-Procedure for the recovery of the optimal polarizations, we have developed a unique and novel "Polarimetric Matched Vector Signal Filter (PMSF)" and a "Polarimetric Matched Image Filter (PMIF)" approach to high resolution polarimetric radar (POL-RAD/SCAT/SAR/RAR/ISAR) imaging for both the coherent and partially coherent cases. A new approach for dealing with partially coherent radar scatter was introduced by establishing a firm and transparent foundation for the Mueller-Stokes operator approach based on the coherency (density) matrix formulation of Emil Wolf for describing time-dependent canonical targets such as fluctuating dipoles, oscillating raindrops, ocean wave scatterers, etc., for purposes of target signal enhancement and clutter rejection under partially coherent conditions.

More recently, we have been successful in introducing the novel concept of "the Polarimetric Matched Vector Signal/Image Filter Technique" to High Resolution Polarimetric Radar (POL-RAD/SAR/RAR/SCAT/ISAR) Imaging. Using the NASA/JPL CV990 C-band POL-SAR data set on the San Francisco Bay Area, the tremendous capabilities of the PMSF and PMIF techniques will be demonstrated.

Various practical cases of coherent radar signal enhancement versus background noise suppression will be demonstrated in order to prove how polarimetric radar techniques will considerably improve on signal/clutter ratio in radar signal and image processing.

# CHAOS IN ELECTROMAGNETIC FIELDS*

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"Chaos" may be qualitatively described as a phenomenon of a nonlinear process or processes which exhibits certain order and coherence despite apparent microscopic randomness. The word does not seem to have a specific definition in widespread use. Chaos has been observed in such diverse fields a hydrodynamics, plasma physics, lasers, solid state physics and complex chemical reactions. But it has not been studied to any significant extent in electromagnetics.

We shall consider some situations in which electromagnetic fields are driven by sources with chaotic components. For example, the amplitude I(t) of a cavity mode with resonant frequency $\omega_0$ and coupled to a nonlinear dielectric with a "Feigenbaum-process" component is described by the second-order differential equation

$$[\varepsilon_1 + \varepsilon_F(t)]\, d^2I/dt^2 + [\omega_0/Q_0 + d\varepsilon_F/dt](dI/dt) + \omega_0^2 I = 0 .$$

Here $Q_0$ is the quality factor, $\varepsilon_1$ is the time-independent component of relative permittivity, and the $\varepsilon_F(t)$-component is governed by the Feigenbaum-process

$$\varepsilon_F(t_{n+1}) = r\varepsilon_F(t_n)\,[1 - \varepsilon_F(t_n)], \quad t_n = n\Delta t_c .$$

$\Delta t_c$ is the process time step and r is the factor which determines successively more complicated cyclic behavior in the range $3<r\leq4$.

We shall examine the behavior of I(t) for various values of the parameters $Q_0$, $\varepsilon_1$, $\varepsilon_F(t_1)$, r, and $\omega_0\Delta t_c$.

We will also discuss to some extent the chaotic behavior of a traveling wave on a transmission line with chaotic elements, and a plane wave propagating through a chaotic medium.

## References

1. Chaos 87. International Conference on the Physics of Chaos and Systems Far From Equilibrium, (Conference held at Monterey, CA, Jan 11-14, 1987), edited by M. Duong-van, Elsevier Science Publishers, North-Holland, Amsterdam, 1987.

2. J. Gleick, Chaos Making a New Science, Viking, New York, 1987 (popularized treatment).

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

## Tuesday AM

Joint AP-S, URSI-F Session 34

**Polarimetric Radar Scattering Analysis**

*Chairs*: W. J. Battles, Lockheed; S. K. Chaudhuri, Univ. of Waterloo

*Room*: San Juan *Time*: 8:15–12:00

| | | |
|---|---|---|
| 8:20 | **Polarimetric Radar Signal Processing**<br>D. Giuli, M. Gherardelli,* Univeristy of Florence | 148 |
| 8:40 | **Target Averages and Decomposition Theorems**<br>J. R. Huynen,* P Q Research | AP-S |
| 9:00 | **Recent Advances in the Development of the Physical Optics Inverse Scattering Theory for Non-Symmetric, Conducting, Closed Shapes the Depolarizing Effects for the Monostatic and Bistatic Cases**<br>B.-Y. Foo,* W.-M. Boerner, University of Illinois at Chicago | 149 |
| 9:20 | **Polarimetric Contrast Optimization for Partially Polarized Waves**<br>M. Tanaka,* Oita University | AP-S |
| 9:40 | **Coffee Break** | |
| 10:00 | **Application of Kennaugh's Targets Characteristic Polarization State Theory to the Polarimetric Interpretation of Remotely Sensed Scattering Targets and Features**<br>A. P. Agrawal,* Y. Yamaguchi, W.-M. Boerner, University of Illinois at Chicago | 150 |
| 10:20 | **Polarimetric Radar Detection of Point Targets in a Forest Environment**<br>M. W. Whitt, F. T. Ulaby,* University of Michigan | AP-S |
| 10:40 | **Optimization Procedures for Scattering Matrices in the Coherent and Partially Coherent Cases**<br>W.-L. Yan,* A. B. Kostinski, W.-M. Boerner, University of Illinois at Chicago | 151 |
| 11:00 | **Optimal Polarizations for Distributed Random Targets - Statistical Analysis of Polarimetric DFVLR Radar Data**<br>K. Tragl,* A. Schroth, E. Luneburg, Institut fur Hochfrequenz, DFVLR | AP-S |
| 11:20 | **Parameter Estimation in Radar Inverse Scattering**<br>A. J. Devaney,* H. R. Raemer, Northeastern University | 152 |
| 11:40 | **Polarimetric ISAR Imaging to Identify Basic Scattering Mechanisms of Geometrically Complicated Objects**<br>G. Dural,* Middle East Technical University, J. D. Young, D. L. Moffatt, Ohio State University | 153 |

# POLARIMETRIC RADAR SIGNAL PROCESSING

D. Giuli, M. Gherardelli*

*Electronics Eng. Dept. - University of Florence - Via S. Marta, 3 - 50139 Florence [ Italy]*

The subject of this paper is the improvement of radar target detection performance by means of polarimetric processing techniques. Specifically the performance of low resolution radars equipped with dual polarisation receiving channels are investigated referring to the improvements obtainable in radar target detection in the presence of ground clutter or intentional polarized noise (jamming).

The actual improvement of radar performance through dual polarization processing can be evaluated when the wave polarization information is retained by a vector measurement process. Based on measurement results, it is shown that while a highly stationary polarization is expected with polarized jamming signals, target and ground clutter have characteristic and considerably different polarization behaviours. Indead the target echo mean polarization changes considerably from scan to scan, even if it is near stationary during dwell time. Conversely ground clutter in urban areas: the echo polarization does not change from scan to scan, even though it is highly non-stationary in space.

The polarization features of the different types of disturbance and targets thus make adaptive polarization filtering profitable. In fact when a high polarization degree and a high stationarity in space and time of disturbance is hypothesized several adaptive polarization cancellers can be proposed for improving the signal-to-clutter ratio.

By utilizing the over mentioned experimental radar data, some filtering simulations upon experimental radar data were carried out for adaptive polarization rejection of ground clutter and polarized jamming signals. For ground clutter suppression two kinds of adaptive cancellers were used: the first one resorts to the storage of the polarization map of the radar coverage area, which is periodically updated every several scans, so that the stored polarization is used to adapt the receiver polarization at successive scans. The second canceller applies a non-linear polarization filtering by estimating the ground clutter parameters at one scan, such as average polarization, polarization state preferred direction of sample alignement over the polarization Poincare' sphere, polarization sample distribution around a mean direction; then the filter adapts its parameters for each vector-signal sample, so as the input signals at successive scans can be attenuated . For jamming rejection adaptive cancellers are proposed which attenuate the undesired signal by a continuous and adaptive estimation of its polarization: this information is used for the optimum setting of the receipt polarization.

It is shown that in both cases good performance can be obtained in terms of signal-to-clutter ratio improvement.

# RECENT ADVANCES IN THE DEVELOPMENT OF THE PHYSICAL OPTICS INVERSE SCATTERING THEORY FOR NON-SYMMETRIC, CONDUCTING, CLOSED SHAPES THE DEPOLARIZING EFFECTS FOR THE MONOSTATIC AND BISTATIC CASES

Bing-Yuen Foo and Wolfgang-M. Boerner

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Advances made in the electromagnetic inverse scattering problem for plane wave incidence on a perfectly conducting closed, convex, but not rotationally symmetric scatterer under the physical optics solution are considered for the monostatic and bistatic cases.

Using Kennaugh's target ramp response formulation, Kennaugh's formula is extended to the bistatic case; and in order to account for the polarization characteristics of vector electromagnetic inverse scattering in both monostatic and bistatic cases, Bennett's polarization correction to physical optics is applied and extended to obtain asymptotic solutions between the phase difference of the co-polarized and the co/cross-polarized elements of the bistatic scattering matrix, and the principal curvature difference at the specular point.

In addition, the effects of the torsional term in the Minkowski-Hurwitz equation of vector differential geometry, which is associated with this problem, are considered and the properties of Huynen's helicity factor are interpreted.

# APPLICATION OF KENNAUGH'S TARGETS CHARACTERISTIC POLARIZATION STATE THEORY TO THE POLARIMETRIC INTERPRETATION OF REMOTELY SENSED SCATTERING TARGETS AND FEATURES

Amit P. Agrawal, Yoshio Yamaguchi and Wolfgang-M. Boerner

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The Kennaugh target characteristic polarization theory for the monostatic reciprocal coherent case is developed in greater detail, emphasizing the ransformation of the scattering matrix under the change of polarization basis via the unitary transformation matrix formulated in terms of the polarization ratio $\rho$. Six characteristic polarization states are determined, and displayed on the Poincaré sphere and on power and phase plots. Several simple target cases are considered for demonstrating the applicability of this useful concept to radar target classification, imaging, and identification in radar remote sensing.

# OPTIMIZATION PROCEDURES FOR SCATTERING MATRICES IN THE COHERENT AND PARTIALLY COHERENT CASES

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Basic aspects of polarimetric radar/lidar target scattering for both the coherent and partially coherent cases are re-examined. The optimization procedures for the coherent case is formulated in terms of a "Three-Stage Procedure" for the general bi-static case. The distinction between the physics of partially polarized versus coherent waves is emphasized leading to a unique formulation for optimal reception of partially polarized waves scattered off a fluctuating ensemble of scatterers of known (measured) Mueller matrices. Expressions for total available intensity versus adjustable polarization-dependent (coherent) intensity are derived using the coherency matrix approach. By formulating a proper covariance matrix, it is shown how the measured Mueller matrix can be tested on measurement errors and how the partially polarized case reduces to the coherent case resulting in a unique set of optimal polarizations.

# PARAMETER ESTIMATION IN RADAR INVERSE SCATTERING†

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The problem of estimating radar target parameters from noisy monostatic and bistatic scattering data is addressed using linearized scattering models and maximum liklihood estimation theory. The problem is formulated using the Born approximation for penetrable targets and small $ka$ values and using the polarization corrected physical optics approximation for conducting targets and large $ka$ values. Both of these approximations are shown to lead to the same *mathematical* inverse problem: namely, that of estimating one or more parameters of a three-dimensional characteristic function from noisy estimates of the function's spatial Fourier transform along contours in Fourier space.

A general computational scheme is presented for computing M.L. estimates of target parameters such as target location and aspect ratio within these approximations for the case of additive Gaussian noise. The M.L. estimation algorithms are tested in a computer simulation study using synthetic scattering data from penetrable and conducting spheroids. The scattering data is generated using the Born and physical optics approximations and a multiple scattering, T matrix based scattering code. Estimates of the target's location and aspect ratio are computed in Monte Carlo simulations for broadband monostatic scattering data and narrow band bistatic scattering data. Cramer Rao bounds for the variance of the parameter estimates are computed and compared with the results obtained in the Monte Carlo simulation.

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†Research sponsored from an SBIR Phase I contract to A.J. Devaney Associates from the Office of Naval Research

‡Also with A.J. Devaney Associates 26 Edmunds Rd. Wellesley, MA 02181

# POLARIMETRIC ISAR IMAGING TO IDENTIFY BASIC SCATTERING MECHANISMS OF GEOMETRICALLY COMPLICATED OBJECTS

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Jonathan D. Young and David L. Moffatt
The Ohio State University ElectroScience Laboratory
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The paper focuses on the identification of basic scattering mechanisms using imaging techniques and polarimetric information. The approach used for generating synthetic target images from electromagnetic scattering data is closely related to both ISAR (Inverse Synthetic Aperture Radar) imaging techniques and CAT (Computer Assisted Tomography). The imaging algorithm combines one-dimensional, band-limited, filtered impulse response signatures with aspect angle information and replaces conventional two-dimensional Fourier transforms which are commonly used for image reconstruction. Two different aircraft models have been investigated in this paper. The first one was a generic aircraft model of electrical length varying 1 to 9 wavelengths at the frequency range of 2 to 18 GHz. The wings and the tail were detachable from the fuselage so that different scattering mechanisms associated with the wings and the tail could be isolated from each other. The second target was a scale model of a Boeing 707 aircraft with an electrical length of 2 to 18 wavelengths at 2 to 18 GHz. frequency band. In both applications, it has been shown that polarization helps for better understanding of the scattering mechanisms and the target geometry.

## Tuesday AM

URSI-B Session 35

### Waveguides

*Chairs*: A. A. Oliner, Polytechnic U. of New York; H. Shigesawa, Doshisha Univ.
*Room*: San Martin *Time*: 8:15–11:40

# TRANSITION BETWEEN AN INTEGRATED DIELECTRIC WAVEGUIDE AND A MICROSTRIP LINE

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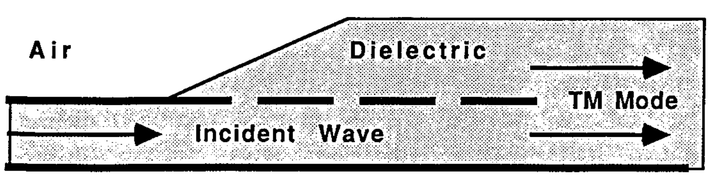
Microstrip technology will have an increasing number of problems associated with it as frequencies of operation are pushed into the millimeter wave region. Among the most important of these will be the increased propagation loss due to the finite condoductivity of the metal.It is not expected that all parts of the circuit will scale with frequency, as the millimeter wave region is entered, and the loss problem cannot entirely be dismissed; for example, the distances involved in power transfer to array elements will not shrink that dramatically. A possible solution to this problem is to use a combination of microstrip lines and integrated, guided wave lines, the loss of which is much less than that of the microstrip. If such a combination of line types is to be practical, an efficient and inexpensive transition must be developed.

In this talk, we will discuss the results of the transition we developed, as shown in the figure. A microstrip line is terminated in a series of capacitive strips. The spacing of the strips is chosen so as to efficiently excite a TM mode in the dielectric waveguide region. The structure can be easily made by first etching the microstrip line, and then gluing another piece of dielectric over it where the dielectric waveguide is to appear. The actual structure only has the thicker dielectric region in those regions of the circuit where the guided wave is to travel. It is difficult to model such a three dimensional structure accurately, and we have therefore looked at the simpler two-dimensional problem of infinitely wide strips. We also have assumed that the thicker dielectric extends over the whole structure. We will present numerical results of the S parameters of such a structure and give design guidelines for an efficient transition. The numerical method used is a moment method for the currents, with a spectral domain evaluation of the matrix elements. We also will present a number of experimental results, which we will compare to the theoretical predictions.



# LINEAR ARRAY OF COAXIALLY-FED MONOPOLE ELEMENTS WITH WAIM SHEET IN A PARALLEL PLATE WAVEGUIDE

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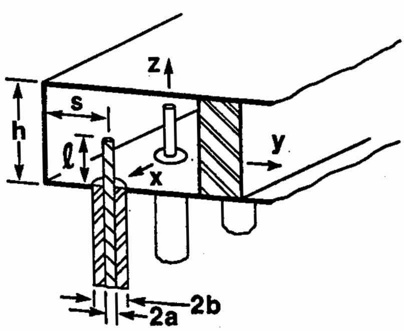
Linear arrays of coaxially-fed monopoles radiating into a parallel plate region are used extensively in various space-fed microwave array antenna systems. In particular, such arrays are employed in space-fed beam forming networks. In addition, the information derived from the study of these arrays is very useful in the design of a large variety of conformal arrays. The performance of a coaxially-fed monopole element in an infinite linear array environment in a parallel plate guide has been extensively analyzed in (B. Tomasic and A. Hessel, IEEE AP-T, March 1988).

In this paper we go a step further and analyze the same array with a dielectric, or so-called WAIM, sheet (E.G. Magill and H.A. Wheeler, IEEE AP-T, January 1966). The purpose of this sheet is to improve the wide-angle, wide-band element performance. The analysis takes into account the geometry of the coaxial feed. Expressions for active admittance, coupling coefficients and element patterns are derived. Numerical results will be presented to illustrate the performance trends.



# TRANSMISSION LINE MODELING OF DRIFT TUBE LINEAR ACCELERATORS

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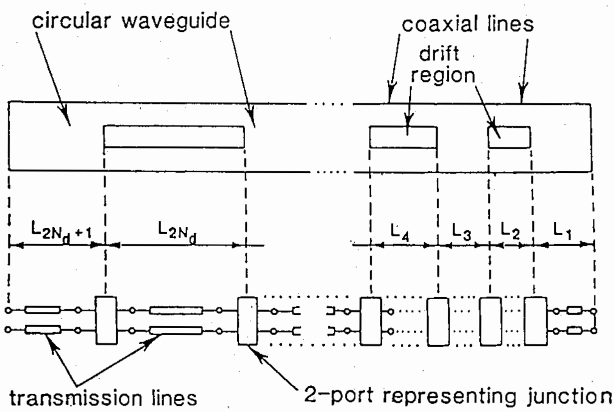
Waveguide discontinuity problems are usually solved by reducing the problem to an integral equation and then solving the integral equation by one of many numerical methods. With increased availability of programs for direct numerical solutions of Maxwell's equations it is often easier to extract the equivalent circuit parameters. Some of the programs were originally designed as CAD tools in linear accelerator design.

The drift-tube linear accelerator consists of a long circular waveguide with a number of coaxial drift tubes, as shown in Fig. 1, together with the network representation. The 2-port parameters for the discontinuity between coaxial and circular waveguides can be calculated in many ways, but, if the end faces are not flat, Maxwell equation solvers are easier to use.

Equivalent circuits were obtained for a short gap between drift-tubes in TEM and $TE_{11}$ modes using SUPERFISH (K. Halbach et al., Particle Accelerators, 7, 213-223, 1976) and URMEL (U. Laustroer, DESY-M-87-03, 1987). The equivalent circuit for a cylindrical post coupling the two modes in a coaxial line, used for stabilization of accelerator cavities, was obtained using MAFIA (R. Klatt et al., Proc. Lin. Acc. Conf., SLAC, 1986). The technique of extracting network parameters and results obtained will be discussed.




Accelerator Cavity and its
Transmission Line Model.

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# CORRUGATED WAVEGUIDE STRUCTURES

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Properties of electromagnetic waves in slow wave structures, where phase velocity is much less than that of light, were studied. The slow wave structures consisted of rectangular serrations or corrugations with a square wave profile. Boundary conditions were obtained for slow wave structures with teeth and slots of variable widths (d-b) and b, respectively. Slot depths were also varying, so that effects of transitions from slow to fast wave structures could be simulated.

Fields in the region above the surface of the slow wave structure and below the structure in the slot regions were expanded in Fourier series and these series were matched at the boundaries of both regions. Results agreed axactly with those for slow wave fields when the square teeth widths approached extremely thin fins [Leon Brillouin, J. Appl. Phys., 19, 1023-1041, 1948].

Results of this study shall be integrated with magnetron-type traveling wave tubes and magnetically insulated transmission line oscillators (MILO) [Raymond W. Lemke and M. C. Clark, J. Appl. Phys., 62, 3436-3440, 1987] in coupling between slow wave into fast wave structures for better efficiency. The MILO, which is the source of microwave power, is a slow wave device. The antenna for MILO is a fast wave device. This study is an excellent model for subsequent analyses and experimental measurements.

# SPLICE LOSS EVALUATION OF SINGLE-MODE TRIANGULAR CORE FIBERS WITH A TRENCH USING VECTOR MODE ANALYSIS

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Unlike many previous approaches based on the scalar mode theory or Gaussian field approximation, the vector mode analysis is used here to investigate the transverse offset and tilt of dispersion-shifted single-mode fibers with a trench at the fibers' zero-dispersion wavelength, *1.55 μm*. This method facilitates the studies of the polarization-dependence of splice losses. For weakly guiding fibers such as the fibers studied here, this dependence becomes negligible.

In the calculations, the fiber core-cladding and trench-cladding index differences $\Delta_1$ and $\Delta_2$ are assumed to be *1%* and *0.4 %*, respectively. *a*, *b* and *c* denote the fiber core radius, and the trench radii, respectively.

The offset and tilt loss sensitivity have been investigated as a function of the normalized trench width at *1.55 μm*, with $b/a=2.0$ and $(c - b)/a$ from *0* to *1.0*. A wider normalized width generally makes the fibers less tolerant to a transverse offset, but more tolerant to tilt. The effects of the trench on the splice losses are somewhat small in both cases. Such a trench can be used to tailor fibers' dispersion characteristics with only a small impact on the splice loss performance.

The effect of the normalized trench position $b/a$ on splice losses is also studied for a fixed normalized trench width $(c- b)/a=0.2$. The core radius *a* is adjusted to yield zero-dispersion at *1.55 μm*. At about $b/a=2.76$, the offset loss reaches a minimum at an offset of 2 *μm*, but the tilt loss reaches a maximum at a *2.5* degree tilt angle. If the tilt angle can be better controlled during splicing, splice losses can be optimized by properly locating the trench to reduce the offset loss. This interesting feature has not been noted previously.

# TE WAVE EXCITATION AND SCATTERING ON ASYMMETRIC PLANAR DIELECTRIC WAVEGUIDE: DIRECT COMPLEX ANALYSIS APPROACH

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An asymmetric planar dielectric waveguide is formed by the tri-layered substrate/film/cover environment, typical of integrated circuits for millimiter and optical wavelengths. The structure supports surface waves when the film-layer guiding region has positive index contrast relative to its surround. An electric Green 's function (believed new) is constructed for the TE field maintained in the film layer by currents immersed in that region. Using a direct complex analysis approach, the Green 's function is expanded in the discrete and continuous propagation spectrum components for the asymmetric planar waveguide. The electric Green 's function is exploited to study scattering of TE surface waves by dielectric obstacles in the film layer.

If the y-axis is normal to the layer interfaces and the waveguiding z-axis is parallel to them, then an x-invariant TE field, having only an x component, is excited by the similar component of current. Spectral analysis in the axial transform domain leads to

$$E_x(y,z) = \int_{LCS} G(y,z|y',z')\, J_x(y',z')\, dy'dz'$$

where LCS designates the longitudinal cross section of the source region and the Green's function has a spectral integral representation. Subsequent to complex transform plane analysis, $G(y,z|y',z')$ is decomposed into the superposition of a discrete surface wave, arising from pole singularities, and a radiative component arising from integrations about substrate/cover branch cuts.

If a dielectric discontinuity having index contrast $\delta n^2 = n^2(y,z) - n_f^2$ is immersed in the film layer, an excess polarization current is excited and maintains a scattered field. This current is proportional to the product of the induced field and the refractive index contrast. Whithin the obstacle the total field $E = E^i + E^s$ consists of the impressed field of an icident wave augmented by the scattered field. Rearranging leads to the EFIE

$$E_x(y,z) - j\omega\varepsilon_0 \int_{LCS} \delta n^2(y',z')\, G(y,z|y',z')\, dy'dz' = E_x^i(y,z)$$

A pulse-Galerkin's solution leads to the induced field, from which scattering coefficients are calculated. Extensive numerical results for various obstacle configurations will be presented.

# RAYS, CAUSTICS AND GAUSSIAN BEAMS IN NONUNIFORM REFRACTIVE WAVEGUIDES

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An asymptotic solution of ray equations

$$\nu^2 \frac{d^2 z}{d\tau^2} = \frac{1}{2}\,\varepsilon_z(x,z)\,, \qquad \frac{d^2 x}{d\tau^2} = \frac{1}{2}\,\varepsilon_x(x,z) \tag{1}$$

for a waveguide with slowly varying dielectric permittivity $\varepsilon(X/L, Z/H)$ has been found by means of "two-times" expansions in small parameter $\nu = H/L \ll 1$. Here, $L$ and $H$ are characteristic longitudinal and transversal scales, $x = X/L$, $z = Z/H$ are normalised Cartesian coordinates. The first-order approximation $z \approx z_0 + \nu z_1$, $x \approx x_0 + \nu^2 x_2$ has the following form

$$\mp\Omega \int_z^{z^+} \frac{dz'}{\sqrt{\varepsilon-Q}} + \nu\frac{\Omega}{\sqrt{Q}} \int_z^{\overset{\pm}{z}} \frac{\varepsilon\, dz'}{\sqrt{\varepsilon-Q}}\; \frac{\partial}{\partial x}\int_{z'}^{z^+} \sqrt{\varepsilon-Q}\; dz'' - \nu\sqrt{Q}\int_z^{z^+}\frac{dz'}{\sqrt{\varepsilon-Q}}\;\frac{\partial}{\partial x}\Big(\Omega\int_{z'}^{\overset{\pm}{z}}\frac{dz''}{\sqrt{\varepsilon-Q}}\Big) =$$

$$= \frac{1}{\nu}\int_0^x \frac{\Omega}{\sqrt{Q}}\, dx' - 2\pi N - C\,, \tag{2}$$

$$\tau = \int_0^x \frac{dx'}{\sqrt{Q}} - \frac{\nu^2}{\sqrt{Q}}\int_z^{\overset{\pm}{z}} \frac{dz'}{\sqrt{\varepsilon-Q}}\;\frac{\partial}{\partial x}\int_{z'}^{\overset{\pm}{z}}\sqrt{\varepsilon-Q}\; dz''$$

Slowly varying functions $Q(x,I)$ and $\Omega(x,I) = -\frac{\pi}{2} Q_I$ must be determined from the adiabatic invariant

$$I = \int_{z^-}^{z^+} \sqrt{\varepsilon-Q}\;\; dz' = Const\,; \qquad \varepsilon(x,\overset{\pm}{z}) = Q(x,I)\,, \tag{3}$$

$N$ is the number of cycle along the oscillating ray trajectory, $C = Const$ its initial phase. The asymptotic solution (2)-(3) holds over large distances $X \sim L$ and simplifies greatly ray tracing. It is especially useful for calculation of the signal strength distribution and other characteristics of the wave field. We show two examples:

1. How to find caustics? One has to calculate the geometric divergency $\mathcal{D}(\tau,I) = |\, z_I\, x_\tau - x_I\, z_\tau \,|$ of a single-parametric family of rays $z = z\,[\tau, I, C(I)]$, $x = x[\tau, I, C(I)]$ and to solve the equation $\mathcal{D}(\tau,I) = 0$. Using Eq.(2) we obtain for $\mathcal{D}$ an analytical expression that enables to draw caustics without ray tracing

2. How a Gaussian beam diverges in a nonuniform waveguide? Its transversal width $d(\tau)$ can be expressed in terms of ray variations $y_1 = \varepsilon^{-1/2}(z_c x_\tau - x_c z_\tau)$, $y_2 = \varepsilon^{-1/2}(z_I x_\tau - x_I z_\tau)$. The approximate solution (2) gives explicite formulas for $y_1$, $y_2$. They show quasiperiodic oscillation of $d(\tau)$ with increasing amplitude $A \sim \int \left(\frac{\Omega}{\sqrt{Q}}\right)_I dx$.

# UHF Radio Channel Models for Indoor Factory Communications

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**(703)-231-6623**

Summary

Radio may eventually be used in factories and office buildings to provide inexpensive, portable communications channels for data and telephone traffic, as well as for mobile robots. To determine typical channel characteristics in factory buildings, extensive UHF impulse response measurements were carried out in five operational factories using a UHF radar capable of resolving multipath components to 7.8 ns resolutions. Measurements revealed that at frequencies above 1 GHz, multipath and shadowing effects (but not RF noise) impair indoor radio link performance. In this paper, we present statistical models for the multipath arrival times and the amplitudes of multipath components in the channel impulse response. Probabilities of path occupancies are also presented. These models have been developed from empirical data, and reveal that surrounding topography plays an important role in channel modeling. The path arrival time and amplitude models are presented as close fits to well-known probability density functions, and are conditioned on topography and transmitter-receiver distance. Wide band indoor radio channel models for manufacturing environments have not appeared previously in the literature.

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This work has been supported by a grant from the Computer Integrated Design, Manufacturing and Automation Center (CIDMAC), Purdue University. The authors are with the Satellite Communications Group at Virginia Tech.

# DOMINANT MODE LEAKAGE FROM PRINTED-CIRCUIT WAVEGUIDES WITH ANISOTROPIC SUBSTRATES

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and

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It is well known that many of the materials used as substrates for microwave and millimeter-wave integrated circuits exhibit dielectric anisotropy. Many full-wave analyses have appeared so far and they reported a significant deviation of the characteristics from the isotropic case for microstrip line, slot line and coplanar waveguide. None of those analyses, however, inquired as to the possibility of dominant mode leakage from those waveguides, caused by the anisotropy. Therefore, the published analyses are incomplete with respect to the propagation characteristics of such waveguides. This paper discusses for the first time such possible leakage problems.

First, let us consider microstrip line with an anisotropic substrate, when the principal crystal axis ( c-axis ) is perpendicular to the substrate surface. Then the dominant mode of the microstrip line has its electric field predominantly along the c-axis. Since this waveguide also includes the conductor-backed dielectric slab regions extending semi-infinitely outside the strip, those regions can also support the dominant $TM_0$ surface wave mode ( polarized mainly in the c-axis and propagating at all frequencies ) and the $TE_1$ surface wave mode ( polarized mainly in the direction perpendicular to the c-axis and propagating above its cutoff frequency ). Our analysis shows that, when the c-axis permittivity of the anisotropic substrate is lower than the permittivity in the plane perpendicular to this axis, an inversion occurs at a certain high value of frequency in the relative phase velocities of the microstrip line dominant mode and the $TE_1$ surface wave mode. At frequencies above this inversion, or crossing, the microstrip line dominant mode leaks power at an angle into the $TE_1$ surface wave mode. Examples of such anisotropic materials include pyrolitic boron nitride and Epsilam 10, and our calculations show that the resulting leakage rates for those materials are quite high.

Unlike the microstrip line, the dominant mode on slot line and coplanar waveguide is polarized mainly in the direction parallel to the substrate surface. The surface wave mode that plays the important role with respect to the leakage effect in this case is the dominant $TM_0$ mode on the dielectric slab with a metal plate on its top surface, in which the electric field is predominantly in the c-axis direction.

The new leakage effect reported here can be very important for millimeter-wave integrated circuits, since such leakage can produce serious unexpected cross talk or coupling problems. A number of numerical discussions to be presented during the talk will clarify this new leakage effect.

## Tuesday PM

URSI-B Special Session 37

### Parallel Computation Techniques for EM Scattering Problems

*Chairs*: W. A. Imbriale, JPL; R. Mittra, U. of Illinois at Urbana

*Room*: Oak *Time*: 1:15–4:40

# Parallel Computing for the Electromagnetic Analyst

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This presentation will survey parallel processing hardware and software topics of interest to practictioners of numerical electromagnetic computations. A taxonomy of parallel computing hardware and an overview of parallel programming styles will be presented, along with parallel programming considerations and measures of parallelism. Topics include SIMD and MIMD machines; message passing, shared memory, and vector-concurrent programming styles; simple and scaled speedup; and the importance of data locality.

These parallel processing concepts will provide the basis for showing the conditions necessary for efficient parallel implementations of numerical methods of electromagnetic computation. Emphasis will be primarily on the method of moments, but finite difference time domain, finite elements, and FFT-based methods will also be mentioned. Parallel solution methods for sparse and dense linear systems will be featured.

# Computation of Electromagnetic Scattering on a Hypercube

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We have applied the computational power of the hypercube parallel computing architecture to the solution of large scale electromagnetic scattering problems. Three classes of scattering analysis codes have been implemented on the Jet propulsion Laboratory/California Institute of Technology Mark IIIfp Hypercube: frequency domain finite element, time domain finite difference, and frequency domain method of moments.

The Mark IIIfp Hypercube is a distributed memory architecture consisting of computing elements called "nodes" which are grouped in configurations of up to 128 nodes. Each node is directly connected to $\log_2 N$ other nodes, where N is the number of nodes in the overall configuration. A node contains 2 Motorola 68020s--one for the application and the other for communication--4 megabytes of dynamic RAM, a Motorola 68882 math co-processor, and a Weitek floating point accelerator. The performance for one node depending on the application is 1-14 million floating point operations per second (MFLOPS) with a typical performance in the range of 1-5 MFLOPS or 128-640 MFLOPS for the 128-node system.

A 2-d and 3-d frequency domain finite element code is currently being implemented on the Mark IIIfp Hypercube. This code permits the analysis of inhomogeneous scattering objects. At a graphics workstation attached to the hypercube an analyst can specify object geometry and appropriate spatial gridding into elements. A computer-aided decomposition tool then assists in a judicious distribution of these elements onto the hypercube nodes so that the workload within nodes, i.e. computation and communication, is well-balanced throughout the hypercube.

A second parallel code developed for the hypercube is a time domain finite difference code which solves the time dependent Maxwell's equation as an initial value problem. Since this code tracks the evolution of scattered fields in time, it is particularly well-suited to the solution of transient field problems.

A third code which has been implemented is the Numerical Electromagnetic Code (NEC-2) developed at Lawrence Livermore National Laboratory. NEC is a frequency domain integral equation formulation modeling a scattering object by wires and/or patches. The memory-resident problem sizes computed on the 32-node Mark III Hypercube have included the inversion of dense (double precision complex) matrices of order 2400. The 128-node Mark IIIfp Hypercube, which will be available April 1989, will extend the maximum in-core problem to 4800 unknowns. The parallel NEC code utilizes node-attached disk drives for retaining previous intermediate solutions so that the scattering analysis can be continued with new additions to the scattering structure.

This paper will describe the size of problem and performance for these scattering codes currently running on the hypercube. The important considerations of effort required to implement code on the parallel architecture and portability will be addressed.

# PARALLEL COMPUTATION WITH THE DISCRETE FOURIER TRANSFORM METHOD APPLIED TO NONORTHOGONAL DIHEDRAL REFLECTORS†

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Many scattering problems, when formulated in term of integral equations, possess the convolution structure. The Discrete Fourier Transform Method (DFTM) is a numerical technique designed to take advantage of this structure by treating both the convolution and the associated differential operators within the framework of discrete Fourier transform technique. Many interesting results have been obtained by using this method.

In this paper, the DFTM has been extended, with the help of an interpolation technique, to treat orthogonal or nonorthogonal dihedral reflectors in such a way that the resulting finite operator equations can be naturally computed in a parallel manner on computers with a limited parallel computing capability such as Cray Y–MP, IBM 3090, VAX 8800 series, etc. The key concept in using the DFTM to perform parallel computing is to first decompose the scatterer into appropriate smaller parts. The scattered field radiated by these parts can be efficiently calculated by using the DFTM at uniformly spaced points in space. Next, a simple and accurate interpolation scheme is used to calculate the incident scattered fields from one part onto the others. Several interpolation techniques were tried, and the one which produced the best results is the Lagrange interpolation method. Since this interpolation scheme can often be implemented in the discrete Fourier transform space, it is extremely easy to incorporate it into the DFTM. Once the mutual interactions are accurately accounted for through their mutual scattered fields, the boundary condition (e.g., the tangential component of the total electric field being zero) on each part can be easily enforced. The resulting discrete operator equations are solved by using the Conjugate Gradient Method on different processors.

Results obtained by using this extension of the DFTM to dihedral reflectors compare favorably with the measurements and with the predictions supplied by Method of Moments. The present technique can be extended to treat coated reflectors, tetrahedrons, and also other kind of scatterers.

†This work is supported by the B–2 Division of Northrop Corporation.

# COMPUTATIONAL ELECTROMAGNETICS USING A CONNECTION MACHINE

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Electromagnetic scattering algorithms are now being implemented on parallel computer architectures. The Connection Machine™ (CM) is particularly attractive for solving such problems because it is massively parallel having 65,536 processors, it has a large 512 Mbyte random access memory, it has bit oriented processing capability, and it has up to 80 Gbytes of on-line fault tolerant disk storage. The robustness of a scattering code can be characterized by problem size and algorithm capabilities such as: scatterer dimensions, its surface model complexity, and its material properties, as well as algorithm run time, and computational dynamic range. Two contemporary computational electromagnetic algorithms, the Method of Moments (MOM) and Finite Difference-Time Domain (FD-TD) were mapped onto the CM. Methodology, robustness, and the results of this effort are presented.

Over the last several decades, MOM has been the accepted standard for electromagnetic scattering predictions. The version adapted for the CM is the triangular surface patch model first introduced by Wilton, Glisson, and Rao. Until recently, applications have been limited to scatterers on the order of a wavelength because of the computational intensity required to solve the linear system to produce surface currents. The CM algorithm is capable of evaluating multiple wavelength scatterers. Results are presented. The accuracy associated with the MOM linear system solution is also discussed in detail. Solution accuracy is assessed not only in terms of problem symmetries but also the word length or arithmetic precision that is used to solve the linear system, a capability totally unique to the CM.

FD-TD is an explicit time stepping finite difference formulation of Maxwell's curl equations. It has broad applicability to the study of electromagnetic scattering by three dimensional objects because the scatterers can be closed or open, conducting, dielectric, magnetic, inhomogeneous, and anisotropic. The scatterer surface model has been generalized from a staircase to a plate model. Implications on run time are discussed. This is important because special case computation that requires only a fraction of processors on a parallel machine "slows" the algorithm down, and suggests that serial implementations might be faster. Examples are given. Large problems that require extensive use of on-line disk storage appear to favor parallel implementation not only because more storage is available but also because the computational cycle does not degrade as quickly as it does on serial machine implementations. Comparisons are drawn and bottlenecks are identified.

# SOLVING ELECTROMAGNETIC SCATTERING PROBLEMS VIA THE METHOD OF MOMENTS ON THE CONNECTION MACHINE

by Stephen D. Gedney* and Raj Mittra
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Over the last two decades, the speed and performance of multiprocessor computers have become increasingly cost effective for solving large, complex scientific problems. The speed of these computers stems from the ability of individual processors to perform independent tasks concurrently. However, in order to harness the full potential of a multiprocessor computer, one must choose an algorithm that best exploits the computer's architecture. In this paper, an algorithm to perform the solution of a general method of moments problem on the massively parallel Connection Machine is presented.

The CM2 is made up of 65,536 processors. Each processor has 64 k-bits of its own local memory and can access data on other processors through a router network which has a hypercube topology. Communication of data over long distances is expensive and should be minimized whenever possible. Furthermore, the CM2 is classified as a Single Instruction Multiple Data (SIMD) multiprocessor computer. This refers to the fact that all 65,536 processors perform the same task concurrently at each time step, while operating on their own local data. In the CM2's SIMD environment, the instruction set is broadcasted in a bit serial manner to all processors and the individual processors may be either active, or rendered inactive for each instruction. Choosing an algorithm that maximizes the ratio of active processors to inactive processors is said to be load balanced.

For the purposes of this paper, the moment method problem is separated into two subtasks: 1) The matrix fill and 2) the matrix solution. The matrix fill procedure of the method of moments problem, which consists of the numerical computation of the matrix elements, is a highly parallel process since there is no inherent interaction required between different parts of the matrix and the computation of each matrix element is an independent process. Therefore, this algorithm can be efficiently mapped onto the Connection Machine. The matrix is then factorized using an LU decomposition with partial pivoting. This factorization algorithm is mapped onto the CM2 in a very efficient manner by minimizing interprocessor communication. This is achieved by storing the full matrix by contiguous blocks on each processor of the CM2. Furthermore, the load-balancing of the algorithm is maintained by implementing an interactive remapping scheme, thus reducing the ratio of inactive to active processors throughout the computation.

## Tuesday PM

URSI-B Session 40

**Method of Moments II**

*Chairs*: A. W. Glisson, U. of Mississippi; D. A. McNamara, U. of Pretoria

*Room*: Cedar *Time*: 1:15–4:20

# MATRIX FORMULATION OF VECTOR OPERATIONS IN ELECTROMAGNETICS ANALYSIS

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The manipulation of vector quatities is necessary procedure in electromagnetic fields and other areas. For most analysis problems, it is generally more efficient to work with matrix operations than with vector operations. In a vector operation, both components and basis of a vector are inseparatable and must be manipulated together, whereas in a matrix operation, components and basis can be dealt with separately and sometimes only vector components are involved. Consequently, most vector operations can be treated more efficiently by simply converting them into matrix operations. It is exceptionally useful for a consecutive vector operation with mixed coordinate basis. Only four basic conversions are required to relate vector to matrix expressions:

(a) a scalar as a 1 x 1 or 3 x 3 diagonal matrix,
(b) a vector or gradient operator as a column matrix,
(c) a dot-product or divergent operator as a row matrix,
(d) a cross-product or curl operator as a square matrix.

Employing this formulation, solutions of Maxwell equations

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \qquad \nabla \times \vec{H} = j\omega\epsilon\vec{E} + \vec{J}$$

with given current distribution $\vec{J}$ can readily be determined exactly without any vector differential operations,

$$\begin{cases} \vec{E}(\vec{r}) = -jk\eta \displaystyle\int_V \frac{e^{-jkR}}{4\pi R} \left\{ \left(1 + \frac{1}{jkR} + \frac{1}{(jkR)^2}\right)(1 - \hat{R}\hat{R}\cdot) + \left(\frac{-2}{jkR} + \frac{-2}{(jkR)^2}\right)\hat{R}\hat{R}\cdot \right\} \vec{J}(\vec{r}\,')\, dv' \\ \vec{H}(\vec{r}) = -jk \displaystyle\int_V \frac{e^{-jkR}}{4\pi R} \left\{ \left(1 + \frac{1}{jkR}\right) \hat{R}\times \right\} \vec{J}(\vec{r}\,')\, dv' \end{cases}$$

where $R = |\vec{r} - \vec{r}\,'|$, $\hat{R} = (\vec{r} - \vec{r}\,')/R$, and $\eta = \sqrt{\mu/\epsilon}$.

It is especially useful in numerical applications, such that the source and field can be expressed in any desired coordinate systems.

Other applications, such as multi-reflector antennas, near field measurement analysis, also will be discussed.

# BORDERED TOEPLITZ MATRICES IN MOMENT METHOD PROBLEMS

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Bordered Toeplitz matrices (Toeplitz matrices bordered by k rows and columns which are non-Toeplitz) occur in a number of electromagnetic problems. The bordered matrix can arise because of certain physical additions to an otherwise Toeplitz problem. Examples are a long top-hat loaded dipole or a long array of dipoles with dummy loads near the ends of the array. The bordered Toeplitz matrix can also arise because of special expansion/weighting functions in one or more regions. Examples are a long wire with special expansion functions at the ends, a wire strip/aperture with special expansion functions at edge, etc.

Codes have been developed for rapid solution of bordered matrix problems. The matrix equation can be solved directly and the matrix inverse can be obtained as well. The number of multiplicative operations is of the order of $(k + 1)n^2$ where k is the number of non-Toeplitz rows/columns and where the Toeplitz Matrix is nxn.

# NUMERICAL CONSIDERATIONS IN INVERTING CERTAIN TOEPLITZ MATRICES

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Many electromagnetic problems are solved numerically by inverting a finite, Toeplitz matrix. Often, this Toeplitz matrix results from the discretization and truncation of an infinite convolution integral involving a known Green's function. A common example is the solution of a problem in a finite domain requiring the inversion of the free-space Green's function. This paper examines how the added properties and information listed below, present in such cases, can be used to improve the inversion of such Toeplitz matrices and the solution of such problems.

First, such matrices are Toeplitz or block-Toeplitz. One efficient method of inverting a Toeplitz matrix involves replacing the Toeplitz matrix by a related circulant matrix. This circulant matrix can be efficiently and accurately inverted using techniques based on the FFT. Previously published Toeplitz inversion methods then require substantial, additional computational effort to extract the inverse of the Toeplitz matrix from the inverse of the circulant matrix. It is shown that this additional computational effort can be almost eliminated by a particular choice of the related circulant matrix. Second, such matrices have values which diminish rapidly away from the diagonal. This often means the condition number of the matrix is large, making inversion by many methods ill-conditioned. Third, although the Green's function in the problem being solved is usually of infinite domain and known everywhere analytically, the desired solution, and its discrete formulation, are usually of finite domain. Truncating the matrices to finite size can introduce substantial errors in the solution. It is shown that these last two properties can be combined with this circulant-based inversion method to yield a method of solving such problems which minimizes the resulting errors.

# ELECTROMAGNETIC SCATTERING BY A GENERAL ANISOTROPIC BODY OF REVOLUTION

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Electromagnetic (EM) scattering by a general anisotropic body of revolution is treated in this paper. The scatterers of primary interests are bodies of revolution (BORs) consisting of anisotropic cladding layers, which are covered on both sides by an anisotropic impedance sheet. The bulk anisotropic materials, when referenced to a set of local orthogonal coordinate systems, are both electrically and magnetically biaxial.

The problem is formulated as a set of coupled integral equations with induced electric and magnetic currents as unknowns. Method of moments, Galerkin's method with pulse basis functions, and extended operators, are utilized to transfer the coupled integral equations into a set of linear equations for the unknown secondary sources. The secondary sources are solved for via matrix inversion and then the far-field data are calculated for the 2D problem.

Curves showing the bistatic and monostatic scattering cross-sections, for a variety of composite anisotropic BORs, are presented. For some composite anisotropic spherical structures, the results obtained from our numerical code are compared with those of an exact series solutions. Our numerical results are found to be quite accurate and convergent. Some numerical aspects of the scattering problem such as the optimum mathematical cell size and shape, matrix size, and criteria for converged solutions will also be discussed.

# AN EFFICIENT MOMENT METHOD ANALYSIS OF FINITE PHASED ARRAYS OF STRIP DIPOLES IN A SUBSTRATE /SUPERSTRATE CONFIGURATION USING AN ASYMPTOTIC CLOSED FORM APPROXIMATION FOR THE PLANAR DOUBLE LAYERED MICROSTRIP GREEN'S FUNCTION

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An efficient analysis of a finite phased array of center-fed strip dipoles in a substrate/superstrate enviroment which employs the newly developed closed form asymptotic representation for the planar double layered microstrip Green's function is presented. Such an analysis is of importance to the proper design of multilayered monolithic phased arrays which are gaining popularity for the application in the milimeter wave regime.

The full wave array analysis via the Moment Method (MM) requires one to calculate the mutual coupling between all possible pair of the elements in the array (some of these are identical via symmetry considerations). The exact Plane Wave Spectral (PWS) integral representation for the double layered microstrip surface Green's function can be utilized for such calculations. However, these calculations require very long computational times. In order to drastically reduce the computational times, the aformentioned asymptotic closed form approximation for the planar double layered microstrip Green's function is utilized. This closed form asymptotic approximation remains accurate even for very small (e.g., a few tenths of the free space wavelength) lateral separations between the source and field points. This representation is particularly very efficient tool for the design optimization procedure where the MM matrix element calculations must be performed for each set of array parameters; e.g., various substrate/superstrate thicknesses and dielectric constants, with different element sizes and spacings.

The various quantiteis of interest, such as the active impedance and reflection coefficient versus scan angles and substrate/superstrate parameters have been found using the present approach for various size arrays. The numerical efficiency of this newly developed approach will be described.

# Computation of Radar Cross-Section of A Circular Cavity using Method of Moments with Hyperboloidal Wave Functions

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A rigorous solution is obtained for the diffraction of a scalar plane wave by a circular cavity that is flush mounted on a plane conducting wall. The wave functions are subjected to the boundary condition of vanishing normal derivative on the wall and also on the inner surface of the cavity. At the opening of the cavity, an externally incident wave will excite wave guide modes which propagate into the cavity, and will partly be scattered out into free space. The scattered waves will be represented in terms of hyperboloidal wave functions. These functions are defined as a class of eigensolutions of the wave equation for oblate spheroidal coordinates. The hyperboloidal wave functions are distinct from, and superior to the conventional oblate spheroidal wave functions for problems involving half space, as in the present study. A matrix equation is formulated from the continuity condition of the fields at the cavity opening. The numerical results will include rigorously calculated radar cross section for various angles and frequencies of the incident plane waves.

# ELECTROMAGNETIC TRANSMISSION THROUGH A SMALL RADOME OF ARBITRARY SHAPE

Umit PEKEL and Ercument ARVAS

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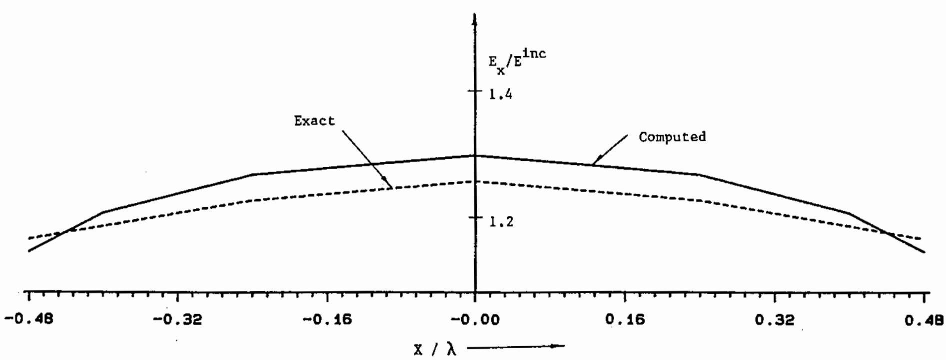
A simple moment solution is given for the electromagnetic field transmitted through a radome of arbitrary shape. The surface equivalence principle is used to replace the inner and the outer surfaces of the radome by equivalent surface electric and magnetic currents radiating in unbounded media. The application of the boundary conditions on the tangential components of the total electric and magnetic field yields a set of coupled integral equations for the surface currents. The combined field approach is used. The surfaces are approximated by triangular pathces and a Galerkin's approach is used. The excitation is taken to be a plane wave (the receive mode) or a dipole inside the radome (the transmit mode). The Von Karman shape radome and the spherical radome are analyzed. The computed results for a spherical radome are in good agreement with the exact data. The figure below compares the magnitudes of the computed and the exact field inside a spherical radome of outside diameter $1.2\lambda_o$, inner diameter $1.0\lambda_o$, and $\epsilon_r = 2.0$. The incident field is an x-polarized, z-travelling plane wave. The radome is centered at the origin, and the field is computed along the x-axis.



# SCATTERING BY AN ARBITRARY CROSS SECTION CHIRAL CYLINDER

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This paper will describe an integral equation and method of moments (MM) solution to the problem of plane wave scattering by a chiral cylinder of arbitrary cross section shape. The constitutive relations of a chiral medium are of the form

$$\mathbf{D} = \epsilon\mathbf{E} + j\xi\mathbf{B} \quad \text{and} \quad \mathbf{H} = \frac{\mathbf{B}}{\mu} + j\xi\mathbf{E}, \tag{1}$$

where $\xi$ is chiral admittance of the medium. If $\xi = 0$, then it is a simple achiral medium.

The solution is begun by developing a chiral medium volume equivalence theorem. This chiral volume equivalence theorem is then used to replace the chiral cylinder by free space and by equivalent electric and magnetic volume polarization currents, $(\mathbf{J}, \mathbf{M})$. A set of two vector coupled integral equations for $(\mathbf{J}, \mathbf{M})$ is obtained by enforcing the chiral volume equivalence theorem in the cylinder. Since the TE and TM polarizations are coupled in a chiral medium, the two coupled vector equations are equivalent to six coupled scalar equations for $(J_x, J_y, J_z)$ and $(M_x, M_y, M_z)$. These six coupled scalar integral equations are then solved by a pulse basis and point matching method of moments solution. Numerical results will be presented, and compared to exact results when available.

## Tuesday PM

URSI-A Session 44

### Measurements II

*Chairs*: M. A. Morgan, Naval Postgraduate School; V. V. Liepa, Univ. of Michigan
*Room*: San Carlos *Time*: 1:15–3:40

## E & H FIELD SENSORS FOR MEASUREMENTS OF TRANSIENTS

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Measurements of transient and pulsed electromagnetic fields are of importance in evaluation of electromagnetic interference and compatibility, and in characterization of these fields in investigations of biological effects of electromagnetic fields. In the latter application, it has only recently been suggested that pulsed or transient features of the electromagnetic exposure field may play an important role in eliciting biological responses. The main challenge presented by these measurements is due to a very wide frequency range of operation required and the requirement to measure both the magnitude and phase of the field. Other desirable characteristics of the sensors are: a wide dynamic range, minimal perturbation of the measured field, isotropic or other well defined directional response, clearly defined spatial resolution, and minimal response to the E-field for H field sensors.

From the two types of possible sensor response, we have opted for the response proportional to the field rather than to the derivative of the field for both E- and H-field sensors. The E-field sensors utilize a spherical antenna (C.E. Baum, in Fast Electrical and Optical Measurements, Vol.1, p.73, 1986 Martinus Nijhoff Publ.). Three sizes of sensors have been selected with upper frequencies of 1500, 850 and 500 MHz, respectively. Passive and active integrators are employed (located in the sphere). Four microstrip lines (200 Ω) in parallel connect the sphere to a 50 Ω balun and a digitizing oscillo scope (Tektronix 7912HB).

The design of magnetic field sensors originally suggested to the authors by Dr. A. Ondrejka from NBS, Boulder, Co. is based on a rigorous analysis of a loop response to an incident electromagnetic field as a function of the loop electrical size and loading impedance (K. Esselle and S.S. Stuchly, 1989 IEEE AP-S Intern. Symp.). The analysis has shown that the highest sensitivity can be obtained for a very small loading resistance. A very small resistance also ensures the widest band for a given loop size. The performance of the system consisting of a small loop, a current transformer and an amplifier has been modelled using a computer simulation program SPICE. Toroidal ferrite cores having high permeability are used as current transformers, and the amplifier comprises a current follower as the first stage, to ensure a low load impedance of the loop and a proper ratio of the circuit resistance to inductance for a wide frequency response.

The sensors are calibrated in a TEM cell in both the frequency and time domains using continuous or pulsed E and H fields.

# RADIOFREQUENCY TIME-DOMAIN HIGH POWER PULSED AUTOMATIC NETWORK ANALYZER

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A time-domain network analyzer has been developed for testing systems subjected to high-power single-event pulsed RF fields. The network analyzer, designed to operate in the frequency range 1 - 100 MHz, consists of a high-power pulsed RF source, a test system, a directional coupler, a high-speed digitizing oscilloscope (HP54200A) and a microcomputer (Compaq Despro 386/20). Parts of the incident and reflected (or transmitted) waves on the test system are coupled into the digitizing oscilloscope where measurements in the time domain for both signals (incident-reflected or incident-transmitted) are performed simultaneously. The outputs are fed to the microcomputer for signal processing.

The software for signal processing was written in C language to perform data acquisition over the IEEE 488 interface bus, complex FFT, graphics display of both time and frequency domain data, and computation of results (reflection or transmission coefficient) and storing necessary data in a disk file.

This automatic network analyzer which measures transmission or reflection coefficient may find wide range applications in the test of systems exposed to ESD, EMP, lightning as well as other single event RF phenomena. Experimental results are presented to demonstrate the capabilities of the network analyzer.

# DETERMINATION OF THE EFFECTS OF COSITE INTERFERENCE AND NOISE ON SYSTEM PERFORMANCE

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Sponsored by NOSC and The Department of the Army

COEDS is a communications engineers workstation developed at the University of Kansas for analysis of colocated communications equipment. The principle task of the COEDS system is to determine the degree of interference at a receiver caused by transmitters at the same site. This data is then used to rate the performance of the receiver and to predict the effects of interference levels on transmission.

Cosite interference results from several situations. The sources analyzed by COEDS are simple broadband noise, spurious transmitter emissions and spurious receiver responses, transmitter and receiver intermodulation, and coupler harmonics. Because the analysis deals with $O(n^2)$ bidirectional transmission paths, and the effects of spurious emissions/response, intermodulation and harmonics are nonlinear, the task of predictive analysis lends itself to a computer based solution.

COEDS predicts interference at a receiver in terms of pseudo-noise, or on tune noise power ($P_{ino}$). Given this on tune power and the ambient noise level ($N_a$), the Interference Margin or Excess Interference Level (EIL) is determined by the relation EIL=$N_a - P_{ino}$. This EIL value is the principle output of the COEDS system. The communications system under consideration will always be noise limited, thus by reducing EIL to a value less than or equal to 0, it is assured that the system is limited by ambient noise and not cosite interference.

A secondary output of the COEDS system is the System and Upper Performance scores. These scores are determined by using the total noise present and the desired signal level to determine S/N. The S/N is then related to standard degradation curves to determine the probability of acceptable reception given the present noise conditions.

In COEDS, a Test Plan is used to take the EIL value predicted for an interference limited system and predict the effects on transmission distance using a link performance tool. The desired signal power for a receiver is increased by the amount of interference noise present to predict the effects of that noise on link performance.

# ELF/VLF RADIO NOISE STATISTICS AT HIGH NORTHERN AND SOUTHERN LATITUDES

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We report some of the first results of the Stanford University global survey of ELF/VLF radio noise. Because noise measurements have been particularly lacking at high latitudes, we have chosen to illustrate the form of our noise data by presenting the results of measurements at the three highest latitude stations: Thule (TH; 76.5° N, 68.8° W) and Søndrestrømfjord (SS; 67.0° N, 50.1° W) in Greenland, and Arrival Heights (AH; 77.8° S, 166.7° E) in the Antarctic. The magnitudes of the geomagnetic latitudes for these three stations range from 87° (TH) down to 77° (SS), thus ensuring that the data from the stations includes representative samples of ELF/VLF radio noise of magnetospheric origin (e.g., chorus and hiss), in addition to the lightning-generated noises (sferics, tweeks, and whistlers) that typically dominate at lower latitudes.

The radio noise statistics computed continuously at each of the three stations consist of the root-mean-square (rms), average, maximum, and minimum amplitudes in 16 narrow frequency bands (5% bandwidth) distributed through the range 10 Hz to 32 kHz. They are computed at the end of every minute from 600 amplitude measurements made at the rate of 10 per second on the envelope of the noise signal emerging from each narrow-band filter. Later processing of these data can, with little additional computation, give the $V_d$ and $F_a$ statistics, and amplitude probability distributions are readily derived from the sampled data.

Comparison of the noise statistics between the three locations reveals many similarities but also a number of major differences. Many of the differences consist simply of changes in the average levels of the statistical quantities. However, some of the changes in the statistics are caused by differences in the nature of the noise, and in particular by the occurrence of magnetospheric noise. This noise consists predominantly of polar chorus, with some hiss, and is concentrated in the range 500 Hz – 2 kHz. It produces a characteristic 'signature' in the noise statistics, which makes its presence easy to identify. Wideband auroral hiss should also be easy to identify in the statistics, but no large events have been identified so far in our data.

# A TEST FIXTURE FOR DETERMINING THE PRESSURE-PROOF INTEGRITY OF SUBMARINE BUOYANT CABLE ANTENNAS

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## Abstract

A simple low-frequency technique for determining the presence of water or moisture in damaged submarine buoyant cable antennas has been developed. It is used primarily as a diagnostic tool for rejecting cables containing traces of sea water.

The method makes use of a test fixture in the form of a curved-plate capacitor. The plate configuration of the capacitor was designed in such a manner that its sensitivity to low levels of moisture (< 0.1 ounce per foot) is accompanied by large percentage increases in capacitance from the nominal dry value. Typical increases in capacitance for such levels have been observed in the range of 17% to 25%, compared with fully saturated cables that exhibit a maximum change of 71%. Theoretical expressions for cable specific gravity and volume of water as functions of percentage increase in capacitance were derived and are shown to compare well with experimental data.

# PERFORMANCE MEASUREMENTS OF AN EXPERIMENTAL THROUGH-THE-EARTH DIGITAL COMMUNICATION SYSTEM

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This paper describes an experimental communication system used to obtain field measurements on the performance of digital receivers processing signals propagated "through-the-earth".

In a companion paper, the authors describe the system, its components, and the performance results associated with characterization of the "through-the-earth" communication channel. In this paper, the digital signals, receivers implemented, and their performance is presented based on measurements taken in the field.

The experimental effort dealt mainly with the generation and propagation of simulated random binary data through approximately 1000 ft. of overburden at two separate sites. The simulated data was transmitted both at baseband and via phase modulation of a carrier. Baseband transmission using NRZ and Biphase signals did not yield successful results due to channel noise predominating at low frequencies. Carrier transmission via BPSK and QPSK modulation proved far more successful due to intentional shifting of the significant signal spectral components to regions less dominated by noise. This however, was tempered by the high frequency channel attenuation effects that introduced signal distortion.

Measured results demonstrate the feasibility of transmitting data at significant rates using low frequency carriers. With moderate input power levels, receiver performance in terms of bit error rate (BER) was measured at various frequencies and data rates. While many combinations of data rates, carrier frequencies, and power levels were tested, the most promising results were obtained for BPSK at a carrier frequency of 900 Hz with a data rate of 300 bps measured at a receiver input signal-to-noise ratio of 16.5 dB. Under these conditions, the BER was measured to have an average value of less than 1/100000. At lower data rates, (which result in greater average bit energy while maintaining constant transmitted power levels), improved BER performance was evident.

The experimental results confirm the feasibilty of transmitting and receiving digital data signals propagated through-the-earth using power levels and data rates that can be achieved in practice. The measured BER system performance was found to be well within the bounds associated with reliable communication links, albeit without performance enhancements such as channel equalization, forward error correction, or adaptive noise suppression. It appears therefore that the described system may be used as design basis of digital communication systems used in establishing contact with miners or personnel located in underground facilities.

## Tuesday PM

Joint AP-S, URSI-B Session 46

**Frequency Selective Surfaces**

*Chairs*: T. Cwik, Jet Propulsion Laboratory; A. Tsao, Ford Aerospace

*Room*: San Martin    *Time*: 1:15–5:00

# AN ASYMPTOTIC APPROACH TO ANALYZING FINITE FREQUENCY-SELECTIVE SURFACES

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Frequency-selective surfaces (FSS) are employed in radomes, dichroic reflector antenna systems, and various other applications. Analysis of planar surfaces has been limited to either the infinite periodic case where Floquet's theorem applies or to relatively small surfaces (consisting of tens of elements) where the moment method and related techniques can be applied. A new approach, requiring only modest computer resources, is proposed for obtaining approximate solutions for the scattered field from finite FSS of moderate to large size.

In the far-field region, the scattering from an infinite periodic surface is identical to that of a "resistive sheet," (i.e., a sheet which supports a current proportional to the total tangential electric field) as long as no grating lobes are present. When the surface is finite, diffraction occurs at the edges. It has been found that in many cases the resistive-sheet far-field edge effect is similar to that of the truncated periodic surface. In these cases the diffraction coefficients for resistive half-planes (J. L. Volakis, IEEE Trans. Antennas Propagat., vol. AP-34, pp. 172-180, Feb. 1986) can be applied to obtain the approximate far field associated with a finite FSS. The value of the parameter which characterizes the resistive sheet (the reactance) is determined by matching reflection coefficients for the infinite case. Because the reactance of the FSS is incident-angle dependent, the infinite FSS calculation is repeated at each incidence angle of interest.

Results will be presented for two-dimensional strip gratings and the region of validity of this technique will be discussed.

## Tuesday PM

URSI-F Session 47

### Propagation and Scattering in Random Media

*Chairs*: A. Ishimaru, U. of Washington; W. C. Chew, U. of Illinois at Urbana

*Room*: San Simeon *Time*: 1:15–4:00

# REMOTE SENSING OF LAYERED RANDOM MEDIA USING OPTIMUM POLARIZATION

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One of the chief objectives of remote sensing is target identification. Although the frequency response and the incident angle response are widely utilized for this purpose, the area of polarization has not been fully exploited; it has been primarily restricted to horizontal and vertical polarization cases only. We propose to explore the choice of other polarizations suitable for the target medium under consideration.

Since the electromagnetic wave scattering from a layered random medium results in partially polarized waves, the Stokes vector formalism is appropriate. Following any of the theoretical procedures suitable for the remote sensing of a layered random medium we calculate the required Mueller matrix.

We then calculate the power received by a receiving antenna with arbitrary polarization. Our intention is to extremize this power keeping the Stokes vectors of the transmitting and receiving antennas as varying parameters. As in any extremizing problem we can either maximize or minimize the received power. The Stokes vector corresponding to the maximum power is useful for target identification while the Stokes vector corresponding to the minimum power is useful for clutter rejection. Often, it is convenient to use the same antenna and polarization for transmission and reception. Besides, this special case greatly simplifies our extremizing procedure. Even here, the extremizing procedure can become intractable if the target is complicated. In such cases only numerical solution is possible. However, several practical cases of interest have fairly easy solutions; these are presented as illustrative examples.

To conclude, we note that along with other parameters, polarization provides a power tool for target classification and clutter rejection in the remote sensing of layered random media.

# AN $N^2$ ALGORITHM FOR THE MULTIPLE SCATTERING SOLUTION OF $N$ SPHERES

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ABSTRACT

The multiple scattering solution of a random assortment of spheres has applications in finding the effective permittivity and the effective propagation constant of of a random medium. However, due to the complexity of the problem, most methods used in the past have relied on statistical averaging approach. A deterministic approach has only been limited to two or three spheres. In this paper, a recursive algorithm to calculate the exact solution of an $N$ random assortment of spheres is described. In this algorithm, the scattering from a single sphere is expressed in a 1-sphere $T$-matrix. Then, the scattering from two spheres is expressed in terms of 2-sphere $T$-matrices which are related to the 1-sphere $T$-matrix. A recursive algorithm to deduce the $(n+1)$-sphere $T$-matrix from the $n$-sphere $T$-matrix is derived. With this recursive algorithm, the multiple scattering from a random assortment of $N$ spheres can be obtained. This results in an $N^2$ algorithm rather than the normal $N^3$ algorithm. Hence, the simulation for nine spheres can be performed on a SUN workstation. As an example, the algorithm is used to calculate the effective permittivity of a random assortment of $N$ dielectric spheres. The effective permittivity deviates from the Maxwell-Garnett result for high contrast and high packing fraction. With high packing fraction, dielectric enhancement at low frequency is possible in such a model.

# PROPAGATION AND DEPOLARIZATION OF AN ARBITRARILY POLARIZED OPTICAL WAVE OBLIQUELY INCIDENT ON A SLAB OF RANDOM MEDIUM

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## ABSTRACT

Though a few studies have been reported on radiative transfer theories with Stokes vectors for polarized electromagnetic waves, all of these studies have restricted the incident wave to normal incidence, linear polarization or circular polarization. These assumptions simplify the problem mathematically because there is no coupling among Fourier components due to the existence of the even and odd properties of the incident specific intensity matrix. In recent years, however, there has been an increased interest in the propagation and scattering of an arbitrarily polarized incident wave. The problem of how a slab of medium containing randomly distributed spherical particles affects the propagation and polarization of an arbitrarily polarized obliquely incident optical wave is investigated in this paper.

We present the general formulation for an arbitrarily polarized plane wave obliquely incident on a slab of medium containing randomly distributed particles using vector radiative transfer theory. To solve the integral-differential radiative transfer equation with Stokes vectors and its boundary conditions, the equation is first changed to a differential equation by the discrete-ordinate method and then decomposed into Fourier components. Unlike the studies before, the equations for each component are coupled now because the incident specific intensity matrix obtained by the full scattering matrix (Mueller matrix) is no longer even or odd. This gives rise to a large system of linear equations. Fortunately, with some manipulation we can separate the coupled equations into two independent groups. An eigenvalue-eigenvector technique is used to solve the differential equation with boundary conditions. For sparse random medium, we can obtain analytic solution of the radiative transfer equation with the first-order scattering approximation.

An experiment which measures complete Stokes vectors versus the azimuth angle at $0.6328\mu$ is made for latex particles. All of the control and data aquisition are carried out on an IBM-PC. The exact solution of the vector radiative transfer theory obtained numerically on a supercomputer Cray X-MP is compared with the analytic first-order scattering approximate solution and the experimental results. The comparison shows that the results are consistent with each other.

# COPOLARIZED AND DEPOLARIZED BACKSCATTERING ENHANCEMENT OF RANDOM DISCRETE SCATTERERS OF LARGE SIZE BASED ON SECOND ORDER LADDER AND CYCLICAL THEORY

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## Abstract

Previous studies have shown an enhancement of the backscattered intensity from random media containing dense distributions of scatterers with sizes ranging from small to moderate. Recently, however, there is experimental evidence of backscattering enhancement from sparse distributions of scatterers of very large size. It was found that the depolarized return shows an amount of enhancement that is unobscured by single Mie scattering. To account for this observation a second order multiple scattering theory has been derived by summing the first and second order ladder terms and the second order cyclical term of the Bethe-Salpeter equation. The cyclical term must be included since this contributes directly to the backscattering enhancement not accounted for in the ladder approximation which is consistent with the transport theory. Mie scattering is used to compute the copolarized and depolarized enhancement for a sparse distribution of scatterers. These results are compared with experimental data and also with calculations based on the second order transport theory. The copolarized enhancement for both cases agree favorably, however the transport theory does not account for the depolarized enhancement in this case. Good comparison with experimental data is obtained for the depolarized return from a slab medium containing a sparse distribution of dielectric spheres with average $ka$ of 298 and optical thickness of 2.

# EFFECTIVE PROPAGATION CONSTANTS AND ATTENUATION RATES FOR DENSE MEDIA WITH DIELECTRIC COATED PARTICLES OF MULTIPLE SIZES

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In this paper we study the effective propagation constants and the attenuation rates in a dense medium consisting of coated dielectric particles having multiple sizes. The coated dielectric particle refers to a particle consisting of a spherical core surrounded by a concentric shell with different permittivities. This has applications to wave propagating and scattering in geophysical terrain and composite materials. The study of scatterers of multiple sizes is important because the particles in natural geophysical terrain are not of identical sizes, they usually follow a size distribution.

In a dense medium, particles do not scatter independently and the effects of correlated scattering have to be included. The correlated scattering can be taken into account by using the quasicrystalline approximation (QCA) or the quasicrystalline approximation with coherent potential (QCA–CP). The pair functions between particles of different sizes are computed by using the Percus–Yevick (PY) approximation. The Lippmann–Schwinger equations for small coated particles under QCA and QCA–CP are solved analytically.

For the case of small coated particles, closed form analytic expressions are obtained for the complex effective propagation constants under both QCA and QCA–CP. For moderate size coated particles, a numerical scheme is used to solve the complex effective propagation constant for QCA. Numerical results are illustrated with ice particles coated with water layer having modified gamma size distribution. This can be used to model wet snow or melting snow.

# TE SURFACE-WAVE SCATTERING BY ARRAYS OF THIN-WIRE CONDUCTORS

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The 2-D scattering of TE surface waves by an array of thin-wire conductors is studied analytically and validated experimentally. A symmetric planar dielectric waveguide is formed by the usual dual-layered substrate/film/cover environment, typical of some integrated circuits for millimeter and optical wavelengths, with identical substrate and cover media. The structure supports TE surface waves when the film-layer guiding region has positive index contrast relative to the surround media. An electric Green's function has been constructed for the field maintained by currents which provide TE excitation. This Green's function is composed of both discrete surface-wave and continuous-spectrum radiative components.

If the x-axis is normal to the layer interfaces and the waveguiding z-axis is parallel to them, then a y-invariant TE electric field having only a y-component is excited by a similar component of current. The array of thin-wire scatterers is placed parallel to the y-axis so induced currents are all y-directed. The wires have infinite extent along y; if they are thin in cross section, then it can be assumed that the field does not change significantly about the wire circumference. A simple equation for the induced current $I_0$ on any single such wire at $(x',z')$, obtained by satisfying the boundary condition at any surface point $(x_s,z_s)$, is

$$E_y(x_s,z_s) = E_y^i(x_s,z_s) + I_0 G_{yy}(x_s,z_s|x',z') = 0$$

where $E_y^i$ is the incident surface-wave field impinging upon the conductor. If there is an array of such wires, then a matrix equation for the induced currents, composed of both "self" (on the matrix diagonal) and "coupling" terms, arises by superposition as

$$\left[ G_{yy}^{mn} \right] \left[ I_n \right] = - \left[ E_{ym}^i \right] .$$

An experimental setup for measurements to validate this theory at millimeter wavelengths is implemented by placing the dielectric slab between two parallel conducting plates, and then placing short segments of the thin array wires between and normal to those plates. This results in the infinite imaging of both the slab and wires. Because the Green's function can be evaluated numerically, calculated reflection and transmission coefficients can be compared with those measured experimentally. It is expected that array parameters will have a significant effect on these coefficients.

# A UNIFIED RAIN ATTENUATION PREDICTION MODEL FOR COMMUNICATIONS LINK FADE PREDICTIONS AND OPTIMAL STOCHASTIC FADE CONTROL DESIGN USING LOCATION DEPENDENT RAIN STATISTICS

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A unified static and dynamic rain attenuation model is presented that provides fade predictions for satellite or terrestrial communications links and establishes a basis for the design of optimal stochastic control algorithms to mitigate the deleterious effects of such fading. As an extension of previously reported work (R. M. Manning, 1987 IEEE AP-S/URSI Symposium Digest, Antennas and Propagation, Vol. 1, pp.16-19), this model is a synthesis and modification of two existing models and represents an attempt to obtain a complete and unified description of the rain attenuation process while, at the same time, providing an analytical formalism for the design of optimal rain fade control algorithms. The mechanisms that drive the rainrate process are left to that which is convolved and represented in the long-term rain statistics compiled for individual locations by the U.S. Weather Service. This approach gives rise to a data base from which the model obtains location dependent rain statistics. The specification of the geographical position of the location in the continental U.S. with $0.5^{\circ}$ resolution as well as its average annual rainfall completely characterize the location, in that three parameters are derived from the data base from which, using this model, one can completely assess the effect of rain attenuation on a communications link. Static (i.e., yearly, time independent) attenuation predictions are derived from a log-normal model. Dynamic attenuation characteristics (i.e., those on the order of seconds, minutes, or hours) derive from a two-component Markov model; the attendant transition probability density provides a complete temporal assessment of fading on a link and, by design, reduces to that of the static model in the appropriate limit. The two-component Markov model is also simplified to a one-component model for calculational purposes. Comparison of the model predictions is made with available experimental observations and agreement is found to be quite good. Making use of the fact that the structure of the Markov model is isomorphic to the state variable approach of stochastic control theory, it is shown how such a modelling formalism provides a basis for the design of optimal, non-linear, Markov rain fade filtering algorithms for control purposes.

A well documented MS-BASIC software package that implements the application of this model for any satellite communications link, complete with the associated rain statistics data base for the continental U.S., will be available and distributed. It can also be obtained from COSMIC, NASA Software for Industry, The University of Georgia, Athens, GA 30602.

## Wednesday All Day

Joint AP-S, URSI-B Invited Poster Session 48

### Numerical Methods

*Chairs*: A. C. Cangellaris, U. of Arizona at Tucson; A. G. Tijhuis, Delft U. of Tech.

*Room*: Donner Pass *Posters Displayed*: 9:30–4:00

*Authors Available*: 2:40–4:00

# GENERALIZED PENCIL-OF-FUNCTION METHOD FOR EXTRACTING POLES OF AN EM SYSTEM FROM ITS TRANSIENT RESPONSE

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## ABSTRACT

A generalized pencil-of-function (GPOF) method for extracting the poles of an EM system from its transient response is developed. The GPOF method needs the solution of a generalized eigenvalue problem to find the poles. This is in contrast to the conventional Prony and Pencil-of-Function methods which yield the solution in two steps, namely, the solution of an ill-conditioned matrix equation and finding the roots of a polynomial. Subspace decomposition is also used to optimize the performance of the GPOF method. The GPOF method has advantages over the Prony method in both computation and noise sensitivity, and approaches the Cramer-Rao bound when SNR is above threshold. An application of the GPOF method to a thin-wire target is also presented.

# A TIME-DEPENDENT METHOD FOR THE NUMERICAL SOLUTION OF WAVE EQUATIONS IN ELECTROMAGNETIC SCATTERING PROBLEMS

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The wave equation that arises from Maxwell's equations can be solved in either frequency-domain or time-domain. The assumption of harmonic time-dependence for the field variables in frequency-domain reduces the wave equation to the Helmholtz equation. Coupled with the media interface condition and the far field radiation condition, the Helmholtz equation defines an electromagnetic scattering process as a boundary value problem. The elliptic nature of this boundary value problem requires simultaneous solution of all unknowns in the exterior of the scatterer. The matrix equation resulting from finite-difference discretization can be solved by direct matrix inversion or by iterative schemes such as the conjugate gradient method.

This paper describes an alternative to solving the frequency-domain Helmholtz equation. It involves reversion of the Helmholtz equation to the wave equation and introduction of time-dependence into the generalized scattering amplitude (AIAA Journal 25, 560-566 and AIAA Paper 88-0180) and Debye amplitude functions (J. Appl. Physics 64, 3785-3791). The scattering problem thus reverts to an initial value problem. The hyperbolic nature of the wave equation allows a time-dependent method to be incorporated so that solutions can be obtained by forward marching in steps of time. At large times, after the transients die out, the solution approaches the steady state of frequency-domain. This is similar to solving the time-dependent fluid dynamics equations as a means of obtaining the steady-state solution in steady flow problems.

Explicit finite-difference scheme is applied to convert the transformed wave equation into a finite-difference equation. For the first order wave equation part, Lax-Wendroff scheme popular in CFD is used, while for the second order wave equation part, central differences in both space and time are used. Both schemes are stable if the conventional CFL condition is satisfied. This time-dependent formulation has been applied to scatterings by long cylinders. Time history of solutions and their convergence to the frequency-domain solution will be presented.

# Generalizations of Electromagnetic FDTD Techniques to Non-Orthogonal Mixed-Polygonal Meshes †

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We have developed an approach to the numerical solution of a system of partial differential equations that models a broad class of two- and three- dimensional electromagnetics problems. This approach is based upon Modified Finite Volume (MFV) techniques for solving Maxwell's equations. MFV methods allow the use of arbitrarily connected mixed-polygonal meshes or grids and thus readily permit the modeling of complicated and irregular objects and structures. Moreover, when applied using regular orthogonal grids, the MFV method reduces to be the canonical and long-used staggered grid finite difference method (FDTD) for Maxwell's equations. Thus the MFV method is a direct irregular grid generalization of the well-understood FDTD method. The MFV methods can be nearly as computationally efficient as the FDTD method and yet can be considerably more accurate because stair-stepped approximations to curved or irregular boundaries are easily avoided.

The validity and accuracy of the MFV method will be demonstrated through several numerical examples for two and three dimensional problems. These will include several canonical test problems including propagation of pulses in a rectangular waveguide and scattering of a pulsed incident field from a perfectly conducting sphere. Comparisons with the exact solutions will be provided. It will also be demonstrated with some two-dimensional scattering problems that the use of mixed-polygonal grids (combinations of triangles, rectangles, tetrahedrons, hexahedrons, etc.) can considerably alleviate the mesh generation difficulties which arise when single element type grids are required. The efficacy of the MFV approach in three dimensions for nontrivial situations will be illustrated. These will include the propagation of pulses in twisted and bent waveguides.

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† This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

# OBSERVATIONS ON THE ERRORS IN FINITE ELEMENT COMPUTATIONS FOR THE HELMHOLTZ EQUATION

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*McDonnell Douglas Research Laboratories*
*A. F. Peterson*
*Electromagnetic Communications Laboratory*
*University of Illinois, Urbana, IL*

The finite-element method (FEM) has emerged as a powerful tool for computation of electromagnetic fields in the presence of material inhomogeneity. Recent sucess in augmenting the FEM with approximate radiation boundary conditions (RBCs) has substantially enhanced the present utility and ultimate potential of FEM in electromagnetics. However, there is only limited understanding of the characteristics of the error incumbent with FEM computation of time-harmonic electromagnetic fields. Peterson (1987 IEEE AP-S Symposium, Blacksbug, VA) has presented results indicating comparable accuracies between FEM and method-of-moments calculations on comparable computational meshes for small dielectric objects. Specifically, accuracies in local fields on the order of a few percent were obtained at a nominal mesh density of 100 nodes per square wavelength.

The present paper presents results of a systematic study of error properties of FEM computations on solution domains as large as seventy-five square wavelengths in extent. It is observed from numerical experiments that the node *density* must be increased as the size of the solution domain is increased in order to obtain a predetermined accuracy in the computed fields. The field errors are manifested as standing waves in the computed fields. For separable geometries, the field error can be computed directly. It is found that the errors for scattered fields computed for a given solution domain using simplex FEM with the Bayliss-Turkel RBC follow the mesh dependency trends predicted by Zlamel (*Numer. Math.*, 12, 1968, 394–409) for Neumann and Dirichlet problems. Specifically, the error decreases with the square of the characteristic dimension of triangles in the FEM mesh and increases in proportion to $1/\sin\theta$, where $\theta$ is the smallest angle appearing in the mesh.

# Time Domain Extrapolation to the Far Field Based on FDTD Calculations

by

Kane S. Yee, David Ingham, and Kurt Shlager
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Summary

A scheme to extrapolate FDTD calculated scattered fields to the far zone is developed here. It could replace the usual extrapolation scheme for a single frequency, in that it yields a spectrum response with only one incident pulse. It seems to be more convenient in time domain calculations and is more in agreement with the spirit of FDTD.

Since the FDTD algorithm was published by one of the present authors in 1966, many authors have used it to numerically solve electromagnetic problems. There have been two areas where workers have found applications of this algorithm. In transient electromagnetics, the surface current induced on scatterers are desired; in steady state (one frequency), one is interested in using the induced surface current to calculate the distant scattered field in various directions. Through the extensive work of A. Taflove and others the FDTD has become a powerful tool in frequency domain RCS calculations. Far field calculations for a single frequency have been obtained through an extrapolation formula from data obtained by running the FDTD to a steady state. Since FDTD is a time domain scheme, it seems to be more natural to calculate time domain response for scattered field, and if a frequency response is desired one can carry out a Fourier transform. This approach also tends to be more resistant to some type of computational error such as arithmetic round off error because each frequency bin depends only on its own frequency component of the calculated fields. The purposed of this paper is to develop such an extrapolation scheme in the time domain.

## Wednesday All Day

Joint AP-S, URSI-B Invited Poster Session 49

### Microstrip Antennas

*Chairs*: Y. T. Lo, U. of Illinois at Urbana; P. T. Lam, Deskin Research Group

*Room*: Donner Pass *Posters Displayed*: 9:30–4:00

*Authors Available*: 2:40–4:00

# INPUT IMPEDANCE OF A MICROSTRIP-FED RECTANGULAR PATCH ANTENNA

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Microstrip antenna arrays are commonly fed by a feed network consisting of microstrips of various characteristic impedances. The design theory for this type of antenna array has been known for sometime. However, except perhaps in the case of Gardiol and Mosig (1985), very few works in the literature addresses the issue regarding the accurate numerical modeling for the input impedance of such an antenna structure. Such a computation has been elusive mainly because of the lack of an efficient algorithm to compute accurately the two-dimensional vector current distribution in the vicinity of the step discontinuity between the microstrip feedline and the patch antenna.

In this work, we should summarize a new algorithm based upon the formulation of a spatial domain moment method. The x-directed and y-directed currents, and the charge distribution are separately approximated by unit step functions. Three sets of rectangular cells, spatially shifted from each other, are chosen in a manner so that the current continuity equation can be evoked after the individual contribution from currents and charges are computed. The method offers the advantage that the leading term of the moment integrals can be computed analytically and only the numerical computation of one dimensional Sommerfeld integrals is needed. This is in direct contrast to the two-dimensional infinite integrals in a typical spectral domain method.

The problem of a rectangular patch antenna with a microstrip feedline is solved accurately in this manner. The microstrip in this case is assumed to be finite in length and is dirven by a voltage source at a suitable distance away from the antenna. Using a de-embedding procedure developed earlier for a related problem, we can accurately extract the input admittance of a microstrip-fed antenna which is independent of the specific excitation scheme used in the computational process. Extension from a one-port to a two-port microstrip antenna will be discussed.

*Bradley L. Brim is now with Hewlett Packard in Santa Rosa, CA. 95401.

# END-CORRECTION NETWORK FOR A PROBE FED MICROSTRIP PATCH ANTENNA

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One of the practical excitation schemes for a microstrip patch antenna is to feed it from under the patch with a coaxial probe. The inner conductor of the coax in this case is connected through a via hole to the patch, while the outer conductor is flush-mounted to the groundplane. To ease the computational effort, excitation is typically handled by one of two methods: one is to replace the actual excitation with a vertical current line-source of constant amplitude, and the other is to assume a magnetic current frill at the coaxial aperture. A simple correction factor corresponding to the self-reactance due to a short-circuited transmission-line of length kt, where kt is the electric thickness of the substrate, is usually added to the input impedance calculation in the first case, while no correction is typically introduced in the second case.

In order to examine more closely the nature of these approximations, we formulated in this work the exact integral equation for the aperture field at the coaxial opening for a microstrip of infinite extent, i.e. a parallel plate with the same substrate. We then proceeded to solve for the apparent input admittance via a variational/mode expansion technique. Since coaxial modes are used to represent the aperture field, a one-term approximation with a TEM mode distribution at the aperture corresponds exactly to the magnetic frill method mentioned earlier. Consequently, the inclusion of the higher order modes allows us to examine the correction needed for this method. On the other hand, since the only propagating mode in the parallel plate region is that of a radial transmission line, a one-term approximation for the Green function in that region gives rise to the same result as the constant current method.

An equivalent circuit consisting of the impedance corresponding to a constant current excitation, in series with a lumped inductive element, and in shunt with a lumped capacitive element, is postulated. The dynamic nature of the two lumped elements is then determined by a curve matching the computed results obtained from the integral equation technique. Provided the location of the excitation is not too close to the edges of a microstrip patch, the same end correction network can be used for the patch of finite dimension if one replaces the impedance of the infinite microstrip patch with one calculated for a finite patch and a constant current excitation.

## Wednesday AM

Joint AP-S, URSI Session 50

**Plenary Session**

*Chair*: R. J. King, Lawrence Livermore National Laboratory

*Room*: Thunderbird Ballroom *Time*: 8:30–12:00

| | | |
|---|---|---|
| 8:30 | **Electromagnetic and Electrochemical Response of Geological Conductors**<br>J. R. Wait,* Univ. of Arizona at Tucson | 210 |
| 9:15 | **Superconductive Electronics - Current Status and Promise for the Future**<br>D. T. Hayes,* Rome Air Development Center | 211 |
| 10:00 | **Coffee Break** | |
| 10:30 | **Electromagnetics of Superconductors**<br>K. K. Mei,* G. C. Liang, T. Van Duzer, Univ. of California, Berkeley | 213 |
| 11:15 | **Frontiers in Antenna Applications**<br>D. B. Rutledge,* California Institute of Technology | 214 |

# ELECTROMAGNETIC AND ELECTROCHEMICAL RESPONSE OF GEOLOGICAL CONDUCTORS

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It is now realized that the earth's crustal layers are not simple lossy dielectrics with fixed parameters. In fact the effective permittivities of actual rocks and soils may exhibit values which are 10, 000 times free space at sufficiently low frequencis (e.g. less than 1000 Hz). Such effects, while less dramatic, extend all the way up to microwaves. Such highly dispersive phenomena greatly complicate quantitative analyses for transient electromagnetic propagation within the earth. We are now beginning to understand such phenomena and the purpose of this paper is to review the subject.Various applications occur in mine communications, geophysical exploration, well logging, ground penetrating radar,and ELF/VLF antenna transmitter design... just to name a few.The theoretical background of the subject is now available( J.R.Wait, "Complex resistivity of the earth", Chap.1, Vol.1,Progress in Electromagnetic Research, edited by J.A. Kong, Elsevier, Amsterdam, 1988)

Dr. Dallas T. Hayes
Rome Air Development Center
Hanscom AFB, MA

## SUPERCONDUCTIVE ELECTRONICS
## CURRENT STATUS AND PROMISE FOR THE FUTURE

The impetus for the development of superconductive electronics has come from the astronomy and signal processing communities. Astronomers want the most sensitive receiver technology can provide. To meet this need superconductive mixers have been built whose sensitivity approaches the quantum limit. Although IBM's decision a few years ago to stop their superconductive computer effort was a setback to the community, the Japanese have forged ahead and are showing good progress in developing microprocessors employing niobium superconductive circuits.

Superconductivity offers three advantages to electronic systems. First, employing superconducting materials one can construct very low loss, dispersionless microstrip transmission lines, which show very low crosstalk. For example, attenuation in lead microstrip lines is at least two orders of magnitude less than in copper lines at the same temperature (4K). These lines show no dispersion up to one third to one half of the gap frequency, which for lead is 700 GHz. Second, weak link or Josephson junction structures, which are superconducting regions separated from each other by narrow superconducting bridges or narrow bands of insulating material, are routinely used to construct low noise detectors and signal sources. Mixers possessing gain and whose sensitivity is limited only by quantum effects are possible with this technology. Third, Josephson junctions can be constructed which switch from the superconducting to the normal state with very short switching times, on the order of picoseconds, and dissipating only microwatts power. This switching energy (10exp-18 joules) is several orders of magnitude less than silicon gates and at least two orders less than the best GaAs gates.

This talk will give an overview of the current state-of-the-art of superconductive electronics. As such we will concentrate on circuits employing low-temperature superconducting materials such as lead (critical temperature Tc=7K), and two refractory materials niobium (Tc=9K) and niobium nitride (Tc=16K). Only for these materials has the processing technology reached the stage to build the circuits which approach the full potential of this technology. We will show examples of mixers and amplifiers using this technology. We will describe an effort to integrate these devices together with a multilithic antenna on a square centimeter silicon chip to form an superconductive monolithic integrated 100 GHz heterodyne receiver. It is the goal of this effort, employing antenna technology such as described in the companion talk by Prof. Rutledge, to develop a fully superconductive phased array receiver. The status of further research in Josephson junction technology and phased-locked arrays of these junctions will be presented. The purpose of this effort is to establish the basis for similar developments at frequencies as high as 1 Terahertz (1000 GHz). Finally we will show some examples of superconductive analog and digital signal processing circuits.

Devices based on low-temperature materials will find many uses. But these will always be in situations where one requires high sensitivity and speed and thus accepts the requirement of cooling to temperatures less than 10K or for operation in space where size, weight and power requirements are the crucial factors. The discovery of high Tc superconducting materials has widened the range of applications to NASA and DoD for many reasons. First, the cooling requirements are reduced appreciably. Whereas to remove a watt at liquid helium temperatures requires 1000 watts of cooling power, only 42 watts is required at liquid nitrogen temperatures. Closed cycle cryocoolers already exist for cooling to 80K. In open cooling systems not only is liquid nitrogen much cheaper than helium, it will also last much longer. Second, while we are developing devices with low-temperature superconductors which will operate at 1THz and have switching speeds of the order of 1 picosecond, with materials possessing ten times higher critical temperature, we can contemplate devices operating close to 10 THz and switching within 0.1 picosecond. Third, as some FET's operating characteristics are enhanced at liquid nitrogen temperatures we can seriously consider hybrid circuits containing semiconductors and superconductors to obtain the best features of both technologies.

Phased array technology is one area for which superconductive electronics holds great promise. At S-band and lower frequencies the accepted architecture consists of components bolted together by wavequides. This technology is still practical at frequencies as high as 20 GHz. However, this approach will becomes impractical at higher frequencies as the component sizes become smaller and the waveguide losses become excessive. In this case a multilithic printed circuit design will be necessary. We will comment on initial efforts to apply superconductive electronics to this area.

# ELECTROMAGNETICS OF SUPERCONDUCTORS

*K. K. Mei, G. C. Liang, and T. Van Duzer*

Department of Electrical Engineering and Computer Sciences
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With the present pace of research and development activities in superconductors, superconductive boundary value problem is suddenly a "hot" subject. To pursue this study, the electromagnetic behavior about a superconducting medium must be clearly understood. If a superconducting surface were a lossless surface (as it is at T=0), it would be electromagnetically almost indistinguishable from a perfecting conducting surface except that magnetic field can penetrate into the superconductor with very small penetration depth (typically 100 nm). However, at microwave frequencies a superconductor is not a lossless material, and the loss is, in fact, proportional to frequency square. Thus, is superconductor just a low loss conductor? What are the boundary conditions of superconductors?

In this paper, we will point out that electromagnetically speaking a superconductor is indeed distinguishable from a fictitious perfect conductor. A superconducting material is more conveniently be treated as a dielectric material with negative real part of dielectric constant as far as electromagnetics is concerned. By considering superconductors as a generalized dielectric material, some superconductive electromagnetic problems are simplified, since the dielectric parameter is an integral part of electromagnetic computation. It does not present any technical difficulty to existing computer programs if a dielectric constant passes from a positive value to a negative one.

In addition to the conceptional discussion of superconductive electromagnetics, this talk will also present a time domain computational method involving dispersive media, such as superconductors or plasma. The method involves a time-domain finite-difference with system function expansion, so that no explicit convolution is required. It thus greatly reduces memory demand and CPU time.

As a consequence of this electromagnetic treatment of a superconductor, the existence of a surface wave on a superconducting surface is also predicted. It is a surface wave which is more tightly bound to the surface than the conventional surface wave.

# Frontiers in Antenna Applications

David Rutledge
*California Institute of Technology*

A major challenge in antennas today is to take full advantage of the continuing improvements in solid-state devices and in integrated-circuit fabrication technology. This is particularly true at millimeter wavelengths, where traditional technology is quite expensive. In this talk, I will discuss our work in imaging arrays and in oscillator grids.

The goal of the work in imaging arrays is to make a millimeter-wave television camera that would allow one to see through fog and smoke. For this, we have developed two-dimensional monolithic focal-plane arrays for 90 GHz and 240 GHz. These are pyramidal horns that are chemically etched in a silicon wafer, with a thin-film metal probe dipole suspended on a 1-$\mu$m thick layer of silicon oxynitride. With room-temperture Schottky-diode detectors, this array would be suitable for terrestrial all-weather imaging. With cooled superconducting tunnel-junction detectors, the array would be applicable to radio astronomy.

The idea of the oscillator-grid work is to combine the output power of a large number of solid-state devices in a single plane wave. This would allow us to make compact high-power solid-state millimeter-wave radar and communications transmitters. These should be more reliable and have much cheaper and lighter power supplies than traditional tube transmitters. Our approach is to place a periodic grid loaded with FET's inside a Fabry-Perot resonator. The approach is analogous to a laser oscillator, with the transistor grid forming the active gain medium. The concept is simple. There are no external locking signals or corporate feed lines; the devices lock through mutual diffraction coupling. There are no individual-device resonators because the cavity resonance determines the frequency. No additional reflector is needed because the output is a diffraction-limited beam. In addition, the scaling properties are attractive. The ERP scales as the fourth power of the diameter, and the AM and FM noise ratios scale as the square of the diameter. In our initial tests with twenty-five 20-mW FET's, we have achieved an ERP of 40 W at 10 GHz.

## Wednesday PM

URSI-B Session 51

### Numerical Methods: Iterative Methods

*Chairs*: R. E. Kleinman, University of Delaware; F. Molinet, Societe MOTHESIM

*Room*: Oak *Time*: 1:15–5:00

# A COMPARISON BETWEEN BICONJUGATE GRADIENT AND GAUSS-SEIDEL ITERATION FOR MULTIGRID SOLUTIONS TO THE SCALAR HELMHOLTZ EQUATION

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Multigrid approaches to finite element schemes in 2-D and 3-D rely on a decomposition of the mesh into a sequence of increasingly fine meshes. Starting with a solver for the finite element scheme at the coarsest mesh level, the multigrid approach then "bootstraps" itself to the solution at the finest mesh level. In many cases, one can prove rigourously that the computation time is *linear* with respect to the total number of unknowns in the problem, and is typically many orders of magnitude faster than standard direct or iterative schemes. Each stage of the bootstrapping process requires a sequence of interpolation and smoothing steps to pass information between the mesh levels. Typical smoothers for self-adjoint problems (e.g. the Helmholtz equation at zero frequency) include Gauss-Seidel and conjugate gradient iterations. As frequency effects become important, however, the efficiency of these methods can deteriorate and, in particular, a conjugate gradient iterative step is better replaced by a bi-conjugate gradient or conjugate gradient squared step.

In this talk, we shall compare and contrast Gauss-Seidel and biconjugate gradient multigrid schemes applied to the scalar Helmholtz equation over a range of frequencies. We find that for the low frequency, quasistatic regime, both schemes work well, with the Gauss-Seidel step resulting in the slightly simpler code. As propagatory effects become important, however, Gauss-Seidel steps can fail unless the lowest level mesh is sufficiently fine. Initial results indicate that the biconjugate scheme does not suffer from this problem and far coarser meshes can be used at the lowest level. Examples will be shown to demonstrate these results together with numerical examples where two and three dimensional problems of 100,000 nodes or more are solved in a few VAX cpu-minutes.

# A Boundary Integral Conjugate Gradient Fast Fourier Transform Method for Solving Two-Dimensional Scattering Problems

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Traditionally, the solution to the scattering from arbitrary, composite two-dimensional structures has been achieved via the Method of Moments. This proven technique becomes less attractive for electrically large bodies, since the storage requirements are $O(N^2)$. The method we present reduces the required storage.

The Boundary Integral Conjugate Gradient Fast Fourier Transform method (BICGFFT) is a variation of the Boundary Integral Method (B.H. McDonald and A. Wexler, IEEE Trans. Ant. Prop., 12, 841-847, 1972). The appropriate Helmholtz equations are solved via the usual Finite Element Method within a rectangular region enclosing the body, while the additional required boundary constraint is provided by the Stratton-Chu relation. The resulting system is solved iteratively by the Conjugate Gradient Fast Fourier Transform method, eliminating a need to generate a full square matrix over the surface of the rectangular boundaries enclosing the scatterer. The advantange of this is, of course, a substantial reduction in memory demand. But most importantly, the formulation involves an FFT, the order of which is one less than the dimensionality of the scatterer. The storage associated with the FFT is the most significant and is $O(N)$. The sub-matrix associated with the finite element portion of the system is highly banded and can be stored efficiently. However, at the cost of additional computational effort, these elements need not be stored but calculated when necessary.

# COMPARING ITERATION FOR DIELECTRICS, EFIE vs MFIE

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When using the EFIE to calculate scattering from dielectrics, it has been noticed that if a regular mesh is used to discretize space, then the moment method matrix has a special form, involving a Toeplitz matrix. This allows both efficient storage of the matrix and efficient application to a trial solution. Thus, iterative methods may be desireable for this calculation. Recently an MFIE approach for this problem has been described. Although this equation has a somewhat different structure, the resulting moment method matrix still does have a Toeplitz component, and each step of an iterative method may still be performed efficiently in an effectively sparse manner.

Given these observations, it is natural to ask if iterative methods will converge more quickly on either of these equations. It has been found that the EFIE results in a matrix which becomes increasingly ill-conditioned as the dielectric constant increases. This means that techniques such as the conjugate gradient, generalized conjugate residual, and the biconjugate gradient all will converge more slowly as the dielectric constant increases. Calculations for an MFIE for dielectrics will be used to determine how quickly its condition number increases with dielectric constant. The convergence rates of various iterative techniques will also be found and compared, for both the EFIE and MFIE formulations.

# AN OPERATOR CORRECTOR ITERATIVE SCHEME

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One of the most persistent problems in electromagnetic modeling is obtaining the solution of the large systems of equations resulting from integral equation models of electrically large scatterers. Although the $N^2$ time and storage requirements for filling the interaction matrix are severe enough, it is the $N^3$ solution times associated with direct matrix solvers (such as LU decompostion) that pose the most serious limitations on the size of scatterers that can be modeled. One method of reducing the solution time for large problems is to use indirect solution techniques. Such techniques are recursive in nature and can lead to significant solution time savings, particularly for certain types of matrix structures.

Classical iterative schemes such as Jacobi or Gauss-Siedel proceed by splitting the original linear system operator into a "dominant" portion (having a simple form and particularly easy method of factorization) and a bordered matrix. The iteration processes then proceed by successive application of the "dominant" (or iteration) operator on the solutions obtained in each step and comparing the boundary behavior of each solution with the true boundary behavior (i.e., the original right hand side). At each iteration corrections are made using the bordered portion of the original matrix operator. In a physical sense, one distinct shortcoming of these techniques is that the iteration operator is not allowed to become "smarter" throughout the iteration process, requiring many iterations to allow one portion of the scatterer to "talk" to another.

In this paper we present a new iterative scheme based on correcting the iteration operator itself in each step. The resulting algorithm exploits coherency trends found in previous iterations and then feeds this information back to the iteration operator. This feedback mechanism permits errors in the solutions to be corrected in fewer iterations since information about how the scatterer interacts with itself is constantly being fed back to the iteration operator. Examples will be presented to show how this technique can be implemented to solve typical large systems of equations efficiently, both from the perspective of the number of iterations and the total time of computation compared to available techniques.

# RECURSIVE ALGORITHMS FOR CALCULATING THE SCATTERING FROM $N$ STRIPS OR DISKS

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ABSTRACT

The reflection operators have been defined and applied to the scattering from strips and disks embedded in layered media in recent papers [*IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 1488–1506, Nov. 1988]. In this paper, algorithms to compute the the reflection operators will be described. From the recursive relations for the reflection operator for $N$ strips or disks, two recursive algorithms are developed to calculate the scattering by $N$ strips or disks. These algorithms use matrices of a finite size and, therefore, are easily programmable. One algorithm is for arbitrary excitation while the other is for a fixed excitation. The recursive algorithms require the inversion and multiplication of small matrices at each stage, and hence, are suitable for programming on smaller computers. Also, if the $N$ strips or disks are identical and equally spaced, symmetry can be exploited to speed up the algorithms. Programs have been developed to calculate the scattering by $N$ strips, and the result converges to the scattering by a large strip when the $N$ strips are touching each other.

# A CONCISE CONJUGATE GRADIENT COMPUTATION OF PLATE PROBLEMS WITH MANY EXCITATIONS

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One of the major difficulties in the application of the Conjugate Gradient algorithm for the analysis of electromagnetic scattering problems is the necessity to carry out the calculation separately for every excitation. A partially successful process for treating jointly several angles of plane wave incidence has been proposed recently (C.F. Smith, A.F. Peterson and R. Mittra, 1987 IEEE AP-S International Symposium digest, pp. 530-533, June 15-19, 1987), where eleven excitations were treated, resulting in appreciable saving of iteration steps. In this work, we span all incident electric fields or incident equivalent currents by a subdomain (pulse type) basis function set. Once the solutions for all unit pulse excitations over the plate are known, they can be combined to produce the solution to any excitation using the weighting coefficients of the incident field.

In our procedure, the plate area is scanned by placing pulse excitations at various locations and performing Conjugate Gradient computations for each of them. The order by which these locations are selected is important: they follow directions determined by an ascending initial error of a Physical Optics initial guess. At each change of location, the result of the previous location is used as the initial guess after a geometrical shift and truncation. The current distribution resulting from any pulse excitation is highly localized. Therefore, many field pulses located away from the edges produce current distributions that are very similar to those obtained on an infinite plate. Therefore, for a sizeable portion of the plate, very few iteration steps are needed.

We analyzed a $2\lambda \times 2\lambda$ plate, with a total of 1089 pulses, or 2178 unknowns including the two polarizations. The total computational cost for all the pulses needed to generate any incident wave is about equal to that of five plane wave excitations. We thus conclude that the usage of the pulse set puts the iterative process on a more predictable basis and significantly reduces the computational cost for a large number of excitations.

# AN IMPROVED CG–FFT SCHEME TO ANALYZE SCATTERING FROM FLAT METALLIC PERIODIC STRUCTURES

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ABSTRACT

A numerical scheme for analyzing periodic arrays of flat metallic patches using the Conjugate Gradient – Fast Fourier Transform (CG–FFT) method will be presented and compared with other CG–FFT schemes. The mixed–potential nature of the considered Electric Field Integral Equation (EFIE) allows to obtain a discrete spectral Green's dyadic function the terms of which decrease asymptotically with the spatial frequency faster than in other approaches. The discretized fields (impressed and scattered) are periodic in the real and spectral domains due to the regular nature of the geometry and excitation field and to the fact that in the real domain the sampling is performed at equidistant discrete points. The periodicity in the spectral domain is used to perform easily all computations without neglecting high spectral–frequency terms. Several results will be given that indicate that the procedure leads to exact computat ios and is faster than other approaches.

# A CGM-FFT SCHEME TO ANALYZE RADIATION AND SCATTERING OF METALLIC SURFACES CONFORMED TO BODIES OF REVOLUTION

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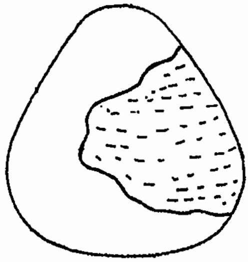
Metallic surfaces conformed to bodies of revolution (Fig. 1) are analyzed using a Conjugate Gradient - Fast Fourier Transform (CG-FFT) method. Rooftop functions are considered to represent the two components of the induced currents. The convolution integrals that appear in the $\varphi$-direction integrals are performed efficiently using the FFT. The CG-FFT scheme is tested with some examples.



-FIGURE 1-

# COMPUTATIONAL DIFFERENCES BETWEEN DIRECT APPLICATION OF CONJUGATE GRADIENT METHOD TO THE SOLUTION OF OPERATOR EQUATIONS AS OPPOSED TO MATRIX EQUATIONS

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ABSTRACT The objective of this presentation is to illustrate the computational differences between application of the conjugate gradient method to the solution of a matrix equation as opposed to the operator equation. As an example consider the deconvolution problem (for $t \geq 0$)

$$\int_0^\infty x(t-\tau)\, h(\tau)\, d\tau = y(t) \quad \text{for } 0 \leq t < \infty \quad \Rightarrow \quad AH = Y$$

This operator equation can be written in a matrix form under the assumption that the input is x(t) the impulse response h(t) and the output y(t) are causal. Therefore for a finite time length

$$\begin{bmatrix} x_1 & & & \\ x_2 & x_1 & & 0 \\ \vdots & \vdots & \ddots & \\ x_n & x_{n-1} & \cdots & x_{n-m} \end{bmatrix}_{N\times M} \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_m \end{bmatrix}_{M\times 1} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}_{N\times 1} \Rightarrow A_M \cdot H_M = Y_M$$

If we apply the CG method to solve the operator equation then we are solving the normal equations $A_M^* \cdot A_M \cdot H_M = A^*_M \cdot Y_M$ where $A^*_M$ is the adjoint matrix of $A_M$. (This is simply the conjugate transpose). Now if we apply the operator equation directly to the solution of the operator equation then we solve

$$A^* A H = A^* Y \quad \text{where} \quad A^* Y = \int_0^\infty x(t-\tau)\, y(t)\, dt$$

Now the problem is how to compute $A^*Y$ in the operator form since x and y are known only upto values n. So some assumption has to be made on how to discretize the adjoint operator so that $A^*Y$ can be evaluated. On the other hand the adjoint matrix operator is quite straightforward as it is simply the transpose of the matrix. In signal processing literature a clear distinction is made between these two cases. $A^*_M \cdot A_M$ is called the covariance matrix of the data, where as $A^*A$ is called the autocorelation matrix of the data. Therefore, when the functions under considerations are causal, there is a difference between application of the conjugate gradient method to the solution of the operator equation as opposed to its application to the matrix equation. This is because, some assumptions has to be made in the computation of the adjoint operator. Several ways of performing this approximate computation is outlined in the literature:

(a) to take a large data length so that the waveforms have become quite small at the tail end [Sarkar, Rao, Dianat- "The Application of the Conjugate Gradient method to the solution of Operator Equations Arising in Electromagnetic Scattering from Wire Antennas", Radio Science, Sept. 1986, pp. 1319-1326; A. Tijhuis- Electromagnetic Inverse Profiling (1987) VNU Press.

(b) to redefine the inner product as a weighted inner product [Tseng and Sarkar, (1987), "Deconvolution of Impulse Response of a Conducting Sphere by the Conjugate Gradient Method", IEEE AP pp. 105-110.]

For time domain techniques where wave forms are causal, the two techniques differ. For some frequency domain problems, where the Green's function is of infinite support and is symmetric, the difference becomes philosophical. Also for nonuniformed sample functions again it is difficult to reach any general conclusions.

# ITERATION TECHNIQUES WITH ENTIRE-DOMAIN EXPANSION FUNCTIONS

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The use of iterative solution techniques applied to the problem of electromagnetic scattering from conducting and coated surfaces will be examined. Galerkin method-of-moments formulations based on entire-domain expansion functions, which have been developed for various types of geometries (L. N. Medgyesi-Mitschang and J. M. Putnam, IEEE Trans. Antennas Propagat., AP-33, 1090 (1985) and AP-35, 790 (1987)), have a number of properties which make them well suited to iterative techniques. The most important property allows an impedance matrix of order N to be completely filled after the computation of only 2N numerical integrations as opposed to $N^2$ integrations with other formulations. The individual matrix elements can be easily recomputed during the iteration process without the need for excessive storage or time-consuming numerical integrations.

Some simple iterative solution techniques will be presented for the cases of scattering from conducting and coated strips. The rate of iteration convergence will be illustrated for various strip widths, coating properties, and incident direction. The iteration methods presented are rapidly convergent and can be applied to electrically large surfaces.

## Wednesday PM

URSI-B Session 53

### Numerical Methods: FDTD II

*Chairs*: A. Taflove, Northwestern University; K. R. Demarest, University of Kansas

*Room*: Pine *Time*: 1:15–4:40

# A Higher Order Finite Difference Scheme For The Solution Of Maxwell's Equations In The Time Domain

Jiayuan Fang* and Kenneth K. Mei
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Since Kane Yee (1966) introduced the time domain finite difference method for solving Maxwell's equations, this method has becoming increasingly widely used for many electromagnetic problems. Although efficient, Yee's method is of second order accuracy. The numerical dispersion of the method may severely affect the accuracy of some computation results. For example, in the simulation of pulse propagation, the waveform of the field will be gradually distorted as the pulse propagates through the medium due to the numerical dispersion of the finite difference scheme. In order to raise the accuracy of the results, one way is to reduce the mesh size which results in increased requirement for computer memory space and CPU time. The alternate way which only requires more CPU time but the same amount of memory space is to use higher order finite difference schemes.

The algorithm proposed here is a fourth order accurate scheme for the solution of Maxwell's equations in three space dimensions. The favorite features of this scheme are as follows. It requires the same amount of memory space as the second order one. The electric and magnetic nodes are distributed the same as those in Yee's mesh. The stability analysis of this scheme shows that its limitation on the size of the time step is not more rigid than the second order scheme. As can be seen from various figures presented, the numerical dispersion of this fourth order scheme is much less than that of the regular second order one, which results in orders of improvement on the accuracy of the phase and much less distortion of the waveform.

# Absorbing Boundary Conditions For The Time Domain Finite Difference Solution Of Maxwell's Equations

Jiayuan Fang* and Kenneth K. Mei
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For the finite difference solution of Maxwell's Equations in an open space, absorbing boundary conditions are used to terminate the computation domain. The quality of absorbing boundary conditions can greatly affect the accuracy of the computational results and the requirements for computer memory space and computation time. The precise description of the quality of an absorbing boundary condition is its corresponding reflection coefficient when it is applied at a boundary. The reflection coefficient of an absorbing boundary condition usually depends not only on the incident angle of the wave striking on the boundary, but also the frequency of the wave, i.e., it also depends on the dispersion relation of the finite difference scheme. Here we will evaluate various absorbing boundary conditions by comparing their reflection coefficients under the consideration of the dispersion relation of the regular second order accurate finite difference scheme (Yee's scheme).

The absorbing boundary conditions to be discussed include various orders of Engquist and Majda's boundary conditions, Liao et al.'s multi-transmitting boundary conditions, Higdon's multi-operator boundary conditions constructed by multiplication of several first order boundary operators for specific incident angles, super-absorbing error cancellation method which was presented in the last symposium, impedance boundary conditions, Lindman's wide angle boundary conditions with the reflection coefficient of a few percent from normal incident to about 89° incident angle, and the improvements on Lindman's boundary condition that significantly reduce the reflection coefficient of the original Lindman's boundary condition in a large range of incident angles.

# THREE-DIMENSIONAL SCALAR AND VECTOR ABSORBING BOUNDARY CONDITIONS BASED UPON THE WILCOX EXPANSION

*Raj Mittra*
*Electromagnetic Communication Laboratory*
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The derivation of the Absorbing Boundary Conditions(ABCs) for mesh truncation is typically based on the asymptotic solution of differential equations for large distances from the origin, and the construction of one way differential operators. (See for instance, Bayliss, Gunzburger and Turkel, SIAM, April 1982; Enguist and Majda, Math. Comp., July 1977; Peterson, Microwave and Opt. Tech. Let., April 1988.) In this paper we present an alternate derivation which makes use of the recursion relationships satisfied by the various terms in the Wilcox's multipole type of expansion for scalar and vector fields. An important feature of this derivation is that it is uniform in nature, i.e., the mathematical construction followed in the derivation applies equally well to both the scalar and vector fields, be they two or three-dimensional. In this paper we will concentrate only on the three-dimensional boundary conditions.

To derive the scalar boundary condition one simply starts with the Wilcox representation of the scattered field, which reads

$$u = [\exp(-jkr)/r] \{ \sum_{n=0} a_n (\theta, \phi)/ r^n \}.$$

Wilcox shows in his classical paper how the higher order coefficients, $a_n$, are related to $a_o$ via recursion relationships. In this paper we demonstrate that when the above expansion is used to derive $u_r$, the resulting series can be readily rearranged to yield the desired second order absorbing boundary condition in the familiar form: $u_r = \alpha(r)\, u + \beta(r)\, D_{\theta\phi}\, u$, where $D_{\theta\phi}$ is the Beltrami operator. The higher order boundary conditions can be readily derived by continuing to follow the procedure outlined above.

The derivation of the vector 3-D boundary condition proceeds exactly along the same lines by starting, once again, with the vector form of Wilcox expansion, say for the E field, and deriving curl E, the quantity needed in the "weak" form of the vector wave equation for the application of the ABC. The paper shows that the expansion for curl E can again be rearranged to yield a form which reads

$$\nabla \times \mathbf{E} = \bar{\alpha}(r)\, \mathbf{E} + \beta(r)\, D_4\, \mathbf{E}$$

The above equation represents desired vector 3-D boundary condition. The expressions for the various operator appearing in the above equation are provided in the paper.

# APPLICATION OF A NEW FDTD FORMULATION TO HIGHLY CONDUCTIVE MATERIALS

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Current Finite Difference Time Domain (FDTD) formulations require the permittivity and conductivity to be specified as constants. However, for many real materials of interest they vary significantly with frequency. The effects of this variation are included in a frequency dependent FDTD formulation, $(FD)^2TD$, by extending the traditional Yee formulation to include discrete time-domain convolution. The accuracy of $(FD)^2TD$ has been demonstrated by computing the reflection coefficient at an air-water interface over a wide frequency band including the effects of the frequency dependent complex permittivity of water. These results have been presented separately (Luebbers, Hunsberger, and Kunz, "FDTD Formulation for Frequency Dependent Permittivity", submitted for presentation at the IEEE AP-S Symposium, San Jose, CA, June 1989). $(FD)^2TD$ extension to frequency dependent permeability and to three dimensions should be straightforward.

While the results for water are encouraging, application of $(FD)^2TD$ to other materials, specifically conductors and plasmas, requires further investigation. This is because the time-domain susceptibility of polar dielectrics, such as water, is fundamentally different than that of conductors, since polar dielectrics have negligible conductivity at zero frequency.

Having obtained the appropriate susceptibility functions, we have investigated the capability of $(FD)^2TD$ to compute electromagnetic interactions with highly conductive materials. Preliminary results indicate that $(FD)^2TD$ is not subject to the same limitation for highly conductive materials that applies to the Yee formulation ($\sigma \cdot \Delta t/\varepsilon < 1$), but can deal with situations where this constraint is greatly exceeded.

These results indicate that $(FD)^2TD$ may be capable of removing two of the fundamental constraints that limit application of FDTD to many problems, since $(FD)^2TD$ seems to be capable of computing directly and explicitly electromagnetic interactions with dispersive media with relatively high values of conductivity.

# FD-TD NUMERICAL MODELING OF ELECTRICALLY LARGE 3-D STRUCTURES, BOTH BARE-METAL AND RAM-LOADED

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In this paper, we report on the computational modeling of the monostatic radar cross section (RCS) patterns of canonical 3-D electrically large targets. The RCS patterns are calculated by using the finite-difference time-domain (FD-TD) method. Three metal targets are considered: a thin flat plate; a trihedral corner reflector; and a model jet engine inlet. For the last two targets, we examine the effect of loading the interior surfaces with a commercially available X-band radar absorbing material (RAM), Emerson & Cuming type AN-73. (This RAM consists of 3 distinct layers of lossy dielectric material with each layer $\frac{1}{8}$" thick.)

We find that FD-TD is a viable means to model the monostatic RCS patterns of 3-D targets which are electrically large (spanning more than $10\lambda_0$) and yet have electrically small details (in the order of $0.1\lambda_0$). We also find that FD-TD yields a computational dynamic range of at least 60dB in obtaining the RCS of targets having deep nulls, and at least 30dB in modeling RCS reduction due to RAM loading.

Last, we find that emerging supercomputers are enabling FD-TD predictions of RCS to be obtained with practical run times measured in the seconds per monostatic observation angle. For example, the RCS pattern of a $5\lambda_0$ x $5\lambda_0$ x $10\lambda_0$ model engine inlet with RAM loading can be obtained via FD-TD on a 6-processor Cray Y-MP at an effective rate of one monostatic angle each 54 seconds. With the Cray-3 (to be released in late 1989), it is anticipated that the time-per-monostatic-angle will drop to only 10 seconds. It should be realized that, during these few seconds, FD-TD provides not only a simple scalar number describing RCS, but also the *complete time history* of the near fields at all points within and near the target and its RAM loading.

# TOWARD COMPREHENSIVE VALIDATION OF THE ROCKWELL DIFFERENTIAL SOLVER FOR MAXWELL'S EQUATIONS

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Rockwell differential solver for Maxwell's equations which was introduced less than two years ago ( V. Shankar and W. F. Hall, URSI Meeting, Boulder, Jan.1988 ) is proven to be a very powerful tool for solving scattering and radiation problems from arbitrary objects. This approach is a time-domain explicit scheme that can be applied to both steady-state and transient problems. The differential solver is based on proven upwind techniques in computational fluid dynamics ( CFD ). Maxwell's equations which are a hyperbolic system of partial differential equations are transformed to a body-fitted set of coordinates and integrated numerically along the characteristic subpaths. This procedure is originally due to Riemann (Sommerfeld, A., Partial Differential Equations in Physics, Academic Press, 1949.) and is better known as Riemann solver in CFD. The Lax-Wendroff algorithm which is second order accurate in space and time is applied to the transform equations. The resulting difference equations are solved numerically. Also, use of the multizoning greatly reduces the geometric complexity of the objects and makes this method free of special treatments and fixes often adopted in other approaches.

Use of the body-fitted coordinates, besides facilitating the implementation of the boundary conditions on the object, actually results in higher accuracy for the computed near and far field quantities. This is achieved by being able to prescribe a high grid resolution where it is needed. Another factor that contributes to the accuracy of this approach is the use of the Lax-Wendroff scheme.

The results we have so far obtained from this method substantiate our claims to the accuracy and versatility of this approach. In the study of the bistatic radar cross section for both conducting and dielectric circular cylinders, we have been able to easily predict at least a 60 dB dynamic range. In most cases our results are almost perfect replicas of the ones from the series solution. We have also been able to accommodate infinite ground plane, half-plane, and frequency dependent material properties into our approach and in all cases the results are validated against either analytical or other independently verified solutions. Many of these results, including some currently in progress near-field validation cases, will be presented at the talk.

# Verification Tools for Large-Scale Finite-Difference Models *

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As computer hardware has advanced in speed and memory, it has become possible to run very large EM simulations; problems with one million elements are becoming commonplace. For problems of this complexity, techniques to verify the correctness of the input model and output results are essential. This requirement is beginning to shift the burden of the computer modeling effort from the numerical solver to the pre- and post-processing arena.

The major pre-processing task for large finite-difference problems is verifying that the discrete model is properly constructed. Two tools developed at LLNL for this purpose will be described: automatic mesh generation and interactive mesh verification. Our mesh generator, based on an interactive solids-modeler, allows the user to create numerical meshes in an intuitive, visual process. Mesh verification is performed with special software on a high-end graphics work-station. The user can interactively rotate, slice, and disassemble the mesh to check its form.

The task of post-processing is two-fold: to verify proper operation of the code and to check the correctness of the numerical solution. For the former, we have developed interactive graphics tools to examine two and three dimensional simulation results. Finally, for the final check on EM calculations, we have built experimental facilities that can verify numerical results. Examples of these tools and procedures will be presented for several recent problems.

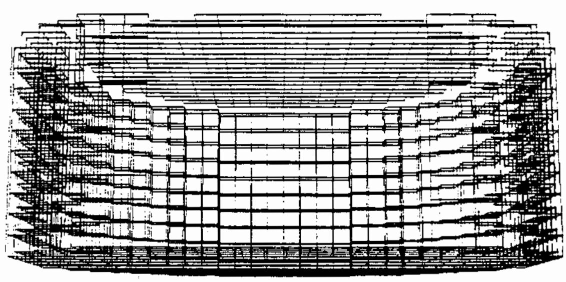

Figure 1 Example image of simple mesh

* Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

# Two Dimensional Finite Difference Time Domain Scattering Computation Using the Control Region Approximation

Robert J. Hall
Brian J. McCartin
*United Technologies Research Center*

The Control Region Approximation is a general finite difference scheme applicable to the scattering of electromagnetic waves by arbitrary two and three dimensional targets. Previous work has been confined to the frequency domain which offers efficient computation for multiple angles of incidence at fixed frequency. In this paper, we extend this approximation technique to the time domain which provides efficient computation for multiple frequencies at fixed angle of incidence. The discussion here is confined to two spatial dimensions.

The incident field is decomposed into transverse electric (TE) and transverse magnetic (TM) fields which are computed independently. For either field, only the axial component need be computed from the wave equation

$$\nabla \cdot (a\nabla u) = b\frac{\partial^2 u}{\partial t^2}$$

where

$$a = 1/\epsilon, \quad b = \mu, \quad u = H_z \quad (TE)$$
$$a = 1/\mu, \quad b = \epsilon, \quad u = E_z \quad (TM),$$

the remaining field components being derivable from the transverse gradient of this component.

This equation is then integrated over a control region resulting in the conservation law

$$\oint a\frac{\partial u}{\partial n}\, dl = \int\int b\frac{\partial^2 u}{\partial t^2}\, dA.$$

Spatial discretization is performed using the Control Region Approximation while temporal discretization is achieved by an explicit central difference in time.

The resulting numerical procedure provides a highly accurate method for computing the scattered fields about targets of general shape and arbitrary material compostion. This will be validated by comparison to known analytical solutions, alternative numerical procedures, and experimental test data.

# ELECTROMAGNETIC WAVE SCATTERING BY A CONDUCTING SPHERE USING ON-SURFACE RADIATION CONDITION APPROACH

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The on-surface radiation condition (OSRC) approach has been previously applied for the analysis of electromagnetic scattering by two dimensional convex shaped objects. The two dimensional electromagnetic scattering problems basically require scalar boundary operators. For the case of two dimensional perfectly conducting objects with either the transverse magnetic or the transverse electric plane wave excitation, it has been shown that substantial simplification in the analysis is obtained for the induced surface currents and radar cross section. The OSRC approach is also successfully applied for the case of two dimensional homogeneous, isotropic dielectric scattering objects. Based on the OSRC approach, the dielectric scattering problem gets decoupled from the exterior, and basically reduces to the analysis of interior fields. The near surface fields and radar cross section results are reported previously for circular and ellipitic dielectric cylinders.

This paper presents an extension of the on-surface radiation condition approach for the analysis of electromagnetic scattering by *three dimensional* convex shaped perfectly conducting objects. A discussion is presented concerning the boundary operators required for the analysis of the three dimensional electromagnetic problems. The boundary operators can be in terms of the vector formulation or the scalar formulation. The vector boundary operators are quite complicated due to the coupled nature of the electromagnetic fields. But the three dimensional scalar boundary operators are quite elegant to apply as previously demonstrated in the implementation of numerical algorithms based on the finite-difference time-domain technique.

In order to demonstrate the use of scalar boundary operators, the three dimensional electromagnetic scattering by a perfectly conducting sphere is presented based on the OSRC approach. The analytical results obtained based on the application of the OSRC are compared with respect to the direct series solution. The induced surface currents on the conducting sphere and radar cross section obtained based on the OSRC are compared with the available numerical data.

## Wednesday PM

Joint AP-S, URSI-B Session 54

### Phased Arrays: Airborne, Space to Space, and Patch Arrays

*Chairs*: N. H. Farhat, University of Pennsylvania; C. Mangenot, Alcatel Espace

*Room*: Cedar *Time*: 1:15–5:00

| | | |
|---|---|---|
| 1:20 | **Improved Computer Simulation of the TCAS III Circular Array Mounted on an Aircraft**<br>R. G. Rojas,* Y. C. Chen, Ohio State University | AP-S |
| 1:40 | **Tracking Error of a Phased Array Antenna**<br>S. Ohmori,* S. Taira, Kashima Space Research Center, M. Austin, Royal Melbourne Institute of Technology | AP-S |
| 2:00 | **Design and Testing of a Large Airborne Phased Array**<br>W. P. Cooke,* J. M. Harris, Georgia Tech. Research Institute | AP-S |
| 2:20 | **A Ka-Band MMIC Phased Array Antenna**<br>J. Huang,* D. Rascoe, A. L. Riley, V. Lubecke, L. Duffy, Jet Propulsion Laboratory | AP-S |
| 2:40 | **An S-Band Distributed Array Antenna for Space to Space Communication**<br>G. W. Raffoul,* Lockheed Engineering and Science Co. | 238 |
| 3:00 | **Coffee Break** | |
| 3:20 | **A Dual Polarized Patch Radiator for Phased Arrays**<br>J. D. Hanfling,* J. J. Schuss, R. E. Morrow, Raytheon | AP-S |
| 3:40 | **Design of Wideband Patch Radiator Phased Arrays**<br>J. J. Schuss,* J. D. Hanfling, R. L. Bauer, Raytheon | AP-S |
| 4:00 | **Element Gain in Phased Array Antennas**<br>H. K. Schuman,* G. A. Bright, Atlantic Research Services Corp., S. Barbour, Grumman Aerospace Corp. | AP-S |
| 4:20 | **Design Considerations in a Hybrid Mechanically/Electronically Steered Planar Array Vehicle Antenna for Mobile Satellite Systems**<br>V. Jamnejad,* Jet Propulsion Laboratory | 239 |
| 4:40 | **Antenna System Parameters for Space Based Radar**<br>C. C. Allen,* Allen Consulting | 240 |

# AN S-BAND DISTRIBUTED ARRAY ANTENNA FOR SPACE TO SPACE COMMUNICATION

GEORGE W. RAFFOUL

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Abstract - This paper describes the development of a planar medium gain distributed array antenna to be flush mounted on the surface of a spacecraft in low earth orbit. The antenna will support low data rate communication with the Tracking and Data Relay Satellite, that is located in geosynchronous orbit, from a low earth orbiting spacecraft like the Space Shuttle or the Space Station. The array is actually composed of two side-by-side arrays with eight active elements in each. One array is designated for transmit and the other for receive. The transmit array consists of 4 X 2 circularly polarized patch elements, eight 7-watt high power amplifiers, eight 3-bit phase shifters, and one 8-way power divider. The receive array is similarly equipped with eight circularly polarized patch elements, eight low noise amplifiers, eight 3-bit phase shifters, and one 8-way power combiner. An additional solitary L-band element supports low gain receive-only communication from a host of ground stations. The three signals (S-band transmit, S-band receive, and L-band receive) are multiplexed into a single input/output port with a triplexer.

The array is designed to point its beam toward the TDRS anywhere within one quadrant of space extending 90° in roll and 180° in pitch. Pointing within this coverage zone is done by a microprocessor-based beam-steering controller which receives the TDRS look angles from the spacecraft's onboard navigation computer. Full spherical coverage of the TDRS is obtained by strategically locating four of these antennas around the body of the spacecraft and switching between them as the spacecraft attitude changes.

Performance data covering antenna gain, axial ratio, circuit losses, and radiation patterns will be discussed. Also, composite coverage of four antennas located around the Space Shuttle cockpit will be illustrated using three-dimensional graphics software.

# DESIGN CONSIDERATIONS IN A HYBRID MECHANICALLY/ELECTRONICALLY STEERED PLANAR ARRAY VEHICLE ANTENNA FOR MOBILE SATELLITE SYSTEMS

Vahraz Jamnejad
Jet Propulsion Laboratory
California Institute of Technology

In recent years a substantial amount of work has been performed at JPL/NASA in the study, design, and development of medium gain (8-12 dB) circularly polarized mobile vehicle antennas for use in future Mobile Satellite Systems (MSS), operating at L-band (1545-1660 MHz) frequencies. Low cost, small size and low-profile are primary design factors for antennas mounted on top of moving vehicles. A variety of antennas have been considered. Both mechanically steered and electronically steered antennas have been developed. These antennas, with a diameter of about 20 to 22 inches, provide close to 10 dBic of gain in the 20 to 60 degrees elevation range required for the coverage of the continental united states (CONUS). Typically, the electronically steered antenna beam is scanned in both azimuth and elevation directions, while mechanically steered antenna provides only azimuth beam steering with a fixed broad beam pattern in elevation.

Here the merits of a new hybrid mechanically/electronically steered design are discussed. In this design azimuth coverage will be accomplished by mechanical rotation, while elevation coverage will be provided by electronic beam switching. It is shown that at least 1 dB of extra gain is obtained by a two-position beam switching scheme as compared with a fixed single beam gain-optimized for elevation coverage. This hybrid antenna provides a suitable compromise in terms of cost and complexity compared with exclusively mechanically or electronically steered antennas. A breadboard version of this type of antenna with a diameter of 27 inches and a height of less than 1.5 inches is under development at Teledyne Ryan Electronics, under contract with JPL/NASA.

# ANTENNA SYSTEM PARAMETERS FOR SPACE BASED RADAR

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## ABSTRACT

A space based radar (SBR) system could provide civil air traffic control and/or military surveillance and target tracking. For such applications, an SBR system should have world-wide coverage, all weather day/night operation, and adequate small target sensitivity. An SBR system for this purpose might consist of a constellation of several satellites at low to medium orbit altitude with a suitable orbit inclination angle and a phased array antenna on each satellite that provides conical coverage about nadir.

The antenna system parameters for such a space based radar system must be properly chosen in order to achieve high SBR system performance. These antenna system parameters are directly related to the satellite orbital parameters, the radar signal processing parameters, and the available satellite power. The parametric relationships required to obtain a desired geographic coverage, target detection sensitivity, and minimum discernible target velocity (MDV) in the absence of clutter-limited operation are presented in this paper.

## Wednesday PM

URSI-A Session 55

### Radiation & Scattering Measurements

*Chairs*: V. V. Varadan, Pennsylvania State U.; R. L. Moore, Georgia Tech.

*Room*: Monterey *Time*: 1:15–3:20

# A NEW FREE-SPACE METHOD FOR EXPLICIT DETERMINATION OF COMPLEX PERMITTIVITY AND COMPLEX PERMEABILITY OF MAGNETIC MATERIALS AT MICROWAVE FREQUENCIES USING BISTATIC MEASUREMENTS

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For determination of complex permittivity $\varepsilon^*$ and complex permeability $\mu^*$ using short-circuit and open-circuit method or reflection and transmission coefficient method, an apriori knowledge of approximate values of $\varepsilon^*$ and $\mu^*$ is required so as to ensure that the sample thickness is less than half wavelength. In the new free-space method, explicit expressions for $\varepsilon^*$ and $\mu^*$ obviates the need for any apriori information about dielectric and magnetic properties of the sample.

A uniform plane wave is incident on a planar sample of magnetic material which is in contact with a perfectly conducting plate. The angle of incidence is between 35° and 65°. $\varepsilon^*$ and $\mu^*$ are obtained from the measurement of reflection coefficient for parallel polarization $\Gamma_{\parallel}$ and reflection coefficient for perpendicular polarization $\Gamma_{\perp}$. A free-space measurement system will be employed for measuring $\Gamma_{\parallel}$ and $\Gamma_{\perp}$. The measurement system and calibration technique will be described and experimental results will be presented for several magnetic materials including FGM – 40 absorber material (manufactured by Emerson and Cuming, Inc., Canton, MA).

# FREE-SPACE MEASUREMENT OF COMPLEX PERMITTIVITY AND COMPLEX PERMEABILITY OF HIGH LOSS MATERIALS AT MICROWAVE FREQUENCIES

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For tailoring electrical properties of radar absorbing materials and anti-reflection coatings, it is necessary to measure complex permittivity $\varepsilon^*$ and complex permeability $\mu^*$. A free-space measurement system operating in the frequency range 8.2 – 40 GHz was used to measure scattering coefficients $S_{11}$ and $S_{21}$ of planar samples. $\varepsilon^*$ and $\mu^*$ are calculated from the measured values of $S_{11}$ and $S_{21}$. The measurement system consists of transmit and receive horn lens antennas, network analyzer, mode transitions and computer. Diffraction effects at the edges of the sample are minimized by using spot-focusing lens antennas. Errors due to multiple reflections between antennas via the surface of the sample were corrected by using free-space TRL (thru, reflect, line) calibration technique. For thin flexible samples, it is required to sandwich the sample between two half-wavelength (at mid-band) quartz plates, so as to eliminate the effect of sagging. Results are reported in the frequency range of 10 – 14 GHz for Teflon, Sodium Borosilicate Glass, Eccogel 1365 – 90 (epoxy resin manufactured by Emerson-Cuming, Inc., Canton, MA), FGM – 40 and AN – 73 (microwave absorbers manufactured by Emerson-Cuming, Inc., Canton, MA).

# COMPARISON OF THREE LOW FREQUENCY MEASUREMENT TECHNIQUES AND CALCULATIONS FOR SMALL DIHEDRAL BACKSCATTERING

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Department of Electrical Engineering
Columbus, Ohio 43212

Measured and calculated backscatter of a small dihedral in the resonance region are presented in the frequency and time domain. Dominant scattering centers at these low frequencies are isolated and identified. The frequencies of interest lead to a ratio of dihedral joint length to wavelength in the range of .01 to 1.5. Measured data were obtained from three RCS ranges:

1. A parallel plate transmission line, with 8" plate spacing and an 8' width. With the tapered transition, its total length is approximately 40'. The microwave hardware used was a pulse modulated Hewlett Packard 8510 Network Analyzer.
2. The Ohio State University (OSU) Compact Range in a special low-frequency configuration
3. The OSU "Big Ear" Radio Telescope as a compact range. (J. D. Kraus, Big Ear, Cygnus-Quasar Books, Powell, Ohio 1976)

Measured results from each of the methods are compared and the contrasting problem areas and strengths are discussed.

Calculated results are based on the UTD method presented by Marhefka and Akhter(Report 717756-3, The Ohio State University ElectroScience Laboratory, Dec. 1988) and Moment Method analysis. The calculated data are compared to physical optics theory and to the measured results.

# THE COMPUTATION, FROM CYLINDRICAL NEAR-FIELD MEASUREMENTS, OF THE ELECTROMAGNETIC FIELD AT ARBITRARY POINTS IN SPACE NEAR AN ANTENNA

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The computation of the asymptotic far-field of an antenna from a set of near-field samples has been done accurately since the development of various theories incorporating probe correction techniques. However, the more general problem of computing the electromagnetic fields at arbitrary points near the antenna has not been widely addressed. This is due to the fact that the evaluation of the radiation integrals proves to be formidable, except for the asymptotic case when the method of stationary phase can be applied.

An algorithm is being developed for the evaluation of these integrals in cylindrical co-ordinates. The radiation integrals are the general weighted sum of all the field modes (Leach & Paris, IEEE Trans, vol. AP-21, no. 4, pp 435-445, July 1973). The weighting coefficients characterize the antenna, and can be computed from probe corrected near-field measurements.

The technique entails expressing the integrand as a well behaved amplitude term multiplied by a harmonic term, in the form

$$I(r,z,\varphi) = \sum_{n} \int A(n,h,r)e^{j\mu(n,h,r,z,\varphi)}dh$$

where $r,z,\varphi$ are the cylindrical co-ordinates. The analytical extraction of phase terms from the amplitude function A allows the phase function $\mu$ to be described analytically. Numerical integration is performed mainly near the stationary points of $\mu$, under the assumption that A and $\mu$ are linear between samples. This method is similar to Ludwig's algorithm (AC Ludwig, IEEE Trans, vol. AP-16, pp767-769, Nov. 1968).

Numerical results will be compared with measurements on various cylindrical surfaces surrounding the antenna, to test the algorithm. Computation of the fields on a large sphere will allow comparison with asymptotic results.

# FAR FIELD PREDICTION OF REFLECTOR ANTENNAS BY PARTIAL MEASUREMENTS

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P.J.Markland and T.J.F.Pavlasek
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and Mitec Electronics Ltd. Pointe Claire. P.Q. Canada

Recent progress in space technology has resulted in the need for large space deployable reflector antennas. Such antennas, of the order of 10-50 m in diameter, are not easily tested on Earth based ranges. They are often not self supporting in a one g environment, and their shape departs from ideal due to inherent structural distortions. Moreover, the preservation of the shape cannot be guaranteed during the mission. Thus, a thorough investigation of the anticipated deterioration of the performance as a function of the distortions of the reflector may be indicated in addition to the standard test procedures. A routine investigation of this type would require fabrication of rigid models of the reflector corresponding to the anticipated distortions, which does not seem practical. As a result, the need to establish a new, reliable and efficient test method not requiring the physical presence of the reflector, has emerged as a challenging problem.

Addressing this need, we propose to carry the measurements forward to the point where the total field from the feed is measured in the absence of the reflector along the imaginary surface of its future location. The presence of an ideal or distorted reflector is then simulated, the aperture field or reflector currents are determined and the far field is predicted. Reflectors defined either numerically or analytically may be considered. Also, whenever auxiliary structures, like the bus or the feed support, are in close enough proximity to the feed to produce noticeable impact on its electrical performance, their presence can be maintained and accounted for. At the same time the impacts of possible inaccuracies in the geometry and feeding, as well as of mutual couplings between the elements, are preserved.

To demonstrate that the implementation of the partial measurement method is feasible and that the results agree with the traditionaly obtained ones, the following activities have been undertaken: 1. a number of representative reflector antennas have been fabricated, 2. a dedicated measuring facility consisting of anechoic room, tri-axial positioner, microwave measuring system with sensing probes, and process control/data acquisition computers has been assembled, 3. software for reflector to aperture transformation has been developed, 4. the far field patterns have been calculated, measured on a far-field range and predicted using the partial measurements method.

The results exhibit far ranging agreement, strongly supporting the concept and its implementation. The method presented here brings a powerful means for resolving the large space deployable reflector antenna measurement problem.

# COMPACT RANGE ANTENNA DESIGN AND ANALYSIS PACKAGE

R. Mompó (1), J. Molina (2), M. Calvo* (1), J.L. Besada (1)

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Single offset and dual offset reflectors both shaped and unshaped, as well as dual cylindrical reflectors, are being considered as reflectors for Compact Range systems in Antennas and RCS measurements. The edge diffraction is an important disturbing effect due to the strong reflector edge illumination required to obtain a low amplitude taper in the PWZ. Serrations and rolled bends are used to reduce edge diffractions.

The geometrical layout of the reflector system is first obtained using simple CAD programs. From the graphic results the designer obtains a rough idea of the reflector (subreflector) dimensions and location in the available room.

The serrations are designed using a ray tracing program that draws the intersections of the cone of rays, diffracted from the serration edges, with the PWZ plane. The serrations are then inclined in order to avoid that any diffracted ray will pass through the quiet zone. Both linear and curved shaped serrations can be handled by the program.

The analysis of the near field produced by the reflector system is done by the integration of the Physical Optics approximation of the main reflector induced currents. The PO currents on any point of the main reflector can be obtained from the feed pattern (directly for single offset reflectors or using either GO + GTD or PO integration on the subreflector in dual systems). The main reflector surface is subdivided in small rectangular patches on which the PO current can be considered constant and such that any point on the PWZ is in the far field of that constant current element. The far field of those constant current cells is easily expressed in closed form and the total field on each point of the PWZ is obtained by superposition of the fields produced by all the cells. The serrations are included in the process by weighting the non rectangular border cells.

As an example, the application of those programs to the design of a Compensated Dual Gregorian Compact Range, similar to the one studied by Burnside et alt. (W.D. Burnside, C.W. Pistorius, M. Gilreath : "A Dual Chamber Gregorian Subreflector for Compact Range Applications". Proc. A.M.T.A. 1987 Meeting, pp 90-95), will be presented.

## Wednesday PM

Joint AP-S, URSI-F Session 59

**Polarimetric SAR Imaging**

*Chairs*: L. W. Root, U. S. Army Missile Command; M. Tanaka, Oita University

*Room*: San Juan *Time*: 1:15–4:40

# Simulation of Polarimetric Radar and Laser Imagery

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This paper describes extensions of previously reported software packages developed to compute cross-section and simulate synthetic aperture imagery at microwave and laser wavelengths. (I.J. LaHaie, 1985 North American Radio Science Meeting Digest, p. 145 and 1987 URSI Radio Science Meeting Digest, p. 163). The simulation technique is reviewed, polarimetric capabilities are described, and example imagery is presented.

The first step of the simulation process is generation of a three-dimensional computer model of a complex target or scene using combinatorial solid geometry. The scene geometry as viewed from the sensor (radar or laser) aspect direction is then sampled using ray casting techniques. Electromagnetic scattering from deterministic surfaces is computed from a generalization of the physical optics approximation. Scattering from randomly rough surfaces is based on realizations drawn from second order statistics which can be obtained from analytical models or experimental data. Multiple reflections, shadowing and obscuration are included in the calculations. Total cross-section is computed from the scattered field and synthetic aperture (range-angle) or real beam (angle-angle) imagery is simulated by convolving the return signal with the spatial impulse response of the sensor system.

Polarization characteristics of both the sensor system and the scattered field are explicitly taken into account. Simulated imagery can be obtained for single channel systems that employ arbitrary transmit and receive polarizations and for polarimetric systems that employ orthogonal polarizations. Polarimetric imagery can be displayed as four separate monochrome images or as false color amplitude overlay and phase difference images. Postprocessing algorithms are used to simulate channel coupling, perform polarization synthesis, and obtain polarization signatures of isolated scattering centers.

# Statistical Classification of Polarimetric SAR Images

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This paper develops statistical algorithms to detect and classify both targets and clutter in polarimetric SAR imagery, and illustrates their performance using P-3 polarimetric SAR data. Our goal is to develop automatic algorithms to discriminate amongst terrain types and detect small targets imbedded in large clutter areas. Extreme aspect sensitivity of target returns, combined with lack of specific target knowledge, suggests that a random target model is most appropriate for initial target detection. We provide theoretical motivation for a generically mismatched target detector that offers good, but suboptimum, detection probability for a variety of simple targets. Following preliminary target detection, it is appropriate to invoke target models of increasing complexity to discriminate target types.

We assume that polarimetric clutter measurements are realizations of locally stationary zero-mean complex joint-Gaussian random processes. A complex-valued covariance matrix characterizes each terrain type. We obtain sample covariance matrices from representative image patches by simple correlation. We assume further an additive Gaussian target model. At each pixel, data consists of a (sub)set of polarimetric measurements, which may be augmented by polarimetric measurements from neighboring pixels. Based on this foundation, we develop maximum likelihood (ML) decision statistics to be computed and compared for each pixel within a SAR scene. The decision statistics are simple quadratic forms involving the (augmented) data measured at each pixel and the covariance matrices that characterize each decision class.

The ML classifier initially assumes that each class is equally probable at each pixel in the scene. Provided that this scheme yields acceptable classification performance, local averaging of the classification decisions provides a spatially-varying estimate of the *a-priori* probabilities which we use, together with the original statistics, to re-classify the scene. This technique, which converges after a few iterations, reduces the number of mis-classifications without blurring region boundaries or sacrificing high-frequency detail. It is a natural means of exploiting the local homogeneity of clutter regions and a practical implementation of maximum *a-posteriori* (MAP) classification, which insures maximum probability of correct classification and minimum probability of incorrect classification.

We illustrate classification performance on a polarimetric P-3 SAR scene by comparing visually and quantitatively the progression of classification improvement from use of scalar measurements (VV channel), through use of fully polarimetric measurements, to use of a combination of polarimetric and spatial measurements. We also demonstrate the unique capability of polarimetric SAR to discriminate amongst simple scattering mechanisms using a ML classifier based on large SNR and TCR. These results indicate that polarimetric SAR systems are much more capable of reliable target and clutter detection and classification than comparable scalar systems, and that the potential reward for further application of rigorous statistical detection theory to automatic SAR scene classification is great.

# POLARIMETRIC SAR FOR TARGET CHARACTERIZATION - THEORY

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Recent advances in polarimetric radar technology have stimulated research in the use of polarimetric data for target detection, classification and characterization. The ability of a SAR to isolate the return from individual scattering centers combined with a polarimetric measurement capability offers the opportunity to extract a high level of information on target features. Past investigations have suggested applications of polarimetry for target characterization using deterministic formulations; however, few results exist specifically quantifying the performance of these methods.

The objectives of this investigation were to develop a rigorous framework for determining the utility of fine resolution, polarimetric SAR data for target characterization and to provide a representative example of achievable performance. Given an image with a few target pixels, a methodology is formulated which extracts detailed information on target features from the polarimetric data associated with each pixel and gives quantitative bounds on the performance of the algorithm.

The analysis of the polarimetric data associated with each target pixel is devised as a two step process. First the pixel is classified as belonging to one of a set of candidate hypotheses corresponding to target features determined by the application of interest. Once the target feature responsible for the scattering is determined, parameter estimation is applied to the data to deduce characteristics of the target features. The target classification problem is formulated as a multiple bayesian hypothesis testing problem. Specifically, the processor (classifier) is designed for minimizing the probability of incorrect classification. The polarimetric data from a complex pixel is modeled as an eight-dimensional real vector, which is the sum of target scattering data, represented by vector functions of random parameters, and Gaussian receiver noise. The signal models are developed from scattering models which reflect polarimetric characteristics of the hypotheses and parameters of interest. After classification, parameters of interest are estimated using a minimum mean square error estimator. Given this rigorous approach, the performance of the classification and estimation algorithms can be quantified in terms of probability of error of the classifier and RMS error of the estimator, respectively, versus signal-to-noise ratio.

In the accompanying paper, this general framework is applied to the specific application of characterization of target surface geometry and numerical results are provided.

# POLARIMETRIC SAR FOR TARGET CHARACTERIZATION - SURFACE CHARACTERIZATION APPLICATION

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As described in the preceding paper, a general framework for using polarimetric data for target characterization has been established which is based on rigorous statistical detection/estimation theory and provides quantitative bounds on algorithm performance. In this paper the application of the general framework to the characterization of target surface features will be discussed.

Given a fine resolution polarimetric SAR image of a complex target, a few pixels will generally be very bright due to significant scattering mechanisms on the target. This "sparse", nonliteral nature of the SAR imagery makes target characterization extremely difficult. The ability of a SAR to isolate the return from individual scattering centers combined with a polarimetric measurement capability offers the opportunity to extract detailed information on target features responsible for the scattering. Specifically, the polarimetric data from a bright pixel will be first classified as arising from the scattering from either a flat plate (or odd bounce planar structure), a dihedral (or even bounce planar structure), a singly curved plate or a doubly curved plate. Once the local scattering geometry is determined, parameters of the local geometry, such as surface curvatures and/or the orientation of the scatterer, will be estimated. This information can potentially provide higher-level features for use in improving target characterization.

Asymptotic high frequency solutions for the scattering, which reflect the polarimetric signatures of the surface features, are used for the signal models. Only dominant specular scattering mechanisms are considered, and image formation is treated such that the scattering matrix of the pixel is assumed to be the same as that for an isolated scatterer. A first-order correction to physical optics is used to determine the polarimetric scattering properties of the curved surfaces. The level of modeling is comprehensive enough to incorporate the polarimetric properties of the scattering, yet simple enough to provide a clear demonstration of the classification/estimation technique.

The statistical detection/estimation processors were implemented numerically, and simulations were carried out using Monte Carlo techniques. Quantitative measures of the algorithms' performance, namely probability of error of the classifier and RMS error of the estimator, respectively, versus signal-to-noise ratio, will be presented for the geometry classes and parameters mentioned above.

# POLARIMETRIC MATCHED FILTER FOR COHERENT IMAGING

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In this paper we focus on image-contrast optimization between two rough-surface classes. Our approach is based strictly on polarimetric filtering, and therefore, no digital image-processing techniques are employed. The approach is tested on a complete polarimetric synthetic aperture radar (POL-SAR) image of the San Francisco Bay area. The data have been taken with the National Acronautics and Space Administration - Jet Propulsion Laboratory CV-990 L-band POL-SAR system, where eight real numbers (complex elements of a 2 x 2 polarization scattering matrix) are associated with each image pixel. Optimal transmitted polarizations (corresponding to maxima or minima of reflected energy) are found for each image pixel, and the results are analyzed statistically via a set of joint two-dimensional histograms. This is done for both of the rough-surface classes. The image response to the "optimal" incident polarization is then simulated digitally by adjusting the receiver polarization according to the modes of the histograms. The corresponding images are computed and displayed with significant image-contrast improvement.

# THE POLARIMETRIC MATCHED FILTER IN POL-SAR IMAGE INTERPRETATION

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Based upon the three-stage procedure for deriving the set of optimal polarizations in the coherent wave case and the novel method for obtaining the optimal adjustable (coherent) polarization intensity for the partially coherent wave case, the novel concept of the polarimetric matched filter in POL-SAR image analysis is presented. Although extensive use is made of probabilistic methods of determining the most likely optimal polarization states, including co/cross-polarization maxima and minima, our PMIF does not implement digital image enhancement methods ("computer-cosmetics"), but only polarimetric wave information contained within the 2 x 2 scattering matrices on a pixel-by-pixel basis.

# Polarization Contrast Enhancement

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In conventional imaging radars operating with a single fixed-polarization antenna for both transmission and reception of radio frequency signal, the scattered wave, a vector quantity, is measured as a scalar quantity. The polarization measurement provides a vector description of the scattered wave. This extra knowledge can provide further insight in the scattering mechanism, help discriminate between targets or ehance particular features.

This paper emphasizes how polarization can be used to ehance contrast between different types of target. The procedure, half analytical and half numerical is general and can be applied for a bistatic case to any arbitrary pair of targets. Because it is based on the Stokes matrix/ Stokes vector representation, the targets of interest can be extended targets. Examples, relying on the JPL full polarimetric L-band radar data include contrast enhancement between urban and natural targets, between urban and ocean targets. It is shown also that the same procedure can be used to maximize the signal to noise ratio.

The research described in this abstract was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

# A POLARIMETRIC MODEL FOR MULTI-PATH IMAGING/IDENTIFICATION ANALYSIS USING POLY-STATIC (BI-STATIC PLUS MONO-STATIC) SCATTERING MATRIX DATA

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## ABSTRACT

The objective of this investigation is to develop a model for target discrimination algorithms in a multi-path, broadband, multi-static environment using the complete broadband multi-static scattering matrix target phenomenology.

Electromagnetic scattering from a complex object, at high frequencies, is dominated by certain specular components. The location of these specular points on the complex object are known as the scattering centers. Generation of these scattering centers is dependent on the geometry of the object and its surroundings with respect to the aspect directions of the transmitters and the receivers. It is shown that the knowledge of the locations, and the local geometrices of these scattering centers are useful in developing multi-path target identification/discrimination algorithms.

In the current work, the multi-path returns are modeled as "image scattering centers". Since these are not actual scattering centers, the bistatic scattering matrix will show behaviour that is different from those of the physical scattering centers. Our approach is to analyze in detail the matrix properties for isolating the primary target scattering center signatures from multi-path generated image signatures.

## Wednesday PM

Joint AP-S, URSI-B Session 60

**Small Antenna Analysis**

*Chairs*: R. H. MacPhie, University of Waterloo; C. E. Baum, Air Force Weapons Lab

*Room*: San Martin *Time*: 1:15–4:20

| | | |
|---|---|---|
| 1:20 | **Optimum Lossy Matching Networks for Resonant Antennas**<br>F. J. Witt,* AT&T Bell Laboratories | AP-S |
| 1:40 | **Variational Analysis for Gain Enhancement and Input Characteristics of Dielectric Loaded Antennas**<br>Y. Sugio,* T. Makimoto, Setsunan University, T. Tsugawa, Osaka Institute of Technology | AP-S |
| 2:00 | **Experimental Study of Gain Enhancement of Dielectric Loaded Antennas with a Ground Plane**<br>T. Tsugawa,* Osaka Institute of Technology, Y. Sugio, T. Makimoto, Setsunan University | AP-S |
| 2:20 | **A Model for the Scattering Current Distribution on Bent, Lossy, Loaded Thin Wires**<br>J. A. Berrie,* L. W. Henderson, Ohio State University | AP-S |
| 2:40 | **Coffee Break** | |
| 3:00 | **Radiation and Impedance Characteristics of a Thin-Wire Transmission Line-Dipole System**<br>R. H. MacPhie,* University of Waterloo | AP-S |
| 3:20 | **On the Thin Toroidal and Elliptical Antennas**<br>C. Zuffada,* F. C. Yang, I. Wong, Kaman Science Corp., C. E. Baum, W. D. Prather, Air Force Weapons Lab | AP-S |
| 3:40 | **A Unified Approach to Antenna Analysis**<br>L. N. Medgyesi-Mitschang,* J. M. Putnam, McDonnell-Douglas | 258 |
| 4:00 | **Undersized Long Backfire Antennas**<br>H. D. Hristov,* G. S. Kirov, J. R. Urumov, Bulgarian Ministry of Education | AP-S |

# A Unified Approach to Antenna Analysis

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Cavity-backed and off-surface antennas have been analyzed by a variety of analytical and numerical methods (W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, 1871). In this investigation we describe a general, unified approach to the study of a variety of antennas, based on surface integral equation formulations. These formulations are solved by the method of moments. To provide maximum flexibility, the solutions use both surface and line representations for the unknowns in the integral equations. Special consideration is given to the transitions and boundaries between these representations. While the theoretical formulation is developed for arbitrarily shaped cavity-backed and off-surface antennas, the specific numerical implementation is developed for radiators with circular cavities and slots. However, part of the radiating structure can be arbitrarily configured. The effects of antenna windows and cavity loadings are incorporated in the analysis. Representative calculations will be given for annular slots with arbitrary probe-excitation, cavity-backed crossed dipolar and spiral antennas, and a variety of off-surface radiators. The radiation characteristics of these configurations will be described and compared to available classical results.

## Wednesday PM

### Joint AP-S, URSI-B Session 61
### Microstrip Antennas IV

*Chairs*: C. H. Chan, U. of Illinois at Urbana; N. G. Alexopoulos, UCLA
*Room*: San Simeon *Time*: 1:15–4:20

# RADIATION FROM A RECTANGULAR LOOP PRINTED ON A PLANAR MICROSTRIP SUBSTRATE

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Lexington, KY 40506-0046

The advent of high speed computers in recent years has increased the importance of developing accurate models to predict the radiated emission from printed circuit traces. In this paper, we model a typical trace as a rectangular loop printed on a grounded dielectric substrate, with the excitation being provided by a delta-gap voltage generator situated on one side of the loop. The current on the loop will be computed by the method of moments using the full-wave microstrip Green's functions [J. R. Mosig and F. E. Gardiol, Advances in Electronics and Electron Physics, vol. 59, 1982]. The far-field radiated by the loop will be determined from the currents. We employ the so-called mixed potential integral equation formulation [J. R. Mosig and F. E. Gardiol, op cit.], commonly used for microstrip antennas of arbitrary shape, to compute the loop current in the frequency range of 30 MHz-1 GHz, in which FCC monitors the radiated emission of electronic equipment. In this frequency range, the dyadic vector potential and the Lorentz-gauge related scalar potential can be simplified by small-argument approximations to a form suitable for their efficient implementation as Green's functions in the integral equations. The surface of the trace is divided into rectangular patches, on which we erect "rooftop" basis functions for the orthogonal trace currents. Although the dominant component of the loop current away from the bends flows longitudinally, the transverse component becomes appreciable at the bends. The testing of the integral equation by two-dimensional pulses for zero tangential electric field on the conductors results in a diagonally-strong matrix, which can be inverted efficiently to yield the current expansion coefficients. The integrals involved in the testing procedure can be evaluated easily since the Green's functions have been reduced to simple forms.

The rectangular loop configuration contains a gap generator on one (shorter) side and a gap discontinuity on the opposite side, where passive components such as monolithic resistors can be mounted. Sample results of computed current distribution and the radiated field will be presented for an open circuit and a short circuit "loading" of the loop. For a thin substrate, at 100 MHz, the radiated field compares well with the field produced by an electrically small rectangular loop above a ground plane in free space. Computation of the input impedance of the loop between 30 MHz-1GHz reveals good agreement between solutions obtained by employing (a) low-frequency approximations, (b) exact Sommerfeld kernels, for the Green's functions. The usage of reduced kernel in the integral equations is thereby justified.

# ANALYSIS OF PROXIMITY-COUPLED MICROSTRIP DIPOLES

**W.I. George* and J.H. Cloete**
**Department of Electrical and Electronic Engineering**
**University of Stellenbosch**
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**South Africa**

The use of two dielectric layers in microstrip dipole arrays improves radiation efficiency, bandwidth, and spurious radiation (Oltman and Huebner, IEEE Trans., Vol. AP-29, No. 1, pp. 151-157, Jan. 1981). The topic has been the subject of many papers, ranging from antenna design using empirical data to numerical analysis of array components.

This paper will compare theoretical results for proximity-coupled printed dipoles, obtained by numerical analysis, with accurately measured data.

The algorithm for numerical analysis is based on the solution, by the moment-method, of the mixed potential integral equation in the spatial domain (Mosig and Gardiol, IEE Proc., Vol. 130, Pt.H, No.2, pp. 175-182, March 1983). Details on the numerical and experimental techniques will be given, as well as observations and recommendations concerning the feed-radiator topology.

The complete analysis of even small arrays is normally beyond the scope of the moment-method, due to the electromagnetic size of the problem. A technique is being sought which will decrease the size of the problem, without compromising the accuracy of the relevant results. This should pave the way to an efficient iterative design process for small arrays.

# RIGOROUS ANALYSIS OF COAXIALLY FED MICROSTRIP ANTENNAS OF ARBITRARY SHAPE—THE MIXED-POTENTIAL INTEGRAL EQUATION APPROACH

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A microstrip antenna of arbitrary shape driven by a coaxial cable with the inner conductor soldered to the patch is studied using a mixed-potential electric field integral equation (MPIE) approach (K. A. Michalski, *AEU*, 39, 317-322, 1985; J. R. Mosig, *IEEE Trans.*, MTT-36, 314-323, 1988). The MPIE is preferable to several other possible variants of the electric field integral equation (EFIE), because it only requires potential forms of the Green's functions, which are less singular and converge faster than the field forms needed in other EFIEs. Another important advantage of the MPIE is its conformity with an existing well-established moment method procedure, originally developed for surfaces of arbitrary shape in free space (A. W. Glisson and D. R. Wilton, *IEEE Trans.*, AP-28, 593-603, 1980; S. M. Rao, et al. ibid., AP-30, 409-418, 1982; S. U. Hwu and D. R. Wilton, Technical Report 87-17, Univ. of Houston, 1987).

In the numerical procedure, a triangle-patch model (S. M. Rao, et al., op. cit.; P. Pichon, et al., *Electron Lett.*, 24, 1214-1215, 1988) is used to approximate the arbtrarily-shaped microstrip and a magnetic current frill (R. C. Hall, et al., *JINA'88 Digest*, 282-285, 1988) is employed to model the coaxial aperture.

Sample numerical results are presented for several cases of interest and are compared with results obtained by other researchers and with experimental data.

# ANALYSIS OF A STACKED PATCH ANTENNA FED BY AN APERTURE COUPLED MICROSTRIP LINE

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*Urbana, Illinois 61801*

The importance of low-cost printed circuit antennas has brought about a continued effort to improve their bandwidth performance at the expense of increased element thickness and multiple layers. This paper presents the analysis of a stacked patch antenna fed by an aperture coupled microstrip line. The boundary value problem for the antenna is analyzed in terms of the integral equations for the equivalent electric currents on the patches and microstrip line and the equivalent magnetic currents representing the aperture.

The dyadic Green functions for the electromagnetic fields due to sources in a multilayered medium are formulated in the spectral domain. This approach relates the dyadic Green functions to the more familiar scalar Green functions for ordinary transmission lines and allows the treatment of an arbitrary number of layers with a minimal increase in effort.

The integral equations are discretized by Galerkin's method and solved on the computer. Techniques designed to enhance the convergence of the spectral domain integrals are described. Important antenna parameters such as the input reflection coefficient are extracted from the solution of the boundary value problem. Thus, problems associated with the proper definition of antenna impedance (which is nonunique) are avoided. Automated measurements of the antenna reflection coefficient in the microstrip waveguide are made via the Thru-Reflect-Line and Line-Reflect-Line calibration techniques and compared with the theory.

# ELECTRIC DYADIC GREEN'S FUNCTION FOR LAYERED MEDIA WITH DIELECTRIC/MAGNETIC CONTRAST

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In the study of layered environments in electronic and optical integrated circuits, integral-operator formulations are increasingly exploited. Construction of such integral operators requires an appropriate Green's function. In this paper, we present the development of a general electric dyadic Green's function for layered structures with magnetic as well as dielectric contrast. The general properties of that Green's dyad are studied.

In the tri-layered environment, a film of thickness t with constitutive parameters $(\epsilon_f,\mu_f)$ is deposited over a substrate $(y<-t)$ described by $(\epsilon_s,\mu_s)$. The region $(y>0)$ is the cover with parameters $(\epsilon_c,\mu_c)$. The arbitrarily directed electric current $\vec{J}$ is immersed in the cover or film region. By Sommerfeld's classical method, a Hertzian-potential dyadic Green's function is found whih satisfies general boundary conditions. The electric Green's dyad is expressed in terms of its Hertzian counterpart as

$$\bar{\bar{G}}^e(\vec{r}|\vec{r}\,') = (k_c^2 + \nabla\nabla\cdot)\bar{\bar{G}}(\vec{r}|\vec{r}\,') + \bar{\bar{L}}\delta(\vec{r}-\vec{r}\,')$$

$$\bar{\bar{G}}(\vec{r}|\vec{r}\,') = \bar{\bar{I}}G^p(\vec{r}|\vec{r}\,') + \bar{\bar{G}}^r(\vec{r},\vec{r}\,')$$

where $\bar{\bar{G}}$ is the Hertzian-potential Green's dyad, $\bar{\bar{L}}$ is a depolarizing dyad, $G^p$ is the principal Green's function, and $\bar{\bar{G}}^r$ is a reflected Green's dyad. The scalar components of the reflected dyad are obtained in 2-D spectral integral representations. The dyadic Green's functions are reducible in certain special cases, such as that of a conducting substrate layer.

The source-point singularity of the electric Green's dyad is studied, and depolarizing dyad $\bar{\bar{L}}$ is identified. It is demonstrated that the electric Green's dyad for layered media of general contrast is reciprocal. Pole singularities of implicated reflection coefficients lead to general discrete surface-wave-mode eigenvalue equations.

The electric dyadic Green's function obtained is applied to the microstrip transmission-line structure with magnetic (ferrite) film and conductor substrate. The EFIE's based upon that Green's function are solved by the MoM and by a perturbation approximation. Numerical results are obtained and compared with those of a structure having a purely dielectric surround.

# TIME DOMAIN FINITE DIFFERENCE ANALYSIS OF ELECTRICALLY THIN AND THICK SUBSTRATE MICROSTRIP ANTENNAS

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In the last ten years, extensive research has been carried out on microstrip antennas. However, most of the previous work, theoretically and experimentally were for antennas on thin substrates. Since thick substrate antennas enjoy broader bandwidth and higher operating frequencies, it is a worthwhile effort to study their performances.

In this research, a pulse is sent out along the feeding microstrip line. Time domain finite difference method is used to simulate the pulse propagation along the microstrip line, and the pulse reflection from, and resonance under the microstrip patch (one can actually see the reflections from the end edge and side edge of the microstrip antenna). Fourier transform is used to obtain frequency results from time domain data. Radiation patterns, resonant frequencies and input impedences of different antennas are computed. The results are in good agreements with the existing experiments or empirical formulas. It should be noted that, in this method, (1) only one time domain simulation is needed to get results of all frequencies of interest; (2) the thick substrate microstrip antennas require less memory and less computation time, because of less oscillation, and this feature just compensates previous researches; (3) it can be easily used to calculate mutual couplings of microstrip antenna elements. Finally, this method is self-consistent, which does not need any empirical information (many other methods do), to get a good result.

# ANALYSIS OF BOW-TIE MICROSTRIP PATCH ANTENNA

by

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Associate Professor
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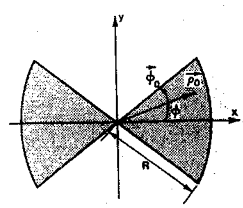
Bow-Tie microstrip conducting patch as a radiating element may have better performance over the ordinary strip dipole element in terms of available bandwidth as it refers to the input impedance and radiation pattern as a single element or in the array environment. Therefore this radiating structure needs investigation.

As a first step in this direction, we need to represent the impressed current on the Bow-Tie patch so that a rigorous field analysis is possible. The patch element is shown below. We assume that the two extremities of the Bow-Tie patch are circular arcs instead of chords.

The current on the patch element may be represented in terms of TE and TM vector mode functions of a sectoral circular cylindrical waveguide with radial variations as $J_\nu(\chi_{\nu p} r)$ and $J'_\nu(\chi_{\nu p} r)$ for TM and TE modes respectively where $\nu = m\pi/\phi$. The dominant mode for the bow-tie path is the $TM_{01}$ mode.

Experimental work carried out on a single element as well as an array of 9 elements with the central element fed by a coaxial line with a broadband balun will be presented and its merits over the strip dipole will be described.



## Thursday AM

URSI-B Session 62

## Numerical Methods: Time Domain Analysis and Applications

*Chairs*: K. S. Yee, Lockheed; S. L. Ray, LLNL

*Room*: Oak *Time*: 8:15–11:40

# APPLICATION OF A TIME-DOMAIN, FINITE-VALUE MAXWELL'S EQUATIONS SOLVER FOR INLETS AND CAVITIES

Vijaya Shankar, William F. Hall, Alireza Mohammadian, and Kimberly Peppi
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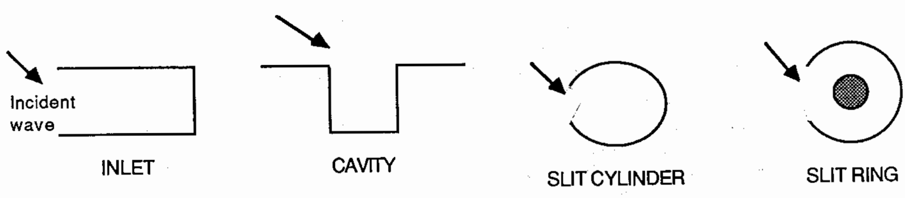
The differential form of the time-domain Maxwell's equations are first cast in a conservation form and then solved using a finite-volume discretization procedure derived from proven Computational Fluid Dynamics (CFD) methods applied to linear/nonlinear gasdynamics equations. The formulation accounts for any variations in the material properties (time, space, and frequency dependent), and can handle thin resistive sheets and lossy coatings by positioning them at finite-volume cell boundaries. The time-domain approach handles both continuous wave (single frequency) and pulse (broadband frequency) incident excitation. Arbitrary shaped objects are modeled by using a body-fitted coordinate transformation. For treatment of complex internal/external structures with many material layers, a multizone framework with ability to handle any type of zonal boundary conditions (perfectly conducting, flux through, zero flux, periodic, nonreflecting outer boundary, resistive card, and lossy coatings, etc.) is implemented. The finite-volume procedure employs an explicit Lax-Wendroff upwind scheme to integrate Maxwell's equations in time. The time domain results are converted to the frequency domain using FFTs, and then a Green's function based near field-to-far field transformation is employed to obtain the bistatic radar cross section.

The method is applied to different inlet and cavity geometries of the type shown below and the results are compared with other existing methods.



# Time–Domain Analysis of Wave–Guide Fed Antennas*

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Electromagnetic time–domain analysis of antennas can yield many results not available in the frequency–domain (*eg.* break–down effects). Especially for pulsed applications where such standard frequency–domain concepts as the far–field boundary are difficult to define, time–domain modeling suggests itself. This work attempts to establish the feasability of time–domain modeling of antennas by creating a realistic source and using it to drive some simple radiators.

We have employed the Finite–Difference Time–Domain (FDTD) method for this purose. A numerical wave–guide source is developed and shown to reproduce the exact time–domain solution for the guide. This source is then used to drive several simple antennas such as horns and reflectors. Since complete field information in space and time is known, a number of important antenna parameters can be derived. We will present results, in both the time and frequency domains, for the antenna impedance, currents on antenna surfaces, and free–space radiation.

Work is in progess by Ziolkowski and Barth at LLNL to develop time–domain near to far–field transforms that would allow the prediction of patterns from such systems.

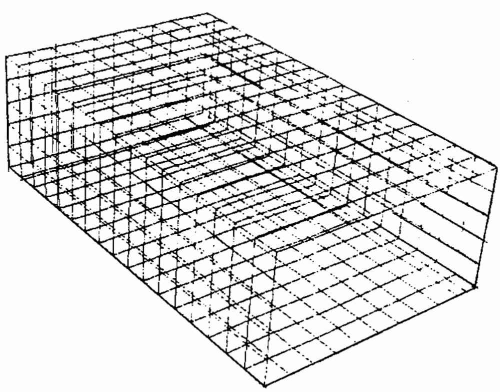

Figure 1 Open–ended wave–guide mesh

* Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

# HIGH POWER MICROWAVE ANTENNA SYSTEMS TIME ANALYSIS †

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Our objective is to model the performance of high power microwave antenna systems in both the frequency and time domains. Our approach is to use TSAR, a three-dimensional finite difference time domain (FDTD) code, to model the antenna structure and the surrounding near field environment. We then use FAR, a general purpose near-to-far field post-processor, to obtain the far field values.

The FAR code uses the equivalence principle. Specifically, the code utilizes the tangential electric and magnetic fields at a specified surface of the FDTD computational volume and calculates the resulting far fields from the equivalent magnetic and electric sources. In this process the sources of errors are sampling density, the length of the excitation pulse, the total time history record length, the time step size, and the size of the FDTD volume. The TSAR-FAR approach will be illustrated with a pulse driven array of dipole elements. The far-field time histories and the resulting frequency domain antenna patterns will be presented. The sizes of the various errors associated with this approach will be discussed in detail; its efficacy will be contrasted with conventional methods.

With an increased interest in high power microwave (HPM) sources there has become an associated need to develop antenna systems that can launch these high power fields. However, because these sources are generally pulsed, conventional CW antenna design considerations are not completely adequate and augmented standards on the system performance must be considered. Additionally, potential nonlinear effects such as the breakdown of gases near the antenna must now be incorporated in the design of these launch systems. These breakdown regions may have deleterious affects on the performance of the antenna system, most notably, its pattern. The application of the combined TSAR-FAR algorithms to modeling the overall performance of a HPM antenna system when breakdown regions occur near the antenna is being studied and will also be discussed.

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† This work was performed by the Lawrence Livermore National Laboratory under the auspices of the U. S. Department of Energy under contract No. W-7405-ENG-48.

# PDE SOLUTION OF ELECTROMAGNETIC SCATTERING BY A BODY OF REVOLUTION USING AN ASYMPTOTIC BOUNDARY CONDITION ON A CYLINDRICAL OUTER BOUNDARY

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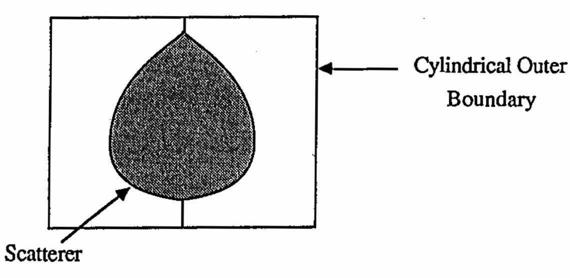
In two recent papers (R. Gordon & R. Mittra, 1988 URSI Digest; R. Mittra & R. Gordon, IEEE T-AP, to appear) we have presented a direct solution of the partial differential equations arising in the problem of electromagnetic scattering by a p.e.c. body of revolution (BOR). In order to reduce the number of unknowns we take advantage of the fact that, for a BOR scatterer, it is possible to formulate the problem in terms of two scalar potentials rather than all six components of the electric and magnetic fields. The potentials we use are modified versions of the coupled azimuthal potentials (CAPs) introduced by Morgan and Mei for the inhomogeneous BOR problem. These potentials satisfy a pair of coupled partial differential equations which must be solved simultaneously by enforcing the numerical approximations of these equations at each point in the mesh surrounding the scatterer. An artificial outer boundary must be used to truncate the mesh. In this paper we show how a cylindrical outer boundary, which is well-suited for long, slender bodies, can be used for this problem. For such scatterers, the use of a cylindrical rather than a spherical outer boundary reduces the number of unknowns needed. The Bayliss-Turkel (B-T) type of absorbing boundary condition cannot be conveniently derived for the potentials used in this problem. Instead, an asymptotic boundary condition obtained from the Wilcox's expansion for the scattered field in terms of powers of $r^{-1}$ is used to truncate the mesh at the outer boundary. This boundary condition is even more convenient to implement than the B-T operator, and is readily generalizable to vector fields.

An important feature of this method is that it enables one to derive a good approximate solution to the scattering problem in just one step. In contrast, the Unimoment method involves a two-step procedure, which not only requires repeated solution of the p.d.e. but the inversion of a full matrix as well. Numerical results are presented for some representative problems and are compared with analytical solutions as well as with those obtained from a Method of Moments approach. The comparisons are found to be quite favorable.



# ELECTROMAGNETIC SCATTERING FROM A PARTIALLY COATED CONDUCTING CYLINDER OF ARBITRARY CROSS SECTION USING MOM AND FD-TD

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It is well known that the scattered field from a conducting body can be modified significantly if the body is coated with a layer of lossy magnetic material . In many applications , partial coating is preferred over complete coating if the scattering reduction performance of the former is comparable with that of the latter .

An infinitely long conducting cylinder of arbitrary cross section coated with strips of lossy magnetic materials and illuminated by a normally incident plane wave is considered . Two different approaches have been used to solve this problem . First , the Maxwell's time-dependent curl equations are solved directly by the finite-difference time-domain (FD-TD) method. Recently developed techniques are used to treat the curvature of the conducting surface and the thin coating on it . Second , three coupled surface integral equations are derived in terms of the equivalent electric and magnetic surface currents on the coating and the conducting surface . The integral equations are solved numerically by the moment method .

The scattered far fields are then determined on the basis of either the tangential E and H fields on a virtual surface in the FD-TD method or the equivalent surface currents in the moment method. The results of these two methods are compared and some useful information concerning the modification of the scattering characteristics of metallic bodies by impedance coating is obtained .

# EFFECTS OF AN IMPEDANCE SHEET ON THE SCATTERING AND RECEIVING CHARACTERISTICS OF A CAVITY-BACKED ANTENNA

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The finite difference time domain method is employed to solve the following problems: (1) the scattering of a plane wave by a thin impedance sheet, (2) the scattering and receiving characteristics of a wire antenna, and (3) the EM field excited by an incident wave in an open cavity on a ground plane.

The techniques used in solving these problems are combined to analyze the scattering and receiving characteristics of a cavity-backed antenna which is covered by an impedance sheet at the antenna aperture. The scattered and received powers by the antenna are determined as functions of the electric properties of the impedance sheet.

To apply the finite difference time domain method to this problem, a modified radiation boundary condition for an infinite ground plane was developed. Also the Faraday's law in integral form was used to determine the scattering of EM wave by a thin impedance sheet.

# FD-TD ANALYSIS OF ELECTROMAGNETIC WAVE RADIATION INVOLVING HORN ANTENNAS

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This paper considers computational modeling of the patterns of electromagnetic wave radiation in systems involving horn antennas, in both two and three dimensions. Using the Finite-Difference Time-Domain (FD-TD) method, simple horn antennas are modeled and the antenna patterns are shown to correspond to experimental and analytic results. The antennas are modeled in two and three dimensions, and the three-dimensional model includes the model of a coaxial feed.

In two dimensions, FD-TD is used to model a horn feeding a parabolic antenna, and again the results are shown to agree with results in the literature. Further extensions of this modeling scheme are also discussed. One interesting application is the direct FD-TD modeling of a compact range. Here a system consisting of a horn antenna feeding an electrically-large ( ~100 $\lambda_0$ ) shaped reflector is modeled in a single 2-D FD-TD grid run on the Cray-2. Initial FD-TD computer results for contour maps of the field magnitude and phase versus spatial position in the model of the compact range are presented.

# FIELD BEHAVIOR NEAR THE VERTEX OF AN INFINITE DIELECTRIC WEDGE CALCULATED USING FD-TD

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There is apparently no analytical solution for the electromagnetic field behavior at and near the vertex of an infinite, lossless, two-dimensional dielectric wedge. This paper provides detailed results for this field behavior. The results are obtained using a purely computational approach: the finite-difference time-domain (FD-TD) solution of Maxwell's curl equations.

Our methodology exploits the time-domain formulation of FD-TD to effectively simulate an infinite dielectric wedge in a finite computational domain. Time-gating is used for a wedge of sufficient size to permit the FD-TD computed fields near the vertex to reach the sinusoidal steady state well before reflections from the back of the wedge reach the vertex. Extensive convergence studies for wedges of varying sizes have conclusively demonstrated that this time-gating procedure does provide a meaningful result for the case of the infinite wedge. Further, extensive studies with respect to spatial resolution of the FD-TD grid have demonstrated convergence of the near vertex fields to within 1% or better.

In order to validate the FD-TD code, we first compared its predictions for surface electric currents induced on a metal strip with the exact solution. We next compared the FD-TD computed electric and magnetic surface currents induced on a square dielectric cylinder with method of moments (MOM) results (both TM and TE polarizations). In all of the test cases, there is an excellent agreement between the FD-TD and the benchmark results.

Our study of the infinite dielectric wedge consisted of examining four cases of wedge and incident field configurations. The first two cases consisted of a TE-polarized plane wave illuminating a 90° wedge along its bisecting angle, and a 45° wedge at grazing incidence to one of its sides. The last two cases consisted of a TM-polarized plane wave illuminating a 90° wedge first along its bisecting angle, and then broadside to one face. We find that FD-TD predicts near-vertex fields having slightly different growth or decay rates than those predicted by existing analytical theory.

# ONE-DIMENSIONAL FINITE DIFFERENCE TIME DOMAIN TECHNIQUE APPLIED TO DETERMINING REFLECTION FROM THE PLASMA LAYER SURROUNDING AN AEROBRAKING VEHICLE

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and

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In the mid 1990's NASA will conduct the Aeroassist Flight Experiment (AFE) which will investigate the flight regime encountered by a spacecraft that makes use of atmospheric assisted braking (aerobraking). The AFE spacecraft will carry a number of flight data instruments, one of which is the Microwave Reflectometer Ionization Sensor (MRIS). The MRIS will use the reflective properties of high temperature plasma to determine the levels of electron density in the forebody shock layer and their distance from the spacecraft.

An electromagnetic wave of a particular frequency propagated into a plasma with varying electron density will encounter a sharp reflecting boundary at the point where the electron density in the plasma reaches the critical electron density $N_{ecr}$ = $1.2405 \times 10^{-8} \times f^2$, where $N_{ecr}$ is given in electrons/cm$^3$ and f is the frequency in Hz. The MRIS will detect specific electron densities by radiating corresponding frequencies and measuring the reflected signal. By measuring the phase delay between the transmitted and received signals (FM-CW radar), the distance to the critical electron density layer can be determined.

In order to interpret the measured data the propagation of the radiated signal through the plasma must be analyzed. This analysis is challenging since the propagation characteristics of the plasma depend upon the plasma's three-dimensional electron density distribution relative to the spacecraft and the MRIS antennas. One approach being considered is to apply a new Finite Difference Time Domain (FDTD) formulation which has the capability of including the effects of the highly dispersive plasma on propagation. The advantage of this approach is that it is more readily extended to arbitrary two and three dimensional geometries than frequency domain solutions. Initial tests for a one-dimensional problem show very promising results.

## Thursday AM

Joint AP-S, URSI-B Session 63

### Numerical Methods: Coated Bodies

*Chairs*: R. F. Harrington, Syracuse University; J. D'Angelo, General Electric

*Room*: Fir *Time*: 8:15–11:40

# MODELING OF RADIATION BY NONUNIFORMLY COATED ANTENNAS

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The use of the approximate impedance boundary condition (IBC) in calculations of electromagnetic scattering by lossy materials is well established. Recent investigations have focused use of the IBC to model scattering from uniformly and nonuniformly coated perfectly conducting bodies (P. L. Huddleston and D.-S. Wang, URSI Radio Science Mtgs., Paper UB02-7, Blacksburg, VA, 1987; Paper B12-7, Syracuse, NY, 1988). When the approximation is valid, reliable results are obtained in a cost-effective manner.

An approach to using the IBC to model radiation by uniformly coated antennas was developed recently (D.-S. Wang and P. L. Huddleston, URSI Radio Science Mtg., Paper B74-8, Syracuse, NY, 1988). It was shown how to choose the surface impedance, where to locate a pseudo-aperture, and what excitation Ansatz to apply in the pseudo-aperture region to best represent the original problem.

In this paper we generalize this approach to the case of radiation by nonuniformly coated antennas. We consider three classes of nonuniformities: (1) an inhomogeneous layer comprising multiple uniform layers, (2) a homogeneous layer of nonconstant thickness, and (3) an inhomogeneous layer comprising multiple uniform subregions. We explore the limits and range of validity of this approximate representation for the foregoing classes of problems.

# APPLICATION OF HIGHER ORDER BOUNDARY CONDITIONS IN SCATTERING BY A MATERIAL DISCONTINUITY IN A METAL-BACKED LAYER

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The scattering properties of discontinuities in grounded or ungrounded thin material layers have often been studied by imposing impedance-type (first-order) boundary conditions at the surface of the material. Unfortunately, many of the solutions so obtained are mediocre at best in providing an accurate representation of the physical problem of interest. Hence, it is pertinent to examine the benefit incurred by imposing higher-order boundary conditions in modeling the scattering properties of the above configurations.

Higher-order boundary conditions for a material-coated ground plane are derived by expanding the exact plane-wave reflection coefficient in a suitable manner. These are subsequently applied to the problem of the scattering by a material discontinuity in a coated ground plane. The problem is formulated by expressing the scattered field in terms of an angular spectrum of plane waves and subsequently applying the boundary conditions along with further considerations to determine the unknown spectra. The resulting integral for the scattered field is evaluated asymptotically to obtain a uniform solution. Numerical results are presented and compared against those obtained through alternative methods.

**ELECTROMAGNETIC SCATTERING BY ARBITRARILY SHAPED BODIES WITH IMPEDANCE BOUNDARY CONDITIONS**

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University of Mississippi
University, MS 38677

Many electromagnetic scattering problems of interest involve imperfectly conducting bodies. One approach to modeling specific classes of such bodies in electromagnetic scattering problems is to impose the impedance (or Leontovich) boundary condition. This approximate boundary condition relates the tangential electric and magnetic fields at the surface of the imperfectly conducting body via an impedance relationship. When the approximation is valid, the numerical model for the physical problem is significantly simplified.

The impedance boundary condition has been investigated by many authors and for various geometrical configurations. In this work the impedance boundary condition formulation is implemented for the solution of electromagnetic scattering problems involving bodies of arbitrary shape. The electric field integral equation triangular patch model (Rao, Wilton, & Glisson, IEEE T-AP, 30, 409-418, 1982) serves as the basis for this development. Within each triangular patch the impedance boundary condition is assumed to vary linearly. Between faces the impedance condition may be discontinuous.

Numerical results have been obtained for monostatic and bistatic scattering by spherical bodies having impedance boundary conditions and the results have been compared with exact solutions (Mie series) where possible. Cases involving both purely real and purely imaginary surface impedances have been considered. Good agreement between numerical results and exact solutions have been obtained except near the spherical cavity resonance frequencies, where the electric field integral equation formulation is known to fail. Data is also presented to illustrate typical convergence rates for the numerical solution.

# COMPUTATION OF FIELD SCATTERING AT PARALLEL CONDUCTORS BY THE MULTIPLE MULTIPOLE (MMP) METHOD

*Dipl.Phys. D.Hoyer, Prof. Dr. H.Singer
Technical University Hamburg-Harburg, F.R. of Germany

A plausible extension of the original MMP-Method consists of building up several sets of multipoles which are called 'segments'. This procedure reduces the number of field sources at low frequencies and avoids the problem of choosing numerically good places for single multipoles. The developed computer code applies for antennas consisting of thick wire structures or any parallel arrangement where the diameters of the wires are not negligible with respect to their distances.

The use of subsections for the discretisation of conductors involves the use of basis functions, which must be solutions of the wave equation. These basis functions result from the separation of variables of the chosen coordinate system. A simple choice would be a cartesian coordinate system. But here the problem arises, that the solutions are not countable. In sherical coordinates solutions are countable and the convergence of a single multipole (SMP) expansion of the scattered field can be usable, if the problem has nearly rotational symmetry.

A better approximation for other geometries is an expansion in multiple spherical coordinate systems with different origins. The place of a multipole is identical with the origin of a spherical coordinate system. For the expansion only a few terms of low orders are needed at a specific origin, if the best positions of the poles are found. This placement is critical with respect to the distance of two neighbored multipoles, because terms of these two multipole expansions may become linear dependent.

A rule of thumb says that the distance of two poles must be greater than the distance of each pole to its next contour point. Therefore the distances of two poles at the center of a cylindrical conductor must be greater than the radius of the conductor. Large distances between two poles result in great approximation errors. So the poles must be set very precisely ( Ch. Hafner, Numerical computation of electromagnetic fields, Springer-Verlag New York ... 1987, p 171 - 198 ). A solution for this problem is to use sets of multipoles with the same coefficients. The distance of multipoles which are members of identical sets may be much smaller. They can be infinitesimally small. Thus the definition of a constant multipole line density along one segment can be made. This restricts the application of the computer code to problems where the length of the individual multipole line is larger than its radius. Suggesting a wavelength-dependent choice of the length of segments, at low frequencies a great reduction of necessary multipole expansions occurs.

## Thursday AM

URSI-F Special Session 66

**Waves in Non-Uniform Layered Media**

*Chairs*: J. R. Wait, University of Arizona; E. Bahar, University of Nebraska

*Room*: Monterey *Time*: 8:15–10:00

# VLF SURFACE IMPEDANCE MAPPING IN NON–UNIFORM COAL SEAMS

David V. Thiel, Division of Science and Technology,
Griffith University, Brisbane, Australia, 4111.

Since 1986, a number of detailed VLF surface impedance surveys have been conducted at a number of open cut coal mines on the North Eastern coast of Australia. The major objective of this work was to assess the utility of such measurements in the location of discontinuities in coal seams including faulting, hard rock intrusions, rock nodules in the coal seam and conductive dykes. Using a surface impedance meter developed in–house, very rapid changes in the surface impedance was evident at the boundaries of these lateral changes. Very accurate mapping of such structures over distances of less than several metres was achieved.

The surface impedance meter uses an unbalanced insulated wire electric field antenna [Thiel,D.V. 1978. Electronics Letts., 14 (25), p 804–805] rather than the more conventional staked balanced antenna. This has the advantages of an improved lateral resolution achievable, an increase in the speed of measurement and improved sensitivity to surface impedance changes [Wu.X.W., & Thiel,D.V., 1989. Trans GRS–27 (1)].

The performance of the system can be explained in terms of the fringing fields found in the vicinity of contact zones of differing conductivity; a model supported by measurements over man–made structures (e.g. underground pipelines), crevasses in ice fields and other lateral discontinuities. The theoretical curves from these models can be matched to some of the results obtained in coal seam investigations and so can be used for coal seam dislocation predictions prior to extensive drilling of the seam and mining.

# AN INVESTIGATION OF THE WAVENUMBER FILTER PROCEDURE USING SYNTHETIC TWO-DIMENSIONAL MAGNETOTELLURIC DATA

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The errors introduced into the interpretation of the magnetotelluric (MT) impedance by lateral heterogeneities in the electrical structure of the Earth can be substantially reduced if the MT impedance is wavenumber filtered prior to interpretation (R.C. Robertson, J. Geophys. Res. 94, 1989). The wavenumber filter process consists of low pass filtering the MT impedance in plane wave space with respect to the wavenumber that corresponds to the axis oriented parallel to the line of the MT survey. The wavenumber filtered MT impedance is a function of the shape of the filter, the filter cutoff wavenumber, and the length of the MT survey line. Ideally, the wavenumber filter procedure requires a survey line of infinite length, and an a priori knowledge of the electrical structure of the region being sounded is required in order to choose the cutoff wavenumber appropriately. Hence, the issues of interest involve obtaining the optimum wavenumber filter function and cutoff wavenumber for a finite length MT survey line without an a priori knowledge of the electrical structure of the region being sounded. These problems are explored by applying the wavenumber filtering process to the MT impedance obtained for a model of the earth consisting of a two-dimensional (2-D) heterogeneous layer on the surface of a horizontally stratified earth. Here, a 2-D heterogeneity implies conductivity variations in one lateral direction in addition to vertical variations. Both E-Parallel and E-Perpendicular polarization to strike (Transverse Electric and Transverse Magnetic, respectively) are considered. The E-Parallel polarization response is similar to the desirable portion of a more general three-dimensional (3-D) response in that the effect of near surface heterogeneities on the MT impedance vanish as frequency is lowered, while the E-Perpendicular polarization response is analogous to the undesirable portion of a more general 3-D response in that lateral conductivity variations near the surface have a significant effect on the MT impedance regardless of frequency. As a result, the filter function and cutoff wavenumber must be chosen so that the MT impedance derived from E-Parallel polarization is essentially unaffected while the undesirable effects introduced by lateral conductivity variations into the MT impedance derived from E-Perpendicular polarization are minimized.

# PHYSICAL INTERPRETATION OF THE FULL WAVE SOLUTIONS FOR THE ELECTROMAGNETIC FIELDS SCATTERED FROM IRREGULAR STRATIFIED MEDIA

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The full wave solutions for the vertically and horizontally polarized electromagnetic fields scattered by irregular stratified media are expressed in terms of double infinite sums. These full wave solutions satisfy the reciprocity relationships in electromagnetic theory. The physical interpretation of each term in the double infinite series provides insights into the nonspecular scattering phenomena for irregular stratified media. It is shown that n+1 different terms of the full wave expansion replace the single nth term of the corresponding geometric optics series. For scattering in the specular direction these n+1 terms become analytically indistinguishable and the full wave solution reduces to the geometric optics solution. The full wave solutions are also consistent with Rice's perturbation solution for rough surface scattering in the low frequency limit. The physical interpretation of the full wave solutions which are based on complete spectral expansions of the fields could be used to construct solutions for the non-specularly scattered fields in complex problems involving irregular stratified media.

# SIMULTANEOUS INVERSION OF TWO-DIMENSIONAL PERMITTIVITY AND CONDUCTIVITY PROFILES EMPLOYING CW DATA

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In this paper we present an inversion algorithm based on a recently developed inversion method referred to as the Renormalized Source-Type Integral Equation approach (T.M. Habashy, E.Y. Chow., and D.G. Dudley, URSI meeting, Blacksburg, Virginia, June 15-19, 1987). This approach can be summarized in three simple steps. In the first step, the induced currents inside the probed medium are determined from the known data on the surface of the medium. Next, the field induced inside the medium is computed from the induced currents. In the final step, the medium parameters are reconstructed from the induced currents and fields obtained in the previous two steps.

The probed medium is assumed to vary in both the horizontal and vertical directions. Such a geometry is commonly encountered in oil well-logging applications where the horizontal variation accounts for invasion of borehole fluids into the rock formation and the vertical variation accounts for vertical bedding within the formation. In this paper, the inversion scheme is demonstrated for the cases where the exciting source is of the dipole type that generates only TE polarized waves. The data required for inversion are the tangential component of the electric field at various frequencies and various locations on the surface of the probed medium.

The derived inversion equation is exact and if approximations are to be made they will occur in the numerical methods employed in the solution of this nonlinear inversion equation. Thus, the major virtue of our method is that the approximations to be used can be under good control and may be improved upon to an arbitrary degree. This is to be distinguished from other methods, e.g., Born inversion, ray tracing, etc., which are inherently approximate and are hard to improve when they give inaccurate results. This inversion approach does not require the solution to the full forward problem and it allows, in some cases, the rigorous study of the degree of nonuniqueness involved in the inversion, a point of great importance in the design problem.

# TRANSIENT RESPONSE OF SOURCES OVER LAYERED MEDIA USING THE DOUBLE DEFORMATION METHOD

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The transient response to electromagnetic sources over a planar, layered medium is evaluated using the double deformation method. The methodology consists of deformation of the Sommerfeld and Laplace integration contours to paths of steepest descent in the complex wavenumber and frequency planes respectively.

The time-domain field solutions are then comprised of pole contributions in both the wavenumber and frequency planes and a double integration over steepest descent paths in both planes. In this approach, causality is demonstrated analytically in an elegant manner.

Given that the singularities may be accurately determined, the various partial solutions appear susceptible to physical interpretation and the methodology is applicable to dispersive conditions.

This will be illustrated by examples. The transient response due to vertical electric (VED) and vertical magnetic dipole (VMD) sources will be presented. A physical interpretation of the contributing factors will be attempted and the solution methodology extended to include lossy media.

## Thursday AM

URSI-B Session 67

## EM Theory II

*Chairs*: D. L. Jaggard, Univ. of Pennsylvania; Z. A. Delecki, Univ. of Ottawa

*Room*: Carmel *Time*: 8:15–12:00

| | | |
|---|---|---|
| 8:20 | **Numerical and Theoretical Investigation of the Deep Null in the Electromagnetic Fields Near a Vertical Magnetic Dipole**<br>A. S. Inan,* Bilkent University, A. C. Fraser-Smith, Stanford University | 290 |
| 8:40 | **The Current Distribution on a Linear Thin-Wire Antenna Embedded in a Chiral Medium**<br>S. Bassiri,* M. Shahshahani, Jet Propulsion Laboratory, N. Engheta, University of Pennsylvania | 291 |
| 9:00 | **Electromagnetic Response of a Coated Body of Revolution in the Field of a Loop**<br>A. A. Kishk,* University of Mississippi, A. Sebak, L. Shafai, University of Manitoba | 292 |
| 9:20 | **The Dipole-Multiplate Reflector Antenna Analyzed in Reception by the Line Integral Physical Optics Method**<br>A. C. Brown, Jr.,* Loral Systems Division, W. K. Kahn, George Washington University | 293 |
| 9:40 | **The Doppler Effect and Aberration in Chiral Media**<br>N. Engheta,* M. W. Kowarz, D. L. Jaggard, University of Pennsylvania | 294 |
| 10:00 | **Fourier Transform of a Linear Distribution with Triangular Support and its Application in Electromagnetics**<br>B. Houshmand,* W. C. Chew, S. W. Lee, Univ. of Illinois at Urbana-Champaign | 295 |
| 10:20 | **Coffee Break** | |
| 10:40 | **Waves in Periodic Chiral Media**<br>D. L. Jaggard,* N. Engheta, M. W. Kowarz, P. Pelet, J. Liu, University of Pennsylvania, Y. Kim, New Jersey Institute of Technology | 296 |
| 11:00 | **Pade Approximation to Electromagnetic Wave Scattering from a Thin Dielectric Elliptic Disc**<br>M. A. Karam,* A. K. Fung, Univ. of Texas at Arlington | 297 |
| 11:20 | **Reflection and Radiation from Tapered Slotlines**<br>J. A. G. Malherbe, J. C. Coetzee,* University of Pretoria | 298 |
| 11:40 | **Verification of a Strong Forward Model Using Parametric Inverse Radiative Transfer**<br>N. Cho, Y. Kim,* G. M. Whitman, New Jersey Institute of Technology | 299 |

# NUMERICAL AND THEORETICAL INVESTIGATION OF THE DEEP NULL IN THE ELECTROMAGNETIC FIELDS NEAR A VERTICAL MAGNETIC DIPOLE

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Department of Electrical & Electronics Enigineerins
Bilkent University, Ankara, Turkey
**A.C. Fraser-Smith**
Space, Telecommunications and Radioscience Laboratory,
Stanford University, Stanford, California 94305

Previous work of Fraser-Smith and Bubenik [*Radio Science*, 11,901,1976] has been extended to further investigate the variations in the characteristics of the deep null that occurs in some of the field components generated along the sea surface by a submerged Vertical Magnetic Dipole radiator. New numerical data describing the null are presented as a function of frequency and distance. The results are compared with those of P. R. Bannister and R. W. King and practical applications are discussed. The sharp nature of this null as indicated by the numerical results may have various applications.

# The Current Distribution on a Linear Thin-Wire Antenna Embedded in a Chiral Medium

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The current distribution on a linear thin-wire antenna of length $2\ell$ embedded in a chiral medium is obtained. Chiral media are described electromagnetically by the constitutive relations $\mathbf{D} = \epsilon\mathbf{E} + i\gamma\mathbf{B}$ and $\mathbf{H} = i\gamma\mathbf{E} + (1/\mu)\mathbf{B}$. The constants $\epsilon$, $\mu$, and $\gamma$ are real and have values that are fixed by the size, the shape, and the spatial distribution of the elements that collectively compose the medium. It has been shown that materials with above constitutive relations exhibit optical activity. Optical activity refers to the rotation of the plane of polarization of waves traversing the medium.

Using the dyadic Green's function (Bassiri et al., Alta Frequenza, **LV-2**, 83-88,1986) for a chiral medium and using the Brillouin method, the differential equation for the current distribution on the antenna is obtained. Possible solutions for the current distribution are discussed and the radiated fields associated with these currents are then evaluated. The effects of chirality on radiated power, polarization and the radiation resistance is discussed.

# *ELECTROMAGNETIC RESPONSE OF A COATED BODY OF REVOLUTION IN THE FIELD OF A LOOP*

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Low frequency responses are often used to detect or identify buried objects. The use of exciting loop at sufficiently low-frequencies minimizes the effect of the air-ground interface as well as the ground conductivity (J. R. Wait, Proc. IEEE 59, 1033-1035, 1971). The primary or incident field is usually generated by a loop antenna and the secondary or scattered field due to an object is detected in the near field zone by the same or another loop antenna. The interpretation of the scattered field behavior provides information about the object size, depth and physical parameters. If the object is coated with a lossy dielectric material, the scattered field depends also on the electromagnetic properties of the coating and thickness.

This paper presents a method for the analysis of electromagnetic scattering from rotationally symmetric three-dimensional perfectly and imperfectly conducting objects coated with a lossy dielectric and located in a medium of infinite extent simulating Ground, Ocean, Ice etc. The excitation is due to a loop antenna carrying a total current $I \exp(j\omega t)$ with arbitrary orientation and location with respect to the body. The problem is formulated in terms of equivalent electric and magnetic surface currents over the body and coating surfaces. An integral equation approach is utilized using proper boundary conditions. These are the continuity of the tangential components of the electric and magnetic fields on the coating surface and impedance boundary conditions on the body's surface to simplify the formulation and reduce the computation efforts. For imperfectly conducting objects, the impedance boundary conditions are reasonable and eliminate the need for the inclusion of the integral equation interior to the body. The resulting coupled integral equations are transformed into a matrix equation using the method of moments. This matrix equation is then solved using standard numerical techniques for the equivalent electric and magnetic surface currents. The near and far scattered fields are determined by integrating surface currents over the coating surface.

The formulation is applied to many configurations with arbitrary loop and dipole excitations. Numerical results for some selected objects and coating parameters are presented in the paper.

# THE DIPOLE - MULTIPLATE REFLECTOR ANTENNA ANALYZED IN RECEPTION BY THE LINE INTEGRAL PHYSICAL OPTICS METHOD

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Washington, DC 20052

Recently the line integral physical optics method (A.C. Brown, Jr., GWU D.S.E.E. Diss., Feb. 1987) and a reflector analysis model (A.C. Brown, Jr. and W.K. Kahn, URSI Dig., June 1987) were developed for computing the fields of dipole illuminated single and multi-plate reflectors. The line integral formulation was based on a transmitting antenna. Good agreement with the classical surface integral computations were obtained for the co-polarized patterns, but poor agreement were obtained for the cross-polarized patterns for some angular regions.

In the receive formulation, good results can be obtained by using the original Maggi-Rubinowicz potential to transform the Kirchhoff surface integral into a line integral. However, the use of a new potential (Asvestas, J. Opt. Soc. Am. A/Vol. 2 No. 6, 896-902, June 1985) has a couple of computational advantages. One, there is no geometrical optics term, so there is no need for additional code to determine whether the virtual receptor dipole is in the illuminated or the shadow region of a plate. Second, the Asvestas potential is continuous across the shadow boundary so that no extraordinary integrating procedures are required to evaluate this potential. The Maggi-Rubinowicz potential is singular at the shadow boundary and cannot be evaluated by any numerical technique. At points near the shadow boundary, it can be evaluated using special numerical integration techniques (A.C. Brown, Jr., URSI Dig., May 1983).

The increased accuracy of the receive formulation occurs because a solution of the electromagnetic problem can be constructed without approximation from the scalar wave vector potential for an incident plane wave. In the transmit case, an approximate dyadic potential has been used in previous computations. Results for some single and multi-plate reflectors illuminated by electric and magnetic dipoles will be presented.

# THE DOPPLER EFFECT AND ABERRATION IN CHIRAL MEDIA

**N. Engheta, M. W. Kowarz and D. L. Jaggard**
**Moore School of Electrical Engineering**
**University of Pennsylvania**
**Philadelphia, PA 19104**

Chiral or optically active materials are described by the constitutive relations

$$\mathbf{D} = \varepsilon \mathbf{E} + i\xi_c \mathbf{B}$$

$$\mathbf{H} = i\xi_c \mathbf{E} + \mathbf{B}/\mu$$

where $\varepsilon$ and $\mu$ are the usual scalar permittivity and permeability of the medium. The chiral admittance $\xi_c$, for the lossless medium, is a real pseudo-scalar, which can be either positive or negative depending on the handedness of the medium. The above constitutive relations describe an isotropic reciprocal medium with two propagating eigenmodes for a given direction, one right-circularly polarized (RCP) and the other left-circularly polarized (LCP).

In this talk, we examine classically the effect of chirality or optical activity on the Doppler shift and the aberration of monochromatic light waves in a chiral medium. Two important instances have been studied. For the first, the observer was assumed to be moving with respect to the medium. We show that, in this case, a single monochromatic plane wave in the stationary frame (material frame) is observed in the moving frame as two plane waves with unequal frequency shifts and differing directions of propagation. This is due to the decomposition of plane waves into two circularly polarized components, RCP and LCP, with different wavenumbers. We also notice that any one of the observed frequencies becomes zero when the observer's velocity, still being less than vacuum speed of light, equals one of the eigenmodes' phase velocities.

In the second case, the source was taken to be moving with respect to the medium and the observer. Under these conditions, for a given monochromatic source and a given direction of propagation, double frequency shifts occur. We observe that, in this instance, any one of the observed frequencies tends to infinity when the source's velocity approaches one of the eigenmodes' phase velocity. This is an indication of the beginning of Cerenkov radiation for such an eigenmode. As the source's velocity exceeds the velocities of the two eigenmodes, the phase fronts of the two propagating waves form a double cone. Furthermore, for a moving source in a dispersive chiral medium, the possibility of observing several spectral components (more than two) for a monochromatic source is discussed.

# Fourier Transform of a Linear Distribution with Triangular Support and Its Application in Electromagnetics

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Abstract

Any surface, no matter how irregular, can be well approximated by a union of triangles. Hence, triangles can be used as the fundemental elemental shape (a simplex) for a two dimensional surface. A linear distribution over each triangle can be used to obtain a piecewise linear approximation of a function defined over a two dimensional surface.

In many applications, the Fourier transform of the current distribution is needed, for examples, in RCS calculation, radiation and diffraction in reflector antennas and spectral Galerkin method. In this paper, a 3-D Fourier transform of a linear distribution with triangular support is derived and its coordinate free representation is presented.

As an example, this formulation is used to evaluate the radiation integral due to a current distribution. The major step in evaluating this integral is to obtain the Fourier transform of the current distribution. To facilitate this, the finite support of the current distribution is divided into triangular patches. On each patch the phase and magnitude of the current are approximated by linear interpolation using the sample values of the current at each node of the patch. Since the Fourier transform of a simplex (triangular patch distribution) is known, the radiation integral for each patch is evaluated readily in closed form. This procedure can also be applied to calculate the near field of a current distribution. We observe that the convergence rate improves over the traditional phase and magnitude staircasing approximation.

# WAVES IN PERIODIC CHIRAL MEDIA

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and

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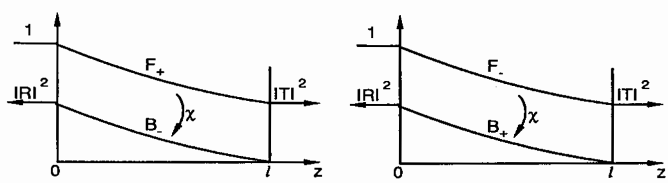
In this talk the propagation properties of electromagnetic waves in a structure that is both chiral and periodic are discussed by using coupled-mode equations. The chirality is characterized by the constitutive relations $\mathbf{D} = \varepsilon\mathbf{E} + i\xi_c\mathbf{B}$ and $\mathbf{H} = i\xi_c\mathbf{E} + \mathbf{B}/\mu$, where $\xi_c$ is the chiral admittance. The periodicity is described by a sinusoidal perturbation of the permittivity, permeability and chiral admittance. The coupled-mode equations are independently derived from both physical considerations and multiple-scale perturbation theory. These equations can be written as

$$\tilde{F}_{\pm}' - i\delta\tilde{F}_{\pm} = i\chi\tilde{B}_{\mp}$$

$$-\tilde{B}_{\mp}' - i\delta\tilde{B}_{\mp} = i\chi\tilde{F}_{\pm}$$

where $\chi$ denotes the coupling per unit length, $\delta$ the phase mismatch per unit length, and $\tilde{F}_{\pm}$ and $\tilde{B}_{\pm}$ are forward (RCP and LCP) and backward (RCP and LCP) eigenmodes, respectively. The coupled-mode equations, for each modal pair ($F_+$ and $B_-$ ) and ($F_-$ and $B_+$ ), are of the same form as those for an achiral periodic medium. However, we have two sets describing the coupling between the incident RCP (LCP) and the reflected LCP (RCP) as described schematically in the figure below.




The coupled-mode equations are also used to examine bandgap structure and reflected and transmitted fields. It is observed that the periodicity affects the magnitude of both the reflected and transmitted waves, while the chirality is predominantly manifested through the polarization state of the transmitted wave. It is observed that the coupling and bandgap size can be tailored when chirality is present, due to the extra degree of freedom afforded by the chirality admittance. The applications of such structures will be addressed.

# PADÉ APPROXIMATION TO ELECTROMAGNETIC WAVE SCATTERING FROM A THIN DIELECTRIC ELLIPTIC DISC

By
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By applying the Helmohltz integral equation to a thin scatterer with arbitrarly shape and choosing a principal volume similar to the scatterer around the Green's function singularity, the field inside the scatterer is expressed as a perturbation series in terms of the exciting field and the polarizability tensor.

Then applying the Helmohltz integral equation once more outside the scatterer ,a perturbation expansion for the scattering amplitude tensor is formulated in terms of the inner field perturbation expansion.

For a plane wave exciting a thin dielectric elliptic disc , the scattered amplitude tensor is obtained through the second order perturbation. Then the energy balance is investigated and the bistatic cross section is formulated. To expand the validity range of the obtained scattering amplitude , the results are recast by Padé approximation.

Numerical calculation is performed to investigate the scattering cross section dependence on the scatterer shape , dimensions and the incident angles. Finally a comparison is made between the calculated and the measured values of the bistatic cross section for some artificial targets.

# REFLECTION AND RADIATION FROM TAPERED SLOTLINES

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A tapered slotline is studied as a transformer between slotline and free space. The tapered line is approximated by a finite series of linear slotline steps of equal electrical length, and the input impedance is found by repeated application of the transmission line equation rather than a cascade of transmission matrices. A wave impedance defined as the ratio between the principal transverse fields is used as the relevant parameter in the transmission line calculations and the input reflection coefficient is calculated.

The performance of three types of taper are studied, viz. an exponential, Klopfenstein and a Hecken taper, and their performance is compared. The latter two tapers are optimal; the Hecken taper suffers from a discontinuity in the impedance level at each end of the taper.

This procedure has previously successfully been applied to a metal-walled waveguide taper, as well as the design of a wideband tapered horn antenna. In the case of the horn antenna, the taper was used to transform between the waveguide impedance and free space. (Malherbe, 1986 AP-S Symp., 743-746). The procedure is relevant to the design of very wide band tapered slot antennas such as the Vivaldi antenna.

# VERIFICATION OF A STRONG FORWARD MODEL USING PARAMETRIC INVERSE RADIATIVE TRANSFER

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Radiative transfer equation has been implemented to investigate wave propagation in random media. Recently, this equation has been used successfully for wave propagation studies in a vegetation modeled by a strong forward scattering profile (F. Schwering & R.A. Johnston, J. of Wave-Material Interaction V1, 205-236, 1986). The phase function of this model can be described by

$$p(\gamma) = \alpha\ (2/\Delta\gamma_s)^2\ \exp(-\gamma^2/\Delta\gamma_s^2) + (1-\alpha)$$

where $\gamma$ and $\Delta\gamma_s$ are the directional cosine and the width of the forward lobe, respectively.

In this paper, we apply a parametric inversion technique to the inverse radiative transfer problem in order to verify the above strong forward model. First, after substitution of the strong forward phase function into the radiative transfer equation, parameters are optimized in such a way that the calculated specific intensity is best fitted to measured data in a root mean square sense. Second, using the root mean square results obtained in the first part, the applicability of the radiative transfer equation to wave propagation in vegetation with a strong forward phase function will be verified. Several examples using both synthetic and experimental data will be presented.

## Thursday AM

URSI-F Session 69

**Propagation and Remote Sensing**

*Chairs*: I. C. Peden, University of Washington; J. B. Snider, NOAA/ERL

*Room*: San Carlos *Time*: 8:15–11:40

# GROUND-BASED MEASUREMENTS OF WATER VAPOR BY MICROWAVE RADIOMETERS OF THE COLORADO RESEARCH NETWORK

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The Wave Propagation Laboratory developed a network of four dual-frequency ground-based microwave radiometers which operated continuously for about three years. In addition to the network radiometers that operated at 20.6 and 31.65 GHz, a transportable and steerable three-channel radiometer, operating at 20.6, 31.65, and 90.0 GHz, was available for comparison measurements. All of these instruments provide 2-min measurements of precipitable water vapor (PWV) and integrated cloud liquid during almost all weather conditions. The accuracy and functional precision of the network radiometers are evaluated by comparison with both National Weather Service and NCAR-operated CLASS radiosondes, and by comparison with the transportable system. Several recent studies using the instruments are presented: combination of PWV observations from the network and from the VAS sounder on GOES, observations of the passage of a moisture front, and the derivation of attenuation statistics relevant to communication studies.

# RADIOMETRIC OBSERVATIONS OF CLOUD LIQUID WATER AT 20, 31, AND 90 GHz

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Remote observations of integrated liquid water contained in marine stratocumulus (MS) clouds were performed during a three week period in July, 1987 as part of project FIRE (First ISCCP Regional Experiment). Observations were made with a three channel (20, 31, and 90 GHz) microwave radiometer designed for simultaneous measurement of precipitable water vapor and integrated liquid water. We present several important results of the observations including liquid water amounts contained in MS clouds and their spectral characteristics, the relationship between liquid spectra and meteorological conditions, and the impact of the observations upon simple parameterizations that relate liquid water content to cloud reflectivity. In addition, the relative merits of 31 and 90 GHz channels in measuring cloud liquid are discussed.

# DUAL-CHANNEL MICROWAVE RADIOMETER FOR AIRBORNE METEOROLOGICAL APPLICATIONS

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NOAA/ERL/Wave Propagation Laboratory
Boulder, Colorado

D.C. Hogg and R.T. Nishiyama
CIRES
Boulder, Colorado

Cloud liquid water and water vapor are important parameters in many meteorological processes. Frequently, it would be desirable to measure the horizontal distribution of these quantities. This paper presents the design of a dual-channel microwave radiometer to be installed on a NOAA research aircraft to measure these parameters. The operating frequencies of the radiometer are 23.87 and 31.65 GHz. Among the design details discussed are: the antenna design, beam-tipping capability, pressure considerations, fairing and wind/rain deflector, and the electronics package.

Among the research applications discussed are the following; hurricane research, extratropical ocean storms, clouds and atmospheric radiative transfer, validation of and research using satellite data, middle-latitude continental mesoscale convective systems, and aircraft icing studies.

# ELECTROMAGNETIC PROPERTIES OF FRACTAL AEROSOL AGGLOMERATES

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and

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The electromagnetic scattering and absorption properties and the amount of smoke and other aerosol particles in the atmosphere play a key role in the climatic predictions using sophisticated models such as the General Circulation Model (GCM) and in examining the climatic impact of smoke clouds. These calculations are also important in determining the effectiveness of smoke clouds in obscuration. The changing characteristics of aerosols and smoke clouds through coagulation is expected to play an important role in predicting its electromagnetic characteristics.

Determining the electromagnetic properties of aerosols, however, require knowledge of its composition, morphology, and quantity. The introduction of the concept of fractal structure in the study of these properties is attractive because it could provide a genuine geometric description of agglomerates.

In this paper the Volume Integral Equation Formulation (VIEF) is applied to calculate the electromagnetic scattering and absorption properties of five types of agglomerates of aerosols with fractal dimension in the range from 1.7 to 1.9. Results for absorption and scattering are presented for three different polarizations of the incident electromagnetic plane wave and at three different wavelengths $\lambda$ = 0.5, 2.0 and 10 μm. The obtained results indicate that the polarization, frequency, the number and size of primary particles, and the structure of the agglomerate play an important role in the calculation of the absorption and scattering properties. Furthermore, the obtained results are compared with those based on the approximate fractal theory and some differences are found. For example, when a comparison was made for the absorption cross section per gram at $\lambda$= 0.5 and 2 μm, the obtained results showed that the difference between the VIEF and the fractal theory varies from 8 to 50 percent, depending on the size and number of primary particles in the agglomerate and the radiation frequency. Other results and comments regarding the validity and accuracy of the fractal theory and other differences such as those due to polarization considerations will be made in the presentation.

# VALIDATION OF SSM/I DETERMINATIONS OF CLOUD LIQUID WATER USING GROUND-BASED MICROWAVE RADIOMETRY

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John Alishouse*
NOAA/NESDIS
Washington, DC

Sheila Snyder and Jennifer Vongsathorn
S. M. Systems and Research Corporation
Landover, Maryland

The Special Sensor Microwave/Imager (SSM/I) was launched June 20, 1987 and is a 7 channel, 4 frequency radiometer. The frequencies are 19, 22, 37, and 85 GHz. The 19, 37, and 85 GHz channels are dual polarization, while the 22 is vertical only. One of the many geophysical parameters to be derived from the SSM/I is the liquid water content (lwc) of clouds. Prior to launch, algorithms were developed to derive the lwc for clouds over both land and ocean. It was the task of the Calibration/Validation Team to validate these algorithms and offer improvements if necessary. Cloud liquid water is not readily inferred from conventional meteorological measurements.

It is possible to infer lwc from upward-looking microwave radiometric measurements. Measurements of upward-looking radiances were made at San Nicholas Island, California, (Project FIRE) and the four NOAA Colorado profiler network sites. The San Nicholas Island measurements were taken by a steerable three frequency radiometer which operates at 20.6, 31.65, and 90.0 GHz; the radiometers of the network sites operate only at the lower two frequencies. Project FIRE data were taken between July 2 and July 19, 1987. Data from the Colorado profiler network are from two extended observation periods, mid-July through mid-October, 1987, and mid-January through mid-April, 1988. Comparisons between upward- and downward-looking retrievals of cloud liquid water will be presented. Methods of compensation for the differing fields of view of the satellite and ground-based instruments will be discussed. Significant differences between retrievals over land and water have been noted.

# A Comparison of Experimental and Theoretical Techniques for Identification of Buried Targets

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Several techniques have been developed to probe the earth for subsurface tunnels. Some success in using VHF electromagnetic waves has been reported using surface or cross-borehole probing. However, the use of electromagnetic techniques to determine the location of a tunnel has never been satisfactorily demonstrated when the a priori tunnel location is unknown.

One experimental and two theoretical techniques are used to further examine the problem of cross-borehole probing. A vertical electric dipole is used as the source of illumination and the tunnel cross-sectional dimension is assumed to be on the order of a wavelength.

The experimental technique uses scale models and composite materials to approximate conditions typical of those for a tunnel in hard rock. A two-dimensional moment method is used to obtain one set of theoretical data. Using this method an exact representation of the tunnel cross-section is obtained, whereas the source is approximated as an infinite line source. The T-matrix method is used to obtain another set of theoretical data. In contrast to the moment method, the T-matrix method incorporates an exact formulation of the dipole source and an approximate representation of the tunnel.

# A Time Domain Focusing Array for Subsurface Mapping

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Northeastern University, Boston, MA

and

Peter G. Mitchell
GEO-CENTERS, INC., Newton Centre, MA

The purpose of using arrays of sources, arrays of receivers, or both, is two-fold. First, arrays allow the quick acquisition of many signals which can be stacked to enhance the signal-to-noise ratio of a desired pulse and hence improve target detection and discrimination. This is especially useful with low energy sources and noise which is incoherent in both space and time. Second, arrays inherently have a directionality associated with them, and they can, therefore, be oriented to transmit and/or receive the maximum signal in a certain direction. This has the obvious advantage of allowing one to focus on a particular object or direction and to reject noise or unwanted signals from other directions. One advantage of using a time domain array over a CW based system is that time gating can be used to localize the area of interest. The array is designed so that contributions from the pulsed elements are concentrated in a small focal region in the earth.

Elements in the array consist of folded TEM horns with resistive loading on the ends similar to a Rhombic Antenna (TEMR elements). Each TEMR element is driven by individual pulsers having a center frequency of a 2GHz. Stripline time delays are used to focus the radiation from the array. Separate receiving elements are used in a complementary system to sample the scattering from the focal region in the earth.

The time domain backscattered signal for targets buried in sand and loam has been obtained. Targets consists of dielectric cylinders of various sizes. The ability of the array to resolve various targets is discussed. Data has been obtained by mechanically shifting the focal region over a volumetric range.

# FINITE ELEMENT METHOD FOR ELECTROMAGNETIC WELL LOGGING IN CYLINDRICAL BOREHOLES

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An electromagnetic well logging system operating at 25 MHz is used commercially to derive the resistivity and dielectric constants of the earth around oil wells from measurements of the attenuation and phase shift of the electromagnetic waves (Huchital, et al "The Deep Propagation Tool: A New Electromagnetic Logging Tool," SPE 10988, 1981). The system uses circular loop antennas distributed on the axis of the well to excite and receive TE polarized waves around a borehole. In this paper, we describe a finite element solution that has been developed to simulate the EM wave propagation in the inhomogeneous earth formation surrounding the borehole.

In the model, we consider the earth as a layered medium traversed by a circular borehole. During the drilling process, the drilling mud can invade into the surrounding rocks. The invasion and the earth layers combine to form a complex inhomogeneous distribution of resistivity and dielectric constants near the borehole. To simulate the axisymmetric EM fields generated by the antenna, we first derive the variational integrals and the finite element formulations. We then divide the earth space into many ring elements, each with a rectangular cross section. The size of the grids are designed following the error criteria of the finite element formulations. The matrix equations are solved by a block Gaussian elimination algorithm. The finite element solution has been verified by comparing the results with those from analytic and semi-analytic solutions.

The algorithm is designed in such a way that users can be free of considerations or know-how of the finite element method. The input data include the geometry of the borehole, earth layers and invasion profiles, along with the resistivity and dielectric constants of the entire region and the antenna arrangements. The generation of the finite element mesh is performed automatically. The output includes both the field distribution over the entire space and the receiver responses. We will present several sets of numerical results for a variety of well logging configurations.

# RESULTS OF SOME THROUGH-THE-EARTH PROPAGATION EXPERIMENTS

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*Lawrence Livermore National Laboratory, Livermore, CA
**Naval Postgraduate School, Monterey, CA

Electromagnetic signals transmitted through-the-earth can be used for communication. Two examples are: 1) communicating with trapped miners, and 2) communicating with a deeply buried military installation. It is not practical to use frequencies normally associated with communication (> a few MHz) since the attenuation would be too large at these frequencies for propagation over distances of interest (> 1000 ft). However, if frequencies in the ELF to low VLF range (30 Hz to 5 kHz) are used, then measurable signals can be transmitted over distances of 1000 ft and more.

We describe experimental work which demonstrates that through-the-earth transmission of electromagnetic signals with frequencies in the 30 Hz to 5 kHz range is possible over distances greater than 1000 ft in representative geologies. In a companion paper (Bukhofzer and Buettner), we describe a practical demonstration of digital communication through-the-earth using various schemes to modulate a CW carrier.

Our experiments took place at two separate sites, the Billie Mine in Death Valley, Ca and the Mississippi Chemical Mine outside Carlsbad, NM. The vertical transmission paths at these sites were 1140 and 965 ft respectively. We employed large, square loops (³ 200 ft side) as transmitter antennas, and calibrated magnetic probes with spectrum analyzers for receivers.

At both sites we measured the vertical component (magnitude and phase) of the transmitted magnetic field as a function of frequency, and found that the results agreed well with computations based on computer codes developed at LLNL. In addition, we measured the background noise spectra for both sites over the same frequency range. These earth transfer function and background noise data established the desired operating range for our previously mentioned digital transmissions (see companion paper).

Our less than optimal systems demonstrate clearly that through-the-earth communication is a viable concept. Great improvements can be realized by the use of forward error correcting codes, appropriate equalizers, and higher transmitter power.

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

## Thursday AM

Joint AP-S, URSI-B Session 70

### SEM, Modes, and Poles

*Chairs*: A. J. Poggio, LLNL; K. M. Chen, Michigan State U.

*Room*: San Juan *Time*: 8:15–12:00

# NEW PROGRESS ON RADAR TARGET DISCRIMINATION USING E-PULSES AND S-PULSES

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We have made some significant progress in the study of radar target discrimination using E-pulses (Extinction pulses) and S-pulses (Single-mode extraction pulse). Two scattering ranges, a ground-plane time-domain scattering range and a free-field anechoic chamber scattering range have been constructed.

In the ground plane scattering range, the existing short monopole receiving antenna was replaced by a long wire receiving antenna, and the dimensions of scale models of various airplanes have been increased. Because of these changes, the signal to noise ratio of measured pulse responses of the target models have been improved, resulting in better overall results.

In the free-field scattering range, the initially used long wire antenna system was replaced by a broad-band horn antenna system. TEM horn antennas (American Electronic Labs) were modified by adding resistors inside the antennas to damp out the ringing (resonances) of the antennas. Two such antennas are used as the transmitting and the receiving antennas. Whole scale models of various airplanes are placed on a wooden pedestal to be illuminated by EM pulses radiated by the horn antenna.

Experimental results obtained in these two scattering ranges, on the discrimination-sensitivity using E-pulses and S-pulses, will be presented.

# K-PULSE ESTIMATION FOR A TARGET WHOSE IMPULSE RESPONSES AT DIFFERENT ASPECTS OR POLARIZATIONS HAVE DIFFERENT COMPLEX NATURAL RESONANCES EXCITED

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In an earlier work by Fok, Moffatt and Wang (IEEE AP-S, AP-35, no 8, pp.926-934), the K-pulse of a target was estimated by minimizing the K-pulse response energy outside the K-pulse response duration. The method did not require a priori information on the target's complex natural resonances to obtain the K-pulse. But it relied on the choice of an impulse response which has all the complex natural resonances excited. This paper extends their theory such that their method can now accommodate targets that have different complex natural resonances excited at different aspect angles or polarizations. Although the impulse response of a target at different aspects, polarizations or bistatic angles may indicate different resonant behaviors, there is only one K-pulse for a target. Through the right-angled bend wire example, the properties of the K-pulse: independence of aspects, polarizations, and locations of the receiver are confirmed.

# SUBSTRUCTURE-RELATED K-PULSE ESTIMATION FOR AN AIRCRAFT FROM FULL-SCALE RADAR DATA

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and
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An approximate K-pulse waveform is generated from measured, noisy, complex S-band backscattered data of an A-4 jet aircraft. The data, measured by a full-scale stepped-frequency radar system, discretely span the frequencies 3.1(0.0048)3.4024 GHz for both vertical and horizontal linear polarizations. At the lowest available measurement frequency, the ratio of the wavelength to the overall length of the aircraft is less than one percent. Therefore, the K-Pulse estimation problem is basically related to some substructures of the aircraft which become resonant over the frequency range of measurements.

The K-Pulse estimate is obtained using a double-combinational, simultaneous late-time response energy minimization technique which utilizes the measurement backscattered data at the aspect angles of 1° and 91°, both for vertical polarization. Since the original data are measured at high frequencies over a very narrow bandwidth, the available data at each synthesis combination are shifted by $\pm j3.09$ GHz and the low-pass weighted superposition of the left and right-shifted spectra is utilized in the estimation procedure for a better numerical exploitation. Such composite spectra are still useful in K-Pulse estimation because they preserve the original target pole information in a frequency shifted manner. The substructure-related dominant poles of the aircraft are extracted as zeros of the resultant K-Pulse spectrum. The basic correctness of the estimation results is demonstrated using the measured data at arbitrarily selected nominal aircraft orientations for both vertical and horizontal polarizations with quite satisfactory results.

# FREQUENCY DOMAIN SEM USING NON-EUCLIDEAN NORMS

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The frequency domain singularity expansion method provides a concise method for characterizing scattering information. Algorithms for extracting poles and zeroes from measured data generally first fit a curve to the measured data (the fit being achieved in a least squares or Euclidean sense) and then extract the poles and zeroes from this fitted curve (e.g., D.A. Ksienski, Radio Sci., 20, 13-19, 1985). Although the algorithm works very well for noiseless data, even small amounts of noise degrade the accuracy of the extracted pole locations. Norms other than least squares can be easily introduced into the curve fitting algorithm and this paper will present the benefit of these norms on the accuracy of the extracted poles.

# SEM WITHOUT THE ENTIRE FUNCTION

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The value of a singularity expansion method (SEM) is strongly dependent on the absence of the unknown entire function in the Mittag-Leffler expansion. A body of theory suggests that a variety of expansions of the current on a perfectly-conducting scatterer can be constructed using only pole terms. We review these expansions and conclude that several of them are incomplete. However, we conjecture that one such form is exact.

The review begins with a clarified explanation of "Class I" and "Class II" SEM. The Class II forms are shown to result from a Mittag-Leffler expansion of some multiplier times the inverse operator. An immediate inference is that a pure pole Class II expansion, if it exists at all, must include not only natural mode terms but heretofore-neglected "internal resonance" terms as well. The net effect of the latter terms on the current is as an entire function which, although formally known as an infinite sum, cannot be practically computed. This observation suggests that the Class II expansions, which are the only ones leading to the often-discussed "time-dependent coupling coefficients," are of limited value.

Class I SEM, on the other hand, results from a Mittag-Leffler expansion of some function times the surface current itself. Internal resonance terms vanish, but the question of an unknown entire function remains. One particular Class I form has been defended on the basis of a conjecture on the asymptotic nature of the inverse integral operator, but we find discrepancies with this conjecture. An alternative conjecture suggests that the surface current is indeed amenable to a pure pole expansion for a wide range of incident fields, including step-function and time-limited finite pulses as well as the impulse function.

The method is illustrated by the example of the sphere. Although the solution is slow to converge in the very early time, the series is nevertheless convergent and exact, with *no* entire function required. The pure pole expansion is used to compute the solution in both time and frequency domains, including the steady state response to a harmonic incident field.

# EXPERIMENTAL INVESTIGATION OF THE PRESENCE OF NATURAL MODE INFORMATION IN THE EARLY TIME CURRENT RESPONSE OF A THIN WIRE

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The transient surface current response of a conducting scatterer is often separated into an early time component (when the excitation field is traversing the target and a late time component (after the excitation has passed). It is well known that the late-time period can be characterized purely in terms of a natural mode series. In addition, it has been suggested that the early time period may also be represented purely in terms of a natural mode sequence (Michalski, Electromagnetics 2, 201-209, 1982). This has significant implications to natural frequency identification using measured data, since the early time component often contains a majority of the signal energy.

This paper will show that, although a natural mode sequence may be a viable mathematical description of the early time, the natural frequencies cannot be obtained experimentally from this time period.

This can be easily seen by considering two thin cylinders of different lengths but identical orientation to an incident field. During the early time period, and before the first reflection from the far end, the current responses on each cylinder must be identical at identical observation points. However, each cylinder has a unique set of natural frequencies. It is obvious that two independent sets of frequencies cannot be extracted from an identical time series, without a priori knowledge of the scatterer.

This paper will investigate that conjecture experimentally. The transient current response on a thin wire scatterer inclined above a groundscreen has been measured, and an attempt has been made to extract the natural frequencies of the wire for various probe positions. It will be shown that *apparent* early time natural modal content is heavily dependent on probe position. It will also be shown that the natural frequencies of the wire are unavailable until the first reflection from the farthest point of the wire returns to the observation point.

# RADAR TARGET DISCRIMINATION USING FREE-FIELD MEASUREMENTS

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The E-pulse radar target discrimination scheme, based on target natural resonances, has been successfully demonstrated using transient scattered field data from a conducting ground plane range. More recently, radar target measurements have been made at MSU using a new free-field transient scattering range, and successful target discrimination has been performed.

The MSU free-field transient range consists of a 12′ x 12′ x 24′ anechoic chamber, with wideband horn antennas used both for transmitting and receiving. The horn antennas have been loaded with a distributed resistance to eliminate the strong resonances which normally occur near the target natural resonances. Excitation is provided using a 0.5 ns pulse of amplitude 40V, and the received waveform is digitized by a waveform processing oscilloscope.

Results will be presented which will demonstrate that several different aircraft targets can be successfully discriminated using the E-pulse technique with free-field measurements. Discrimination will be accomplished using both E-pulses and single-mode discrimination signals.

# THE NATURAL FREQUENCIES OF AN IMPEDANCE STRIP

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The natural frequencies or resonances of an impedance strip are determined using two different techniques. The first technique uses the relationship between the high–frequency interactions of waves on the strip combined with a resonance condition. The high–frequency interactions are due to multiple edge diffraction of the surface rays on the strip. These are determined by a modified GTD approach and together with a ray–closure condition on the strip identify the natural frequencies. Some results using this approach were presented for a resistive coating and TM–polarization (J.D. Kotulski, 1988 URSI Symposium, Syracuse). The work presented here extends the previous analysis to include TE polarization and a surface impedance which allows the existence of a surface wave. The results obtained by this ray–tracking method are then compared to an alternative formulation of the problem. A moment–method solution of the appropriate integral equation is used to generate the impedance matrix. The resonances are then found by locating the zeroes of the determinant of this matrix.

## Thursday AM

### Joint AP-S, URSI-B Session 72

### Apertures and Aperture Coupling

*Chairs*: R. J. King, Lawrence Livermore Lab; R. R. McLeod, Lawrence Livermore Lab

*Room*: San Simeon *Time*: 8:15–11:00

# EXPONENTIAL APERTURE DISTRIBUTION FOR LOW SIDELOBE AND NARROW BEAMWIDTH RADIATION PATTERNS

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Radiation patterns of narrow beamwidth with required sidelobe level and structure can be generated from a line source by Taylor's aperture distribution. Many other types of aperture distribution functions like cosinusoidal, triangular, circular, parabolic, trapezoidal and raised cosinusoidal functions are reported in the literature (M.T.Ma, Theory and appliction of antenna arrays, 1974). These functions result in radiation patterns with sidelobes varying from about - 17 to - 31 dB and main beamwidths ranging from 0.05 to 0.08 (Sin θ - domain).

The investigations carried out by the authors reveal that a simple exponential type of aperture distribution function of the form

$$A\,(x_n) = e^{-|x_n|} \qquad \text{for } -1 \leq x_n \leq 1$$

where $x_n = (2n-N-1)/N$, N being the number of radiating elements in the array, yields a radiation pattern with its first sidelobe at - 25 dB. The main beamwidth is found to be 0.04 (Sin θ - domain).

The computations are carried out to obtain the radiation patterns for an array of isotropic radiators whose normalised array length is 50 and number of elements in the array is 100. The computations are repeated for the same array length and the same number of short collinear dipoles in an array. It is found from the results that these arrays yield identical radiation patterns.

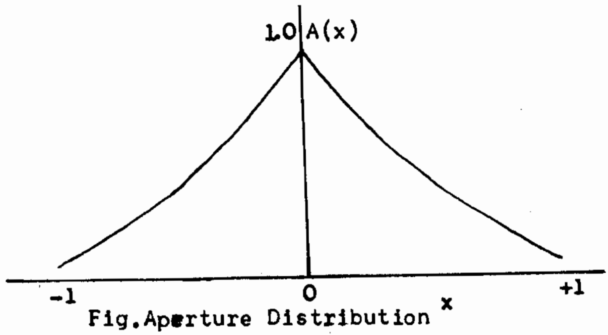


Fig.Aperture Distribution

## ABSTRACT

# ON THE EXCITATION OF A DIELECTRIC COVERED SLOT BY A MICROSTRIP LINE IN A CAVITY

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A high frequency array antenna design is proposed which optimizes total radiated power through spatial power combining. The array is constructed of slots individually excited by microstrip lines. Each microstrip line is excited by an active device and shielded by a rectangular cavity to reduce coupling. The dielectric cover thickness and the orientations of the microstrip lines and slots are selected to control the radiation pattern and mutual coupling.

The analysis is formulated by equating the tangential H-fields at the slot resulting in coupled integral equations. The derivation of the cavity dyadic Green's function needed in the integral equations is presented in terms of vector wave functions. Above the slot, an infinite ground plane covered by a thin dielectric layer is assumed and the analysis of the resulting Sommerfeld integral is briefly described. Application of the Method of Moments using rooftop basis functions leads to matrix representation of the integral equations which is solved by matrix inversion.

Results are presented which show the coupling of the microstrip to the slot as a function of position and orientation of each in the cavity. The design procedure for the array is briefly outlined.

# RADIATION BY SLOTS ON AN IMPEDANCE WEDGE

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R. Tiberio*, G. Pelosi
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Dept. of Electrical Engineering, The Ohio State University

Recently, a high-frequency solution has been presented for the diffraction by a wedge with surface impedance faces, when both the source and the observation points are located at finite distances from its edge [R. Tiberio et al., IEEE Trans. Antennas Propagat., vol. AP-37, no. 2, Feb. 1989]. There the total field is represented as the sum of the Geometrical Optics (GO) field, surface waves and a diffracted field. High-frequency expressions for the total field are given in the format of the Uniform GTD (UTD). The diffracted field includes contributions which provide the continuity of the total field at the shadow boundaries of both the GO field and the surface waves. The first contribution, which has the same structure as that for a perfectly conducting wedge, vanishes when at least either the source or the observation point is located on the impedance face of the wedge.

In this paper the above formulation is extended to treat the radiation by sources located on the surface of the wedge. To this end a higher order term is included in the asymptotic evaluation of the integral representation of the field. The same analysis is employed to evaluate a non-vanishing field contribution when both the source and the receiver are located on the faces of the wedge.

This solution is applied to investigate the scattering mechanism excited by a slot on an impedance wedge, including surface wave contributions. Also, the application to the coupling between two slots is considered.

Numerical results are presented that show that this technique may provide a useful tool in designing slot array and surface wave antennas.

# ANALYSIS OF APERTURES ON METALLIC PLATES INCLUDING PLANE FINITENESS AND MUTUAL COUPLING

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ABSTRACT

Designing of horn clusters for conformed beams antennas on board of satellites needs an accuracy simulation of copolar and cross polar components of their field patterns. This simulation should include mutual couplings between horns and a suitable modelling of horns surroundings.

In this work the horn surroundings is modelled by a finite metallic plate that holds horn mouths (this is a real situation in some clusters e.g. ATLANTIS antenna (M. Calvo et alt. Proc. of URSI Meeting 1988 ). Horn radiation is computed using classic methods (electric field model, Chu model) corrected with the addition of diffracted rays (calculated by GTD) at the edges of the finite metallic plate.

The influence of the flat flange over simple horn mouths is computed using GTD techniques (C.A. Balanis. IEEE T.A.P. July 1970, pp 561-563., C.K. Cockrell et alt. IEEE T.A.P. Vol 22. May 1974.) .Fresnel's field expressions are used for near diffracting edges of circular and polygonal plates.

The mutual coupling between horns and its effect in pattern radiation is also studied. The procedure is to compute mutual admittances ($C_{ij}^{mn}$) and mutual impedances ($D_{ij}^{mn}$) evaluating the field created by the j-th aperture over the i-th aperture in a modal serie which fits the field on i-th one. Field created by j-th aperture is calculated by means of electric field model or Chu model, including plane edge diffracted rays. Finally, aperture power wave coefficients ($a_n^i, b_n^i$) are obtained from the main mode of the input waveguide of each horn, from the generalized scattering matrix of the horns, and from the scattering coupling matrix between modes (computed with $C_{ij}^{mn}$ and $D_{ij}^{mn}$), following the procedure described in (J.B.Clarricoats et alt. IEE Proc. Vol 131, Pt H, June 1984).

Radiation and coupling integrals are computed by Gauss Legendre quadratures. This procedure let us analyze any kind of horns with analytic modes.

Some results obtained with smooth conical horns over metallic plates of several diameters will be presented.

## Thursday PM

Joint AP-S, URSI-B Session 74

### Numerical Techniques: Finite Element Methods

*Chairs*: Z. Pantic-Tanner, U. Illinois, Urbana; K. Umashankar, U. Illinois, Chicago

*Room*: Fir *Time*: 1:15–5:00

# SOLUTION OF THE 3-D VECTOR WAVE EQUATION IN AN OPEN REGION USING THE FINITE ELEMENT METHOD

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Three-dimensional electromagnetic scattering problems are of great interest to engineers and researchers. However, numerical solutions for practical 3-D problems are not currently feasible with traditional integral equation approaches due to the large amount of computer storage and time needed for solution. A differential equation solution approach for electromagnetic scattering problems has the advantage of producing a sparse system of equations which can be solved in a fraction of the time of that for an equivalent full matrix solution. The limiting factor in any differential equation solution is the size of the solution domain which must be discretized.

In practice, the infinite solution region is truncated at some finite distance away from the scatterer by an artificial boundary. Over the artificial boundary a radiating boundary condition is applied so that the boundary appears to the internal region to be infinite. The 3-D vector wave equation is solved using the finite element method in the internal region.

The finite element method for 3-D electromagnetic scattering problems will be described along with a vector 3-D radiating boundary condition. The accuracy of the radiating boundary condition will be given for various size scatterers as compared to eigenfunction and integral equation solutions. Problem solution times will be given for some commercially available supercomputers.

# AN INVESTIGATION OF ABSORBING BOUNDARY CONDITIONS AS APPLIED TO THE FINITE ELEMENT SOLUTION OF 2-D OPEN REGION ELECTROSTATIC PROBLEMS

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The traditional integral equation method for solving quasi-TEM planar structure problems is not always suitable for complex geometries. The finite element method of solution is not structure dependant and therefore allows for the solution of problems with general cross-sectional gemeotries. As currently being used, the finite element method is not commpetitive in open region problems with the integral equation method due to the large solution domain that must be discretized.

Previously, the open region electrostatic problems were truncated at some distance from the structure, and a homogeneous Dirichlet condition was applied on the outer boundary to approximate the boundary condition that the potential must go to zero at infinity. The use of an absorbing boundary condition (ABC) on the outer boundary gives a closer approximation to the inifinite region problem and thus the outer boundary can be placed closer to the structure.

The 2-D absorbing boundary condition for Laplace's equation as applied to electrostatic problems will be derived. Results for some representative planar transmission-line problems will be given with respect to the boundary distance and radiation condition order. Computer time comparisons will be made for the finite element solution using the ABC against other traditional solution methods.

# EFFECT OF EXACT AND APPROXIMATE RADIATION BOUNDARY CONDITIONS ON SOLUTION OF SCATTERING PROBLEMS BY THE FINITE ELEMENT METHOD

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Recent comparison of analytic radar cross sections and scattered fields for plane wave scattering by a dielectric, conducting, and coated conducting objects with the corresponding numerical results, obtained by a finite element code implementing local boundary conditions (e.g. Bayliss-Turkel type), has revealed non-negligible deviations. These deviations are partly attributed to the inherent discretization in the finite element approximation, and partly to replacement of the exact, global radiation boundary condition by a local boundary condition. The purpose of the present study is to explore the validity of the local boundary conditions by comparing them with two extensions of the finite element method, including the open region problem and incorporating the exact boundary conditions.

The first is the hybrid finite element method, in which the exterior is described by a surface integral equation, applied to a surface closely conforming with the scatterer; the interior is described by conventional finite elements. The second is the boundary element method, in which the boundary integral is discretized, resulting in reduction of the problem dimensionality by one when the medium is homogeneous. For inhomogeneous media that cannot be easily decomposed into homogeneous blocks one can combine finite elements in the inhomogeneous regions with boundary elements in the homogeneous regions.

The methods are applied numerically to 2-D scattering from perfectly conducting and coated conducting cylinders of various cross sections, and compared numerically with the finite element code involving the approximate local boundary conditions. Comparisons of accuracy, ease of implementation, and relative efficiency of the codes are made. These methods are also formulated in the 3-D case, and the anticipated numerical performance of the 3-D code, currently underway, is estimated.

# ON THE USE OF HIGH-ORDER INFINITE ELEMENTS IN QUASI-STATIC SOLUTION USING FEM

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*University of Illinois, Urbana, Illinois 61801*

The conventional finite-element method(FEM), which uses only ordinary elements, is not directly suited for treating open-region problems. Thus, these problems are typically handled only approximately by truncating the infinite region to a finite one, and placing a perfectly conducting shield at the outer boundary of this finite region. This, in effect, reduces the the original open region problem into a close one and enables one to apply the standard FEM method. However, the drawback in this approach is that, in order to achieve accurate results, the shield has to be placed far away from the structure being analyzed. This, in turn, results in a large FEM mesh and creates storage difficulties when solving large problems. In addition, the location of the shield has to be determined via numerical experiments, e.g., by moving the shield away from the conductors until satisfactory convergence of the solution is achieved.

An approach to circumventing the mesh truncation problem is to treat the open-region problem using special, infinite elements. Instead of truncating the open region and placing a shield at the outer boundary, the entire infinite region is now divided into two sub-regions, viz., the near-field and far-field regions. In the planar transmission line problems, that are of interest in this paper, the near-field region contains all the conductors and is divided into ordinary triangular elements. In contrast, the far-field region is divided into infinite elements which model the behavior of the field in the far zone in accordance with the asymptotic analytical solution. The nodes that lie on the interface between the two zones are common to both the ordinary and infinite elements. The potential in an infinite elements is expressed in terms of these nodes only. For the type of open region problems considered in this paper, the conductors are placed either above a single ground plane or between two parallel ground planes. For these configurations, the infinite elements ar typically chosen such that they have a 1/r decay built in the expansion functions. Again, the location of the interface between the near and far-field boundaries can be found via numerical experimentation. The advantage of employing the infinite elements is that the mesh size, and hence the computation time, can be significantly reduced.

In this paper we propose the use of high-order infinite elements, which include both the 1/r and 1/r**2 terms and show that that they provide additional reduction in the total mesh size. The use of these higher order elements enables one to bring in the far-field boundary even closer to the conductors, with just one additional layer of nodes in the far-field region. Numerical results show that the use of the second-order elements can reduce the FEM mesh size significantly in comparison to that required for the first-order elements.

# A New Hybrid Moment/Finite Element Method for Electromagnetic Scattering from Arbitrarily Shaped Inhomogeneous Dielectric Objects

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The problems of electromagnetic scattering due to inhomogeneous, lossy, and arbitrarily shaped dielectric bodies have received intensitive interest because of their presence in many practical applications. Many formulations have been devised to treat them. Among them are the moment method formulations using either surface or volume currents and the hybrid formulations that combines the finite element method to treat the interior inhomogeneities with either the wave harmonics (Unimoment method) or the integral equation method (for example, the extended boundary condition method and the boundary element method) to treat the unbounded problem. The later two methods are referred to as the finite element-boundary integral formulation (or FEBI) and the hybrid boundary element and finite element method (or BEM/FEM), respectively. Integral equation methods such as the method of moments treat the unbounded region very effectively. They, however, become computationally disadvantageous due to the resulting large and full matrix if complex inhomogeneities are present. In contrast, the finite element method handles inhomogeneties very easily and the finite element matrix is banded, sparse, and easy to compute. However, it is most suitable for a pure boundary value problem. Therefore, the hybrid methods that combine the finite element method with the integral equation method (e.g. FEBI and BEM/FEM) or the wave harmonics (unimoment method) are computationally efficient for problems involving complex inhomogeneities.

In this paper, we propose a new hybrid method that combines the method of moments with the finite element method, which has comparable advantages with the FEBI formulation and the hybrid BEM/FEM method. In addition, it facilitates the use of established moment method. The basic technique is to apply the equivalence principle and transform the original problem into the interior and exterior problems that are coupled on the exterior dielectric body surface through the continuities of the tangential electric field and magnetic field. The interior problem involving inhomogeneous medium is solved by the finite element method and the exterior problem is solved by the moment method. The coupling of the interior and exterior problems on their common surface results in a matrix equation for the equivalent current sources for the interior and exterior problems. In this paper two dimensional numerical results are presented to check the validity and accuracy of the method. Excellent agreement has been obtained with the exact eigenfunction solution, the unimoment solution, and Richmond's pure moment solution.

# AN EFFICIENT HYBRID FINITE ELEMENT METHOD FOR DENSELY COATED CONDUCTORS

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## Abstract

Hybrid finite element methods are a combination of standard finite element analysis and boundary element methods. Finite elements are used in and around the scattering object, where they are best able to model complex geometries and inhomogeneous materials. Boundary elements are used to provide a near field exact radiation boundary condition. A two dimensional code was written implementing this method for both TE and TM polarizations. This code was compared, for accuracy and efficiency, with the Mie series solution and with a method of moments code. The comparison involved the scattering from a conducting circular cylinder coated with physically thin optically thick material. In this case, a very high sampling rate is required in and around the coating. Finite elements are used here and to reduce the sampling to a very low rate away from the scatterer, outside the evanescent field, where the field is smooth. The finite element equations for this part of the problem are sparse and are solved efficiently and stably with banded LU decomposition with partial pivoting. A boundary integral solution is then applied at this low sampling rate to provide the exact near field radiation condition. The matrix representing these equations is dense but small due to the low sampling rate. It was found that the code is highly accurate and more efficient than the method of moments for this problem.

# ACCURATE ANALYSIS OF ANISOTROPIC MULTICONDUCTOR TRANSMISSION LINES STRUCTURES WITH FIELD SINGULARITIES EMPLOYING AN EFFICIENT FINITE ELEMENT METHOD SELF ADAPTIVE MESH SCHEME

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Félix Hernández-Gil. Telefónica, Investigación y Desarrollo. Lérida 43. Madrid 28020. Spain.

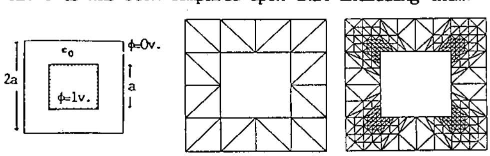
Finite Element Method is a powerful tool for microwave field problems analysis, but for accurate results it requires a mesh generation that take into account field distribution and singularities. This implies a difficulty to produce accurate and efficient fully automatic analysis programs.

A self adaptive algorithm that provides a new method for automatic mesh generation, with adequate field singularities handling is presented. It may be applied to any FEM formulation: transmission lines quasi-static or full-wave approach, discontinuties analysis, etc. The application of an adaptive scheme to microstrip-line structures quasi-static and full-wave FEM analysis represents a new contribution to this subject.

A summary of algorithm basis follows. The FEM is applied to a coarse initial mesh automatically generated from the structure description. The solution error is analyzed (D.W.Kelly,J.P. de S.R.Gago,O.C.Zienkiewicz,I. Babuska.IntJ.Num.Meth.Eng.,19,1593-1619,1983), providing information about if further mesh refinement is required and where to refine it; a better mesh locally-adapted is produced. The process will continue until a prescribed criterium is achieved. At each mesh step, FEM equations are solved by means of a preconditioned conjugate gradient iterative method.

Not only linear and higher order -for better field description and accurate curved boundaries consideration- ordinary triangular elements are provided, but also infinite and singular ones.

Good accuracy is obtained: figure 1 refers to a test structure; table I compares results with previous ones. Moderate CPU time is needed. Results of figure 2a) structure analysis are shown in figure 2b) and table II. Performance of the self adaptive analysis program without the infinite and singular elements has been compared upon that including them.

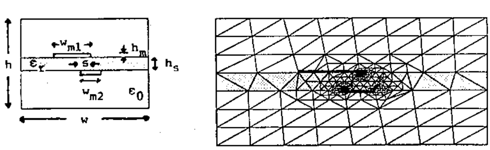



1a) 1b) 1c)

Figure 1. Square coaxial structure.
a)Structure. b)Initial mesh. c)Mesh step number 4.

| Mesh steps | $C_0/c_0$ | Error % |
|---|---|---|
| 5 | 10.240897 | 0.066 |
| 6 | 10.237448 | 0.033 |
| 7 | 10.235449 | 0.013 |
| [1] | 10.3644 | |
| Exact* | 10.2341 | |

Table I.Results.Pol.dg.=2
*[1]Daly,COMPEL,I.J.Math. E.E.Eng.,3,n.2,65-78,1984
*Carson,Cambrell,IEEE MTT-14,497-498 Oct.1966




2a) 2b)

Figure 2.Stripline-like asymmetric offset parallel coupler .
a)Structure. b)Mesh step for boundary conditions $\phi_1$=0v.,$\phi_2$=1v.

$C_{11} = 0.21195*10^{-9}$
$C_{22} = 0.19250*10^{-9}$
$C_{12} = -0.16498*10^{-9}$
$C_{011} = 0.42042*10^{-10}$
$C_{022} = 0.31714*10^{-10}$
$C_{012} = -0.17265*10^{-10}$

Table II.Results.
w=7.12mm,h=3.56mm, $h_s$=.508mm,$h_m$=0.mm, $w_{m1}$=1.6mm,$w_{m2}$=.8mm, s=.4mm,$\varepsilon_{11}$=9.4,$\varepsilon_{12}$=0. $\varepsilon_{22}$=11.6,pol.deg.=2.

## Thursday PM

Joint AP-S, URSI-F Session 77

### Layered Media

*Chairs*: D. G. Dudley, University of Arizona; D. R. Jackson, University of Houston

*Room*: Monterey *Time*: 1:15–4:40

# THREE-DIMENSIONAL ELECTROMAGNETIC GROUND RESPONSE FOR A MULTI-LAYERED EARTH WITH APPLICATION TO THE TWO-DIMENSIONAL/TWO-REGION CASE

Ira Kohlberg, Kohlberg Associates, Inc., Alexandria, VA

This investigation is concerned with the development of a mathematical proof that for an N-layer earth-model, including three-dimensional variations in the electromagnetic fields and frequency dependence of electrical parameters, it is possible to express the three components of the electric field and the vertical component of the magnetic field on the surface of the earth as a space-time integration of the two horizontal components of the magnetic field. It is shown that if

$$Y_i(\vec{r}_s,t) = \{H_{zs}, E_{xs}, E_{ys}, E_{zs}\} \quad ,$$

then every member of the set $Y_i$ on the surface of a finitely conducting earth is related to the horizontal components of the magnetic field through the equation

$$Y_i(\vec{r}_s,t) = \int_0^t \int_{\vec{r}_s'} T_{ix}(\vec{r}_s - \vec{r}_s', t-t') H_{xs}(\vec{r}_s',t')dt'dx'dy'$$

$$+ \int_0^t \int_{\vec{r}_s'} T_{iy}(\vec{r}_s - \vec{r}_s', t-t') H_{ys}(\vec{r}_s',t')dt'dx'dy' \quad ,$$

where the T's can be interpreted as Green's functions.

The general theory is applied to the Two-Dimensional/Two-Region case. The solution, which relates the surface components of the electric field to the two horizontal components of the magnetic field, is achieved by deriving a universal functional form for a dimensionless Green's function. This Green's function provides increasingly more accurate approximations to the response for each successive reflection from the second layer.

**Spectral Views and Alternative Representations of the Electro-Static Green's Function in Layered Dielectrics**

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Spectral views and alternative representations of the Green's function in layered dielectrics sandwiched by two grounded planes, or atop a grounded plane, are derived under electro-static condition in a similar way to the dynamic case [I.T. Lu, "Collective Ray and Hybrid Ray-Mode Method for Source Excited Propagation in a Multi-Layered Media - I. Formulation", 1988 National Radio Science Meeting, URSI, Colorado]. The Green's function is first represented by a spectral integral. Here, we have only evanescent spectra. By deforming the integration contour to enclose all pole singularities or the branch cut, the modal solution is represented by a sum of residues or an integral, respectively. These poles are related to the transverse resonance of the structure when the layered dielectrics are sandwiched by two grounded planes and, the branch cut is related to continuous spectrum when there is only one grounded plane. Alternatively, by series expansions of the resonance denominator in the integrand, one has sums of image integrals, which are equivalent to the conventional image solution. In analogy to the hybrid ray-mode method in the dynamic case, collective image schemes are derived to improve the convergence properties of the image solution. A combination of these alternative representations enables one to compute the Green's function efficiently for all possible arrangements of source and observer locations. Applications to analyze multiconductor transmission lines in mulltilayered dielectric media are also presented.

# LOCATION OF THE LEAKY-WAVE POLES OF A DIELECTRIC LAYER IN THE STATIC LIMIT

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Houston, TX 77204-4793

The use of a dielectric layer as a substrate for microwave and millimeter-wave applications is quite common. The modal solutions which may propagate on such layers have been extensively studied in the past. In particular, it is well known that the higher modes of a dielectric layer have a cutoff frequency above which they propagate as bound (slow) surface waves, with a real longitudinal propagation constant. Below the cutoff frequency they become leaky (fast) however, with complex longitudinal propagation constants. In some cases, these complex propagation constants can have real and imaginary parts of comparable magnitude. As a result, the task of numerically locating their position in the complex plane can become rather difficult.

In this presentation, we show a novel technique to derive simple and very accurate analytical expressions for the real and imaginary parts of the complex longitudinal propagation constant for the leaky waves on a dielectric layer in the static limit. Both TE and TM cases are treated, with or without a metal ground plane on one side of the layer. The TM leaky-wave poles are shown to approach complex constants as the frequency tends to zero, so that both the phase and attenuation constants ($\beta$ and $\alpha$) approach finite limiting values. The TE modes exhibit a different behavior however, with $\beta$ becoming infinite while $\alpha$ still approaches a finite limit. In the steepest-descent plane the TM-mode poles approach fixed points in the improper region as the frequency tends to zero, while the TE-mode poles descend downward, asymptotically approaching vertical lines.

Numerical results will be presented to show how the tracking of the complex pole locations at higher frequencies may be easily accomplished by using the low frequency locations as starting values. Knowledge of the leaky-wave pole locations may be used to predict and avoid any unwanted behavior related to the excitation of leaky higher modes.

[1] **Presently with the European Space Research and Technology Centre Postbus 299, 2200 AG Noordwijk ZH The Netherlands**

# APPROXIMATE FORMULAS FOR SURFACE WAVE POLES IN LAYERED MEDIA

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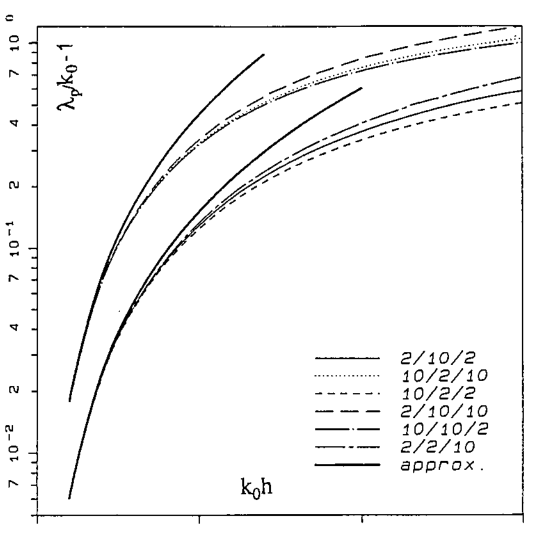
Ecole Polytechnique Fédérale de Lausanne, Switzerland

The theory of electromagnetic wave propagation in flat layered media can be found in many textbooks (for instance, J.A.Kong, Theory of Electromagnetic Waves, John Wiley & Sons, New York, 1975). It is shown that the eigenmodes associated with a structure formed by N layers sandwidched between two seminfinite media correspond to surface waves of TE and TM type. The propagation constants of these modes are obtained as roots of a characteristic equation involving transcendental functions and whose complexity grows quickly with the number of layers. The roots must therefore be obtained by numerical techniques. In this paper, we derive closed-form approximations for these roots which are accurate for an arbitrary number of electrically thin layers (roughly less than a tenth of a wavelength). These analytical approximations provide a good insight on how the surface wave parameters depend on the frequency, dielectric constant, thickness and number of layers. The formulas remain valid if the lower seminfinite medium is replaced by a ground plane (the multilayered microstrip). Thus, approximate analytical estimations of the power carried by the surface wave and of the radiation efficiency of a microstrip patch are possible. These approximations are also useful as starting points in a numerical search of the roots.

The figure presents the normalized propagation constant of the lowest TE-mode for a substrate formed by three dielectric layers of identical thickness, whose dielectric constants are either $\varepsilon_r$=10 or $\varepsilon_r$=2. All possible combinations of layers have been investigated. The exact results, obtained by a numerical search in the complex plane, show that for thin layers the propagation constant depends only sligthly on the relative position of the layers. This fact is confirmed by the approximate formula (solid line) which is independent of a permutation of the layers.



# WAVE PHENOMENA IN THE PRESENCE OF SHAPED AND TRUNCATED LAYERED DIELECTRICS: I-FORMULATION

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Weber Research Institute
Polytechnic University, Route 110, Farmingdale, NY 11735 USA

Sections of shaped single layer and multilayer dielectric materials find application for guiding, transmission, shielding, etc. The shaping may involve varying layer thickness, smooth curvature, and truncation. Determining source-excited electromagnetic wave behavior in the presence of such structures poses problems of substantial complexity. The approach taken here is to treat various noncanonical structural features as weak deviations from canonical, rigorously solvable prototypes. For effects of shaping, the canonical prototype selected here is a perfectly conducting circular cylinder covered with circular cylindrical dielectric layers of homogeneous composition. The previously developed three-dimensional vector Green's function for this structure (L.W. Pearson, Radio Science, Vol. 21, pp. 559-569, 1986) is generalized to allow for variable radius of curvature, variable layer thickness and (or) variable permittivities. The analysis, which is approximate, involves adiabatic Fourier transforms, spectral scaling, local resonance conditions and local modes, and, it is carried out in an infinitely extended azimuthal domain to remove the circular cylindrical $2\pi$-periodicity constraint. Alternative representations in integral and series form are derived which are best suited to characterizing particular wave phenomena, such as ray fields, guided modes, hybrid combinations, etc. Special consideration is given to layers whose thickness is small compared to the exterior wavelength. Helical truncation of such layers for the circular cylindrical prototype forms the canonical problem for end effects; this is treated formally by edge adapted spectral parametrization. Asymptotic reduction of these formal results is discussed in the companion paper.

# WAVE PHENOMENA IN THE PRESENCE OF SHAPED AND TRUNCATED LAYERED DIELECTRICS: II-ASYMPTOTICS WITH RAY INTERPRETATION

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Department of Electrical Engineering/Computer Science
Weber Research Institute
Polytechnic University, Route 110, Farmingdale, NY 11735 USA

Formal alternative representations of the three-dimensional electromagnetic vector Green's function for a multilayer dielectric, whose shape and composition deviates weakly from a circular cylindrical prototype, have been derived in companion paper. These formal results are now reduced by asymptotic methods applicable in the high frequency regime to yield a ray-optical description comprising leaky trapped and creeping layer guided local modes in addition to the geometrically reflected rays. The dipole-excited local mode fields follow surface ray trajectories determined by phase matching with the incident ray; due to the anisotropy of the modal dispersion relations in the longitudinal-azimuthal surface wavenumber domain, the local modes propagate like ray fields in an equivalent two-dimensional anisotropic medium. For thin layers with respect to the exterior wavelength, truncations generate edge coupled reflected modes and edge diffracted radiation fields. In essence, the results extend the geometrical theory of diffraction to configurations that contain shaped and truncated layered dielectrics.

# AN ALTERNATE APPROACH TO THE PROBLEM OF SCATTERING BY A SPHERE EMBEDDED IN A PLANE

BY R. DONNELLY & J. WALSH

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St. John's, Newfoundland, Canada, A1B 3X5

The results of a study of the electromagnetic scattering from a sphere embedded in a horizontal plane are presented. The formulation of the problem arises as a special instance of a previous general work by the authors, and does not follow the conventional methods of solving electromagnetic boundary value problems. Rather, it is based on a generalized function interpretation of the field quantities in the various regions. In the initial formulation the source field is arbitrary and the ensuing equations directly relate the unknown electric field and specified source field intensities. The boundary conditions evolve directly from the formulation as auxiliary equations. An expression for the electric field at any point on the surface is given for a sphere at arbitrary depth. This expression is used to develop a radar-range equation and a radar cross-section. Finally, a discussion is given as to the relevance of this work to scattering from sea-ice and icebergs.

## Thursday PM

Joint AP-S, URSI-B Session 78

**Millimeter Wave Antennas**

*Chairs*: D. B. Rutledge, Cal. Tech.; S. L. Chuang, U. of Illinois at Urbana

*Room*: Carmel *Time*: 1:15–3:00

# TOTAL MILLIMETER-WAVE POWER TRANSMITTED THROUGH UNIFORMLY ILLUMINATED SEMICONDUCTOR PANEL SCANNED WITH A STRIP OF SHADOW

M.H.RAHNAVARD
Electrical Engineering Department
Shiraz University,Shiraz,Iran

One of the needs in air traffic is to know the environmental situation under any weather condition. Visible or IR radar will fail in adverse weather because of high attenuation but there are several windows in millimeter wave region with low attenuation in bad weather concition (Weibel,C.H. and Dressel, H.O. 1967, Proc. IEEE, 55,497). One of the methods to convert millimeter wave to visible light is by using illuminated semiconductor panel. Semiconductor panels are used as image convertors in both transmission and reflection mode of operation (Jacobs, H.et.al, 1967,J.Opt. Soc. 57,913). In both cases the response of illuminated semiconductor panel is important. Excess carrier in moving strip illuminated semconductor panel is obtained by Rahnavard, et.al. (Rahnavard, et.al.J.Applied Physics, Vol.46,No. 3,March 1975, PP. 1229-1234). Using the above result attenuation coefficient and reflection coefficient for this case are also studied (Rahnavard, et.al. Sensor and Actuator Journal. Vol.12,No.4, pp.367-374(1987)). Transmission coefficient and local power transmission through uniformly illuminated semiconductor panel scanned with a strip of shadow are also studied (Rahnavard, et.al. Appl. Opt.26,pp.1213-1215, April 1987, Rahnavard, Microwave and Optical Technology letters,Vol. 1,No.6,pp.211-214). In this paper total transmitted power through uniformly illuminated semiconductor panel scanned with a strip of shadow vs. velocigy of the moving shadow strip, width of the moving shadow strip, attenuation etc. are studied.

# Total Millimeter Wave Power Reflectd from Moving Strip Illuminated Semiconductor Panel

M.H.RAHNAVARD
EE Dept.,Shiraz University
Shiraz,Iran

One of the needs in air traffic is to know the environmental situation under any weather condition. Visible and IR radar will fail in adverse weather because of high attenuation but there are several windows in millimeter wave region with low attenuation in bad weather condition (Weibel,C.H.and Dressel,H.O. 1967, Proc. IEEE, 55,497). One of the method to convert millimeter wave to visible light is by using illuminated semiconductor panel. Semiconductor panels are used as image convertors in both transmission and reflection mode of operation (Jacobs, H.et.al. 1967, J.Opt. Soc.57,913,). In both cases the response of illuminated semiconductor panel is important. Excess carrier in moving strip illuminated semiconductor panel is obtained by Rahnavard,M.H.et.al. (Rahnavard, M.H.et.al.,J.Appl. Physics, Vol.46,No.3,March 1975,pp. 1229-1234). Using the above result attenuation coefficient and reflection coefficient for this case are also studied (Rahnavard, M.H.et.al., Sensor and Actuator Journal Vol.12, No.4,pp. 367-374 (1987)). Local millimeter wave power reflected from moving strip illuminated semiconductor is also studied (Rahnavard, M.H.et.al. Proc. of SPIE Vol. 794 Modern Optical Characterization Techniques for Semiconductors and Semiconductor Devices (1987) pp. 266-271). In this paper total reflected millimeter wave power from moving strip illuminated semiconductor panel as a function of strip velocity,width,of the strip, etc. is considered.

# Optically Controlled Dielectric Resonator Oscillator for Millimeter Wave Applications

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* Drexel University, Center for Microwave- Lightwave Engineering, ECE Dept., Phila., Pa.

Over the past years there has been an increased interest in the use of the Millimeter Wave (MMW) frequency spectrum for communications and radar. Advances in solid-state device research, and Microwave Integrated Circuits (MIC) and Monolithic Microwave Integrated Circuits (MMIC) circuit fabrication has improved the performance and reduced the cost of MMW circuits. Systems such as active phased array antennas, which are made of many closely spaced individually controlled Transmit/Receive (T/R) modules, each with its own radiating element will use MIC and MMIC circuits. Distribution and synchronization of the MMW signals to each of these T/R modules is a formidable task requiring large amounts of metal waveguide or coaxial transmission lines for a distribution network limiting the system's capabilities. To circumvent these problems, fiber optic cables and electro-optic components can be used as a distribution network for microwave, millimeter wave, and control signals (phase shift, signal processing, etc.). Fiber optic cables have many advantages which can be exploited for MMW array antennas. These lightweight fiber optic cables have a larger bandwidth than conventional metallic transmission line, immunity from interference such as EMI and EMP, and very high isolation between adjacent cables.

Millimeter wave systems employing solid-state devices for power generation commonly use Gunn oscillators. In sophisticated systems requiring low noise, highly stable oscillators, Gunn oscillator performance can be improved with the use of a dielectric resonator as its frequency selective element. The dielectric resonator provides a high Q circuit which reduces oscillator noise and improves temperature and frequency stability over distributed element or lumped element resonators. For this investigation a Ka-band Dielectric Resonator Oscillator (DRO) using a Gunn device as the active element was designed as a millimeter wave source. The frequency of oscillation was controlled via a fiber optic link to demonstrate the ability of using optics as a distributive network.

The construction of the DRO is, as shown in Fig. 1, fabricated on a 0.010 inch thick duroid microstrip, with a packaged Gunn diode and a cylindrical dielectric resonator.The DRO was made optically sensitive by placing a photoconductor on top of the dielectric resonator. The photosensitive material chosen was high resistivity GaAs . Optical illumination of the GaAs increases the photoconductivity causing a perturbation of the fields around the dielectric resonator increasing the oscillating frequency. Optical tuning of the oscillator was obtained by a laser diode via an optical fiber through the hole in the top of the cavity. A maximum shift of the oscillator frequency observed was 4 MHz with 3 mw of optical power, however this was not repeatable due to the sensitivity of the position of the sample and the fiber. Changes of 2.5 MHz were observed with repeatability as shown in Fig. 2.

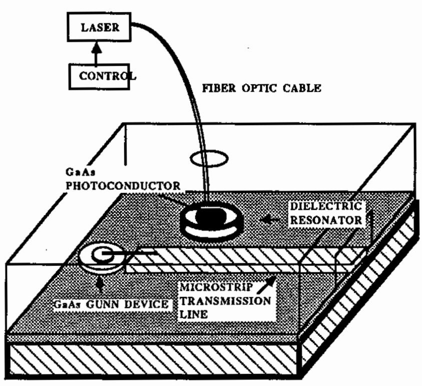


Fig. 1 Optically Controlled Dielectric Resonator Oscillator

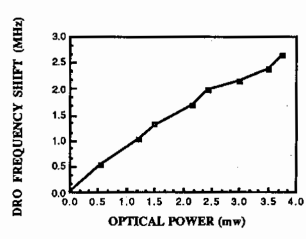


Fig. 2 Frequency shift as a function of optical power.

## Thursday PM

Joint AP-S, URSI-A,F Session 79

**Radar and Antenna Mesurements and Imaging**

*Chairs*: D. G. Falconer, SRI International; B. J. Cown, GTRI

*Room*: San Jose/Santa Clara *Time*: 1:15–5:00

# NEAR-FIELD SCATTERING MEASUREMENTS AND DATA PROCESSING TECHNIQUES FOR DETERMINING RCS

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Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia

Near-field measurement techniques have been used for antennas since the early 1970's. Due to advances in near-field measurement hardware and data processing capabilities and the current interest in radar cross-section (RCS) of complex targets, these near-field techniques are being investigated for determining the near-field and far-field bistatic and monostatic RCS. This paper addresses the issues of efficient acquisition and processing of the requisite scattered near-field electric field data for complex targets that are electrically and physically large, i.e., military aircraft/vehicles at micro/millimeter wave frequencies. Previous results of bistatic near-field measurements using compact range illumination and planar scanning of a small receiving probe are presented and discussed. Technical advances that overcome previous limitations of near-field measurements for large targets are discussed, and the notion of using probe arrays for rapid acquisition of near-field scattering data is examined. Several combinations of target illumination and near-field scanning techniques are considered. The techniques considered encompass mechanical and electronic scanning methods using single probes, one-dimensional (1-D) probe arrays, and two dimensional (2-D) probe arrays to accomplish the near-field scanning of the receiving surface, combined with either (a) compact range illumination or (b) "synthesized" plane wave illumination employing a single probe, a 1-D probe array, or a 2-D probe array. The problem of extracting the targets' Plane Wave (PW) scattering dyadic function from near-field data measured on planar, cylindrical or spherical surfaces is examined. In particular, a general Spherical Angular Function (SAF) integral formulation of near-field coupling/scattering for non-planar measurement geometries is presented, and an approximate "deconvolution" technique for computing the PW scattering dyadic function for electrically/physically large targets is described.

# IMAGE PROCESSING FOR DIAGNOSIS OF DISPERSIVE SCATTERING CENTERS

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This paper will present the results of gating in the two-dimensional image domain and the frequency-angle domain. Frequency-angle backscatter data were collected in the OSU Compact Range (Walton, E. K. and Young J. D., "The Ohio State University Compact Radar Cross-Section Measurement Range"' IEEE Trans. A & P, Vol. AP-32, Nov. 1984, pp. 1218-1224) over a bandwidth of 2 - 18 GHz and with angular resolution which satisfied the sampling theorem (Mensa, D. L., High Resolution Radar Imaging, Artech House, Norwood, Mass., 1981). These data were used to construct two-dimensional ISAR images of the targets.

Gating in the image domain was used to extract azimuth pattern and signature information about individual scattering centers. Gating in the frequency-angle domain was used to illustrate how the relative contributions of the scattering centers change depending on the look angle and frequency region being measured. In both cases the results were compared to theoretical predictions.

The results demonstrate the dispersive characteristics of scattering centers which are not evident in the image. Those artifacts introduced by the windowing process, depending on gating window size and character, are also discussed.

# RCS DECOMPOSITION BY AREA GATING

*Ron M. Ueberschaer*

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*ABSTRACT*

Range gating is a well-known technique for analyzing the RCS of individual scattering centers of a radar target. Unfortunately, for many targets, multiple scattering centers often exist within a single range bin, and cannot be separated by the range gating technique. Area gating is a straightforward two-dimensional extension to the range gating technique which overcomes this limitation. It is based upon 2D RCS imaging. By isolating a particular area in the image plane, the frequency and angle dependence of the scattering from that area of the target can be analyzed.

This paper begins with a review of the range gating procedure and 2D RCS imaging concepts. An outline and detailed description of the steps in the area gating procedure are then given, with experimental examples. Guidelines are established for the required data, methods of interpolation, placement of area gates, removal of windowing effects, and validation of results.

# IMAGE RECONSTRUCTION FOCUSING IN MICROWAVE HOLOGRAPHIC DIAGNOSTICS

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Y. Rahmat-Samii,UCLA,Los Angeles,CA 90024

**Abstract**

Far field measurements of antennas are made with respect to a phase reference plane which is determined by the measurement apparatus. The antenna surface can be reconstructed in this reference plane by utilization of microwave holographic techniques (Y. Rahmat-Samii, Radio Science, 13,1205-1217,1984). This plane does not necessarily provide the clearest surface reconstruction due to spatial divergence of the scattered rays from the antenna. By shifting the reference plane, the antenna surface may be more suitably focused and lend a better reconstruction of the antenna surface.

Reflectors with various types of distortions and dimensions are simulated with software and a far field is generated with respect to a specified phase reference. The reference plane is then moved by a proper manipulation of the far-field data. Different reference planes are selected, and other software reconstructs the surface distortions with respect to those planes by utilizing microwave holographic techniques.

Results indicate that selecting a reference plane as close to the reflector surface as possible provides the clearest reconstruction of the reflector surface. The image focusing is more pronounced for reflector antennas with small F/D ratio or small diameters. Further investigations will include reconstruction of planar array surfaces.

# CALIBRATION TARGETS FOR RCS MEASUREMENTS

*P.L.E. Uslenghi, S.F. Kawalko
Department of Electrical Engineering and Computer Science
University of Illinois at Chicago

B. Audone
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Caselle Torinese, Italy

A class of metallic objects which may be used as targets for calibration of radar ranges is suggested and studied in detail. With reference to rectangular (x, y, z) and spherical (r, θ, φ) coordinates, the targets consist of a metallic sphere occupying the region $0 \leq r \leq a$, that is intersected by one or more of three thin metallic circular disks of radius $r = b > a$, lying in the planes $x = 0$, $y = 0$ and $z = 0$, respectively. Such targets present the dual advantage of a simple geometry which is amenable to detailed study by analytical and numerical techniques, and of generating a cross-polarized component in the backscattered field.

Three targets are considered: a sphere with three disks; a sphere with two disks located in the planes $x = 0$ and $y = 0$; a sphere with one disk located in the plane $z = 0$. In all cases, the primary field is a plane wave of arbitrary polarization, incident in the first quadrant ($0 \leq \theta, \phi \leq \pi/2$).

The backscattered field up to moderately high frequencies is determined via either an integral equation which is solved numerically by method-of-moments techniques, or by expressing the fields in the regions $a \leq r \leq b$ and $b \leq r \leq \infty$ as two infinite series of spherical wavefunctions that are matched at $r = b$ after truncation.

The backscattered field at high frequencies is determined using the geometrical theory of diffraction. Contributions due to specular reflection and to first - and second-order edge-diffracted rays are considered. Corrections due to caustics and to the small but nonzero disk thickness are introduced. Comparisons are made with the results obtained by analytic-numerical methods.

# EXTRAPOLATION OF SWEPT-FREQUENCY RCS MEASUREMENTS TO THE FAR ZONE

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Electromagnetic Sciences Laboratory
Menlo Park, California 94025

ISAR imaging makes use of swept-frequency RCS data to form an approximate picture of the radar target. The imaging algorithms presume that the RCS measurements have been taken in the far zone. In practice, the RCS engineer may find it convenient or necessary to take the swept-frequency measurements in the near zone. To avoid image distortions, one must either correct the recorded data for near-zone effects before forming the ISAR image or modify the imaging algorithms themselves to prevent image distortions. As most imaging algorithms are fairly optimized, we have looked at how one might correct the recorded imagery prior to applying ISAR algorithms.

It was determined that better extrapolation accuracies and more manageable data arrays could be achieved by correcting the recorded RCS pattern one frequency at a time, rather than treating all frequencies simultaneously. As the illumination frequency is usually stepped faster than the azimuthal or elevational coordinates on an RCS range or in an anechoic chamber, this approach requires that the recorded data be completely reordered so that the near-field RCS patterns at each illumination frequency are available for extrapolation with our time-harmonic codes [D. G. Falconer, *Trans. AP-S*, vol. 8, no. 6, p. 822, 1988]. Many uses of ISAR imaging call for immediate extrapolation of the recorded data. To meet this need, we have employed FFT algorithms to effect the required Fourier transformations and direct-access files to store/retrieve our data sets. With these techniques and a MicroVax, we can extrapolate data sets with 200 frequency components and 270 azimuthal angles in about 20 minutes.

# ESTIMATION OF NEAR-ZONE BISTATIC RCS LEVELS USING FAR-ZONE MONOSTATIC RCS MEASUREMENTS

David G. Falconer, Ph.D.
SRI International
Remote Measurements Laboratory
Menlo Park, California 94025

We have developed and validated an algorithmic procedure for estimating bistatic RCS levels in the near zone using monostatic RCS measurements taken in the far zone. Our procedure begins with far-zone measurements of the monostatic amplitude, $A_m$, and a typical bisecting angle, $\theta_o$, about which one wishes to estimate the near-zone bistatic amplitude, $A_b$. A 60-degree window is first centered on the selected angle, $\theta_o$. We next resample the far-zone measurements of the monostatic amplitude, $A_m(k,R,\theta)$, where k is the radiation wavenumber, R the far-zone range, and $\theta$ the monostatic scattering angle, measured relative to the window's center. In particular, we follow Mensa [*High-Resolution Radar Imaging*, Artech, WDC, 1981] and convert the uniform samples in $\theta$ to uniform samples in sin $\theta$, obtaining thereby a new data set of the form $A(k,R,\sin\theta)$. Next, we inverse Fourier transform the resampled data by applying the kernel $\exp(+i2kx \sin\theta)$ and then integrating with respect to the natural transform variable, $(k \sin\theta)/2\pi$. The latter operation yields the equivalent obliquity factor, O(x) [D. G. Falconer, *IEEE Trans. AP-S*, vol. 36, p. 822, 1987]. To estimate the desired near-zone field, we multiply the *equivalent obliquity factor* by the phase factor $\exp[ikx^2(1/2R' + 1/2R")]$, where R' and R" are the illumination and observation ranges at which one wishes to estimate the near-zone amplitude. Next, we forward transform the modified obliquity factor by applying the kernel $\exp[-ikx(\sin\theta' + \sin\theta")]$ and then integrating with respect to the spatial variable x, where $\theta'$ and $\theta"$ are the illumination and observation angles at which one wishes to estimate the bistatic amplitude. Finally, we resample the transformed factor with respect to both sin $\theta'$ and sin $\theta"$, thereby obtaining the desired estimate of the bistatic amplitude $A_b(k,R',R",\theta',\theta")$.

The above procedure has direct and important application in assessing the expected performance of semiactive seeker missiles, since the radar systems used by such missiles operate bistatically in the near zone of the target aircraft or vessel. In particular, the above procedure allows the performance analyst to properly assess how glint and scintillation may be expected to vary with bistatic angle and near-zone range.

# A PHYSICAL MODEL FOR DETECTION WITH OVER-THE-HORIZON RADAR

Ronald L. Fante* and Sachidulal Dhar
The MITRE Corporation
Bedford, Massachusetts 01730

A model for over-the-horizon detection has been developed that proposes multipath and Faraday rotation as the root causes of target-signal-strength fluctuations, with additional longer-term fluctuations produced by ionospheric variations. Using this model the probability of detection has been computed for targets with arbitrary polarization properties. It is found that both multipath and Faraday rotation strongly influence the detection statistics, with the effect being greatest for linearly-polarized and less dramatic for symmetrical targets.

## Thursday PM

Joint AP-S, URSI-B Session 80

**Transient Scattering & Propagation**

*Chairs*: A. G. Tijhuis, Delft Univ. of Tech.; E. J. Rothwell, Michigan State Univ.

*Room*: San Carlos *Time*: 1:15–3:40

| | | |
|---|---|---|
| 1:20 | **Time Domain Analysis of Signal Propagation in Planar Transmission Lines and Discontinuities**<br>R. L. Geiger,* R. Mittra, Univ. of Illinois at Urbana-Champaign | 358 |
| 1:40 | **Some Important Properties of the Impulse Response for the Bistatic Case**<br>S.-M. Lin,* Northwestern Polytechnical Univ., Xi'an | AP-S |
| 2:00 | **A Luneberg-Kline Expansion Solution for the Transient Scattering of Cylindrical Waves by a Circular Cylinder**<br>J. Ma, I. R. Ciric,* University of Manitoba | AP-S |
| 2:20 | **Time Domain Electromagnetic Scattering from Thin, Conducting Surfaces Using the Electric Field Integral Equation**<br>P. D. Smith,* University of Dundee | 359 |
| 2:40 | **Coffee Break** | |
| 3:00 | **On the Self-Focusing of Beams During Linear Propagation**<br>P. P. Banerjee,* Syracuse University, T.-C. Poon, Virginia Polytechnic Institute | 360 |
| 3:20 | **Comparison of Experimental and Numerical Results for Transient Electromagnetic Fields Induced on a Scale Model Aircraft by Current Injection Technique**<br>J. Grando,* G. Labaune, J. C. Alliot, F. Issac, A. Delannoy, ONERA | AP-S |

# TIME DOMAIN ANALYSIS OF SIGNAL PROPAGATION IN PLANAR TRANSMISSION LINES AND DISCONTINUITIES

*Robert L. Geiger* and Raj Mittra*
Electromagnetic Communication Laboratory
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The development of design rules for automated, computer-aided design of microwave and digital circuits is greatly facilitated if the propagation characteristics of various transmission lines, and the scattering properties of discontinuities in these lines, is readily available to the circuit designer in a convenient form. The increasing compactness, speed, complexity and the cost associated with the design iteration of an integrated circuit board makes it invaluable to have access to accurate simulation models that provide knowledge of circuit performance before actual construction. In this paper we employ a modified version of the transmission line method (TLM) for modeling three-dimensional electromagnetic fields, employed in an earlier paper by Yoshida and Fukai for graphical display of signal propagation in stripline structures, to investigate the modeling and simulation problems in integrated circuits.

The TLM method used by Yoshida and Fukai to construct a time-domain solution of Maxwell's equations placed each of the six field components on a different spatial node. Unfortunately, such a field representation makes the modeling of complex structures a formidable task, as it requires a great many nodal points to achieve a desired resolution. This may perhaps explain why complex discontinuities in microwave circuits have not been investigated in the past using the conventional TLM. However, the condensed node version of the TLM, proposed by Johns obviates this problem as it places all the six components of the electric and magnetic fields at the same nodal point.

Field distributions for several different microstrip geometries are computed in this paper using the condensed node TLM, including those for layered structures. The knowledge of the time signature of the field distribution is not only useful in determining the dispersion characteristics of uniform lines but is also helpful in examining how various design choices affect the VSWR, electromagnetic interference and crosstalk noise.

Graphical displays of field component magnitude for representative problems will be presented in selected planes at selected time intervals. These graphical displays will be used to identify some of the causes of transmission difficulty in microstrip structures such as layered integrated circuit packages. A discussion of the practical aspects of implementing the TLM method on the computer and the use of absorbing boundary condtions for mesh truncation are included in the paper.

# Time Domain Electromagnetic Scattering from Thin, Conducting Surfaces Using the Electric Field Integral Equation

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We consider the problem of transient scattering of electromagnetic pulses from thin, perfectly conducting surfaces and discuss a solution procedure based on solving the time dependent electric field integral equation (EFIE)

$$\left[\frac{\partial \mathbf{A}}{\partial t} + \nabla\phi - \mathbf{E}^i\right]_{\tan} = 0 \qquad (1)$$

on the surface (where $\mathbf{E}^i$ is the incident electric field and $\mathbf{A}$, $\phi$, denote the vector and scalar potentials), together with the continuity equation

$$\nabla_o . \mathbf{J} + \frac{\partial \rho}{\partial t} = 0 \qquad (2)$$

(where $\mathbf{J}$, $\rho$, denote the induced currents and charges on the surface and $\nabla_o . \mathbf{J}$ denotes the surface divergence of $\mathbf{J}$) to obtain the current on the surface by a time-marching technique. Such a solution procedure generally encounters 3 main difficulties:

(i) the EFIE contains derivatives along the surface which must be evaluated numerically;
(ii) the condition that the normal component of the current must vanish on the edges must be enforced;
(iii) time marching solutions of transient problems generally have a tendency to become numerically unstable at large times.

Considering first a flat plate of arbitrary shape we describe a solution procedure which deals with difficulties (i) and (ii) in a very simple manner and which is found to be stable at large times. This procedure is based on a finite difference solution of the coupled equations (1) and (2) using a set of 3 overlapping grids on the surface to discretise the equations. These grids are similar to those used previously (A. W. Glisson, D. R. Wilton, IEEE Trans. Ant. Prop. AP-28, 593-603, 1980), to obtain frequency domain solutions for scattering from bent plates and are chosen in such a manner that the surface derivatives in (1) and (2) can be easily evaluated by simple finite difference formulae.

In addition a von-Neumann type stability analysis provides a stability criterion relating the grid size to the time step which ensures the stability of the solution. This result is particularly important, since the instability usually encountered in time marching solutions of the EFIE has restricted its usefulness to rather short time scales, and forced the development of other, more cumbersome, solution methods, such as the conjugate gradient method. Finally, the above solution procedure can be extended to cope with general curved surfaces using triangular patch basis functions (defined by S. M. Rao, D. R. Wilton, A. W. Glisson, IEEE Trans. Ant. Prop. AP-30, 409-418, 1982).

# ON THE SELF-FOCUSING OF BEAMS DURING LINEAR PROPAGATION

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## ABSTRACT

Self-focusing of beams during propagation in a nonlinear medium is well-known (see, for instance, A.K. Ghatak and K. Thyagarajan: Contemporary Optics, Plenum NY 1978). This occurs primarily due to the fact that in a nonlinear medium the refractive index is dependent on the intensity distribution during propagation. In linear media, the presence of so-called diffractionless beams is known to researchers in the optics area. Also, image synthesis using self-imaging concepts have been reported (Packross et al Opt. Comm. 56 (6) 1986). In both cases, the cause of the aforementioned effects is due to the special shape of the initial amplitude profile of the beam. For instance, in the former case the beam profile has a Bessel-function dependence, while in the latter, the initial beam profile is spatially periodic.

In this talk, we provide a systematic approach to studying these effects through the use of (a) the eikonal equations in the presence of diffraction and (b) the transfer function approach to propagation. The nature of the initial amplitude (and phase) profile of the beam required to produce self-focusing/self-imaging effects are studied, and examples are provided. It is shown that the diffractionless beams and self-imaging examples stated earlier follow as special cases of our general approach.

PPB wishes to acknowledge the support of the National Science Foundation under Grant no. MIP 8657765, and a matching grant from Xerox Corporation.

## Thursday PM

URSI-F,H Session 81

### Communication Through the Atmosphere and Ionosphere

*Chairs*: D. H. Cheng, NUSC; I. Ishihara, Nat. Defense Academy of Japan

*Room*: San Juan *Time*: 1:15–4:00

# HYBRID RAY-MODE-PE FORMULATION OF HIGH FREQUENCY PROPAGATION IN A BILINEAR TROPOSPHERIC SURFACE DUCT

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Analytical modeling of high frequency propagation in tropospheric elevated or surface ducts by normal (trapped) and leaky modes is inconvenient because of the large number of modes that may be required. Moreover, synthesis with normal modes, while accurate when the refractive index varies only with height, does not incisively model the physics of the propagation process in those domains where that process is essentially ray-like or beam-like. A hybrid ray-mode-PE (parabolic equation) formulation has been developed, which combines the various wave processes self-consistently. It appears that legitimate ray fields (with caustic corrections, when required) furnish an efficient model away from the strong trapping regime near the lower boundary and the trapped-to-leaky transition near the upper boundary of the duct, with a few whispering gallery modes included in the boundary layer near the bottom, and a number of (trapped and leaky) transitional modes near the top. A PE-propagator can be substituted for essentially forward propagating modes. This parametrization is tested on a bilinear refractive index height profile, and compared with a modal reference solution. The numerical comparisons reveal the observation domains where the hybrid algorithm is effective. The ray-PE format is readily extended to weak longitudinal variations in the index profile.

# MODELING AND SIMULATING SECONDARY FADING STATISTICS OF MOBILE SATELLITE SIGNALS

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Mobile satellite systems being planned for the 1990's will have to contend with severe multipath and vegetative fading and will have small link margins. Statistical models of the signal fading behavior are a convenient method of predicting system reliability and availability prior to the launch of a working satellite system. The models used to predict the fade distributions of mobile satellite signals are based on the primary statistical behavior of the signal and describe only the gross signal fading behavior. The secondary fading statistics of the signal (level crossing rate and average fade duration) are also of importance in mobile satellite system design. The secondary statistics of the fading signal are related to the received signal multipath spectrum and autocorrelation. While no explicit models exist to describe the secondary statistics, results have been obtained from a software propagation simulator that was built on primary statistic models. Results comparing simulated data and measured data will be presented.

# GLOBAL-SCALE MODELLING OF ENVIRONMENTAL EFFECTS ON HF SYSTEMS

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We have developed a three-dimensional global-scale code for the testing, simulation, verification and validation of ground-based, airborne, and space-borne hf systems. The code employs internationally-accepted and tested empirical models for the ionosphere, atmosphere and auroral boundaries. Coupled with a fully-three-dimensional ray tracing module we can simulate and test the environmental influences associated with seasonal, solar cycle, diurnal and geomagnetic controls. In its current form our model specifies the electron densities over the 80 - 1000 km altitude regime, and includes ion and neutral atmospheric species and density distributions as well as all particle temperatures. The ray tracing component accounts for all relevant collision terms and the influences of the geomagnetic field, while the specification of the environmental components are provided by the International Reference Ionosphere, the MSIS (for the neutral atmosphere), and the Feldstein, DMSP and NOAA/TIROS models (for the boundaries of the auroral oval). We can determine the propagation characteristics for hf communications or over-the-horizon radar systems including the influences of ducting, ionospheric tilts, and seasonal, solar-cycle and geomagnetic controls. We will present and describe the code components, verification data, and specific illustrations of code applications to the diagnostics of an hf communications channel and to barrier placement and clutter-to-noise ratios for over-the-horizon radar systems.

# SPREAD SPECTRUM HF COMMUNICATION IN THE AURORAL ZONE OVER A 300-KM PATH

**David H. S. Cheng*, David J. Saleem, Paul M. Mileski; Naval Underwater Systems Center**
**Eivind V. Thrane; Norwegian Defence Research Establishment**

High Frequency (HF) communication in the auroral zone is difficult due to the rapidly varying characteristics of the ionosphere. This study was done to demonstrate the need for frequency flexibility and to explore spread spectrum techniques to improve reliability of HF communications.

A medium range test circuit was set-up in Norway with the transmitter located at the Andoya Rocket Range at Andenes and the receiving station at Alta. They are about 300-km apart. A digitally coded message of 15120 databits in length was transmitted on 9 carrier frequencies in succession: 3.0, 4.5, 6.0, 8.5, 10.5, 12.5, 14.5, 17.0, and 19.0 . At each frequency, five different bandwidths were used: 0.4, 6.0, 20.0, 80.0, and 120.0 kHz. All were modulated using a direct sequence spread spectrum technique with a spreading code length of 31 bits except at 0.4 kHz, which was transmitted in a conventional mode for comparison purposes. Each cycle of frequencies and bandwidths took 52 minutes to transmit and was repeated every hour for most of August through November 1987. The ionospheric conditions were monitored with a riometer, magnetometer, and a vertical sounder, all located at the Andoya Rocket Range.

Time availability as a function of bit error rate was determined for each hour of the day for each combination of bandwidth and carrier frequency. Spread spectrum modulation increased the time availability at all frequencies tested, although bit error rates were found to increase with bandwidth. The best carrier frequency for both spread spectrum and conventional modes was 4.5 MHz with the spread spectrum bandwidth of 6 kHz having the highest time availability. All carrier frequencies over 6 MHz were poor in comparison.

Preliminary results indicate that time availabilities of 70-80% with an accepted bit error rate of 10% are possible using spread spectrum techniques.

# HIGH THRUPUT BURST TELECOMMUNICATIONS: NOVEL ADAPTIVE HF/ METEORBURST SYSTEM DESIGN

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The mode of communication,whether be the transmission of information from a transmitter to a receiver or the 'fetching' or 'retrieval' of information from a transmitter by a receiver, may be continuous or burst. The burst transmission may be due to intermittent source data or intermittent channel availability or the combination of both.In this paper,we consider burst channel characterization by network parameters,burst interval and waiting times, and discuss design issues for obtaining survivable author proposed high thruput meteorburst/HF telecommunication system(A.K.Gupta and J.R.Herman, URSI Radio Science Meeting,Boulder,Jan. 1988;A.K.Gupta,IEEE Int. AP Symposium and URSI meeting,Syracuse,June 1988).

Specifically,we design an adaptive high data rate MBC system and an adaptive HF communication system,utilizing coded MFSK signalling, multichannel diversity,frequency management techniques such as frequency -hopping(FH) and this author proposed high-supperession adaptive filtering.Some of the coding schemes analyzed in this paper are: orthogonal codes,dual-K codes,Reed-Solomon codes and concatenated codes. The multichannel diversity may be some combination of waveform,frequency and space diversity. The transmitted waveforms are compared on the basis of complexity,time-varying bit energy to noise ratio,bandwidth expansion factor and number of chips required to maintain a high average data rate or average thruput at specified bit error rate.

For meteorburst channel,we relate the network parameters of the proposed 'modified Rician' model(A.K.Gupta and J.R.Herman,IEEE Int. AP Symposium and URSI meeting ,Syracuse,June 1988) in terms of link parameters and propose a telecommunication model interms of M/M/1 with bulk arrivals of size 2. The model is modified in the sense that both Rician components are present in a time period rather than at any instantaneous time.Assuming negligible burst duration and poission meteor arrivals for underdense and overdense trails with x and y parameters,the prob. density of epochs of the combined returns is shown to be poission with parameter x+y.For Rayleigh channel and finite burst interval,the waiting time distribution is obtained from the probility theory under the assumption of known prob. distributions of epochs and burst interval.For modified Rician model,the waiting time distribution is obtained from the queuing theory model.Such telecommunication model is thus useful in analyzing multimedia multichannel systems.

# PARAMETRIC INVERSION OF ONE-DIMENSIONAL ELECTRON DENSITY PROFILES

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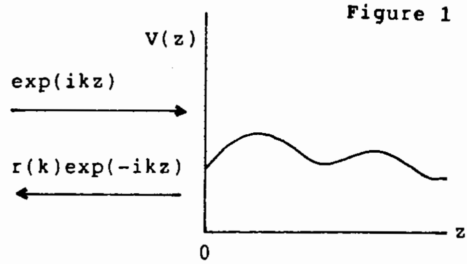
In this paper, parametric inverse scattering theory is implemented to reconstruct electron density profiles. Specifically, the one-dimensional electron density profile V(z) is obtained based on the knowledge of the reflection coefficient r(k) through a parametric inversion. The geometry under consideration is shown in Fig. 1. This problem has been previously investigated by both exact and perturbational algorithms. However, the applicability of the exact algorithm is limited to the class of reflection coefficients such as rational functions. In addition, we show here that the perturbational solution is not robust with high frequency noise. Physical origin of this instability will be discussed.

Here, we implement a parametric inverse scattering in order to enhance both the accuracy and the robustness of the perturbational solution. That is, a perturbational solution with a proper bandlimitation becomes an trial function of a desired profile. Two undetermined parameters, which avoid significant amplitude and phase errors, are introduced into the trial function. Then two parameters are optimized such that they yield least mean square errors in the reflection coefficient. The advantages and disadvantages of this approach will be presented with several examples.

Figure 1



POTENTIAL IONOSPHERIC LIMITATIONS ON SPACE-BASED RADAR PERFORMANCE

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Ionospheric effects on radar signals can pose serious limitations to the performance of space-based radars in trans-ionospheric surveillance missions. As such, it is necessary to understand those effects which can limit SBR performance and to treat the ionosphere as one of the design constraints on system performance. Irregularities in the ionosphere can contribute significant clutter and can cause amplitude and phase scintillation on target returns. If a single, linearly polarized radar signal is used, Faraday rotation can produce large return signal loss. These effects can vary greatly, being dependent upon SBR design frequency, geographic region of operation, viewing angle with respect to the earth's magnetic field, time of day, season and state of solar and geomagnetic activity. The largest effects occur in the equatorial and near-equatorial regions of the world, where the Faraday rotation can be a maximum, and where the scintillation effects are greatest. The ionosphere above the polar cap and auroral regions, can also have important effects on SBR performance.

Potential impacts on SBR performance can be minimized in the design phase by careful consideration of ionospheric effects on the radar return signal. The impact of a particular effect will be highly dependent upon design parameters such as frequency, altitude, integration time, and coverage geometry. In order to provide corrections for the ionosphere for various systems, including potential SBRs, the U. S. Air Force Air Weather Service is deploying a number of ionosphere monitoring stations which will input in real time to greatly improved models of the ionospheric parameters which can affect SBR operation. These systems will ultimately provide real time specification and short term predictions of ionospheric behavior over specific regions for operational users.

## Thursday PM

URSI-B Session 82

### High Frequency Diffraction II

*Chairs*: P. H. Pathak, Ohio State University; R.-C. Chou, Ohio State University
*Room*: San Martin *Time*: 1:15–4:00

# FAR-ZONE REFLECTION FROM 2-D SUPERQUADRIC SURFACES

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The Geometrical Optics (GO) reflection from a smooth 2-D subclass of superquadric surfaces is examined. These smooth convex surfaces exhibit points of zero curvarture, from which GO predicts unbounded reflected fields. In order to obtain a uniform result, a transition function is derived via an asymptotic analysis of the Physical Optics formulation.

The transition function augments the GO expressions producing a bounded and accurate result for the reflected field. The heart of the transition function is a family of functions related to the so-called diffraction catastrophe integrals which, in the context of this analysis, furnish an oscillatory pattern effect which is characteristic of radiating apertures.

Solutions are obtained for the bistatic reflected fields for two cases:

1) the entire family of superelliptic cylinders when the reflection point is located on the zero-curvature point,

2) those cylinders accociated with a superelliptic parameter of three when the reflection point is located anywhere on the cylinder surface.

The solution, consisting of GO together with the transition function, shows excellent agreement with results obtained by both Physical Optics and the Method of Moments.

# OFF-AXIS BACKSCATTERING FROM CONE-SPHERE

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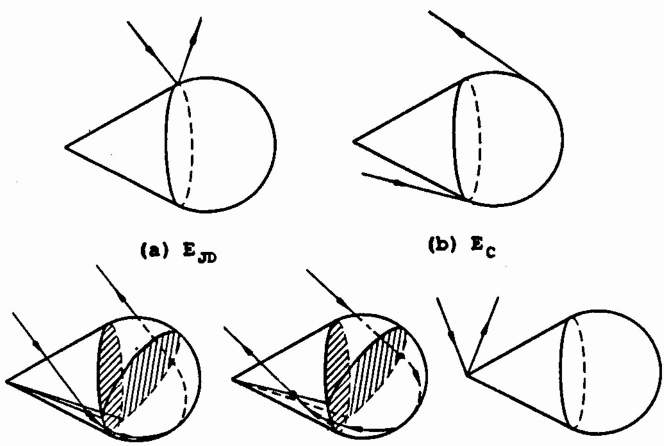
EM scattering from conducting cone-sphere in the principle planes is generated by a UTD solution. This is to the best of our knowledge the first UTD solution for non axial backscattering for the cone-sphere. Several diffraction mechanisms are introduced. One of these ($E_{GDC}$) is the ray initiated at the shadow boundary, creeps over the cone surface and eventually diffracts off the principle plane to the backscattering direction. This and other significant rays ( illustrated in the following figure ) will be dicussed.



(a) $E_{JD}$ (b) $E_C$

(c) $E_{GDC}$ (d) $E_{CDG}$ (e) $E_{TD}$

The results of the UTD solution are compared with those obtained from a moment method solution for an included cone angle of 30°. The results are in execellent agreement.

# MULTIPLE DIFFRACTION PAST A LINEAR ARRAY OF MANY EQUALLY SPACED KNIFE EDGES

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We have considered the high frequency diffraction of electromagnetic waves past an array of parallel half planes. The half planes are assumed to be equally spaced and of equal height so that their edges all lie in a plane. Both incident plane waves and cylindrical waves are considered for propagation nearly parallel to the plane of the edges. In this case each edge lies near the shadow boundary of the previous edge, and the multiple diffraction process cannot be treated by the Geometrical Theory of Diffraction. Using the physical optics approximation it is possible to represent the field in the form of a n-dimensional Fresnel integral. The multiple integral, in general, can only be evaluated numerically. However, if we restrict ourselves to computing the filed incident on successive edges, a physically incisive solution is achieved by utilizing Boersma's closed-form results for relevant n-fold integrals whose integrands containing the exponential of a specific quadratic form. For small glancing angles $\theta$, this expression allows for numerical evaluation for both incident plane and cylindrical waves, even if the number of edges is as high as 1000. The edge fields are found to depend on the single parameter $\theta\sqrt{d/\lambda}$, where d is the spacing between edges and $\lambda$ is the wavelength. For the special case of incidence parallel to the edges, our results are in agreement with those previously derived by Lee.

For the case of plane wave incidence from above the plane of the edges, the edge fields are found to settle to a finite value. This settling phenomena can be understood with reference to Fresnel zone theory. The edge fields due to a cylindrical wave incident from above can also be interpreted in terms of the settling phenomena after many edges. When the fields are incident from below the plane of the edges, the edge fields decrease rapidly with edge number, even for small angles.

# SCATTERING BY CAVITY-BACKED CRACKS

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A topic of some concern in radar cross section studies is the scattering from the gap or crack that may exist where two component parts of a target come together. Even if the crack is wholly or partially filled with a material, it can still provide a significant contribution to the overall scattering pattern of the target, and it is then necessary to develop methods for predicting the scattering.

One method for doing this was described in a recent paper (T.B.A. Senior and J.L. Volakis, submitted to *IEEE Trans. AP-S* ). For a place wave of either principal polarization incident on a narrow ($kw << 1$) resistive strip insert in an otherwise perfectly conducting plane, the quasi-static integral equations for the currents induced in the strip were solved in a pseudo-analytical manner, leading to expressions for the far zone scattered field that are accurate for almost any resistivity R of the insert. If, instead, the insert is characterized by a surface impedance $\eta$, the results differ only in having R replaced by $\eta/2$ and the scattered field doubled, and this suggests that for a narrow gap backed by a cavity, the scattered field can be obtained by identifying $\eta$ with the impedance looking into the cavity.

An alternative approach is to use the equivalence principle to develop coupled integral equations for the electric and magnetic currents which exist on the walls of the cavity and in the aperture, and this is the method employed here. For an incident plane wave either H- or E-polarized, the integral equations are derived for a cavity of arbitrary shape filled with a homogeneous material. The equations are solved by the moment method and data for a variety of simple cavities are presented. For gap widths which are electrically small the results are compared with those obtained using the previous method. When the cavity is rectangular, a simple quasi-static expression is available for the impedance looking in, and in this case at least, the agreement is very good.

# ON THE USE OF A BEAM METHOD FOR ANALYZING THE EM SCATTERING BY OPEN-ENDED WAVEGUIDE CAVITIES

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The high frequency scattering from the interior of a relatively arbitrarily shaped open ended waveguide cavity which is illuminated by an external EM plane wave in free space is analyzed using a beam shooting method. It is assumed that the waveguide cavity contains an interior termination which is a planar boundary. The cavity walls and the termination can be perfectly conducting or contain a thin layer of material coating. This method provides a useful alternative to modal as well as geometrical optics ray shooting methods for reasons which will be made clear shortly.

In this beam method, the aperture is divided into subapertures, and the field incident in the aperture at the opening of the cavity is expanded in terms of a set of well focused, shifted, and rotated Gaussian beams (GB). The initial conditions on the GBs are found quite accurately from the radiation patterns of the subapertures in the absence of the cavity walls. These GBs are then launched into the cavity and tracked via multiple reflections at the interior cavity walls using the real paraxial approximation. Such a procedure whereby the beams are tracked paraxially along their beam axes is thus referred to as the real paraxial Gaussian beam (PGB) method. It is found that the beams need to be tracked only once independent of the incident angle making this a highly useful feature of the PGB approach. This is in contrast to the geometric optics (GO) ray shooting approach where a new set of rays must be tracked, via multiple reflections at the cavity walls, for each new incident angle. Also, a generalized reciprocity argument can be developed to show that beams need to be tracked only from the open end to the termination, and not back, to find the interior cavity scattering. Furthermore the PGB method contains the effects of waves diffracted into the cavity via the edges at the open end which the GO ray method does not. In addition, the PGB overcomes the limitation of GO rays at caustics within the cavity. The PGB method also overcomes the limitation of the modal approach at high frequencies where an extremely large number of modes are excited within the cavity making the modal approach inefficient. Unlike the PGB method, the modal approach is of course restricted only to waveguide cavity shapes for which modes can be found. However, the PGB approximation tends to lose accuracy due to the distortion of the beams at each interior reflection; thus, typically, cavity lengths less than 3 or 4 times the cavity width can be treated well by the PGB approximation. Numerical results will be illustrated for some 2-D S-shaped cavities and compared with results based on a reference modal solution.

# ON RAY METHODS IN COMPUTING THE ELECTROMAGNETIC SCATTERING FROM OPEN-ENDED CAVITIES

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One problem of considerable recent interest is that of the electromagnetic scattering from open-ended cavities and inlets. For high frequency scattering from arbitrarily shaped cavities in which modes cannot be easily defined or found, the geometric optics (GO) ray approach has proved to be very promising. Ray methods allow for the realistic modelling of complex targets. Basic ray methods in inlet applications model an incident plane wave as a dense grid of parallel GO rays that are "shot" into the cavity aperture. The rays are allowed to bounce within the cavity until they exit the cavity. Physical optics is then used to sum up the far field scattering contribution from each ray. Other variations of the ray method include a generalized ray tracing approach in which the cavity aperture is divided into sub-apertures, and a cone of rays in different directions and with different amplitude weightings are launched into the cavity from each sub-aperture. Another method which requires the fewer rays to be traced is a real paraxial Gaussian beam tracing technique.

The basic ray method is conceptually simple and highly versatile. However, it neglects the fields coupled into the cavity interior via edge diffraction by the aperture. Additionally, a new set of rays must be traced for each new incident angle. Both the generalized ray tracing method and the Gaussian Beam tracing method overcomes both of these limitations and implicitly includes the interior effects of aperture edge diffraction as well as requiring only one ray/beam tracing for a wide range of incident angles. For arbitrary aperture shapes, the generalized ray method has the added complexity of defining sub-apertures. And the Gaussian beam method has the main limitation that the beams become more distorted the further they propagate inside a curved cavity and restricts the length/width ratio of cavities that can be analyzed by this method.

Typical numerical results based on the different approaches will be presented, and the pros and cons of these approaches will be discussed.

# 1990

## IEEE AP-S International Symposium & URSI Radio Science Meeting

**May 7 – 11, 1990**

**Dallas Convention Center**
**Dallas, Texas**

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26. Other

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- A-4. Measurements Using Scale Models
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- A-6. Measurement Standards
- A-7. Monolithic millimeter wave integrated circuits
- A-8. Other

B. Fields and Waves
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- B-7. Optical Control of EM Devices
- B-8. Other

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- E-4. Other

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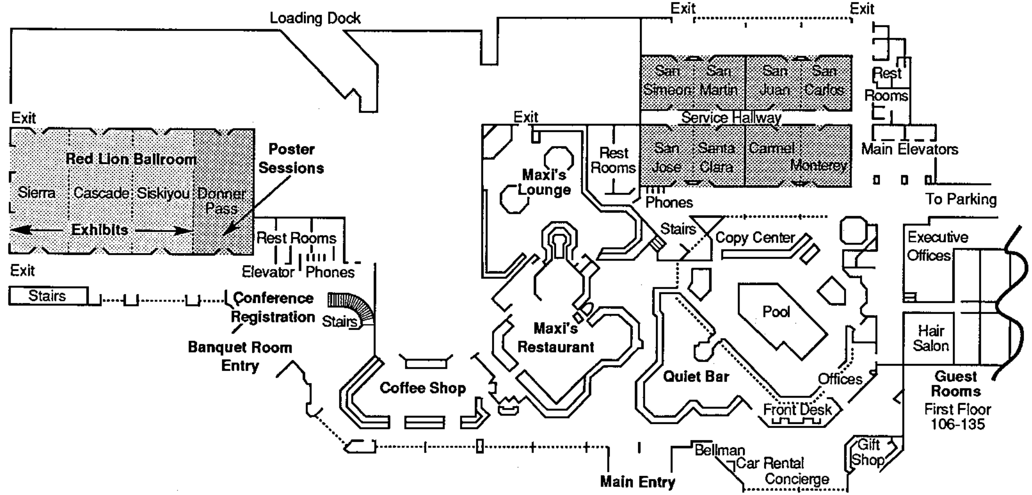
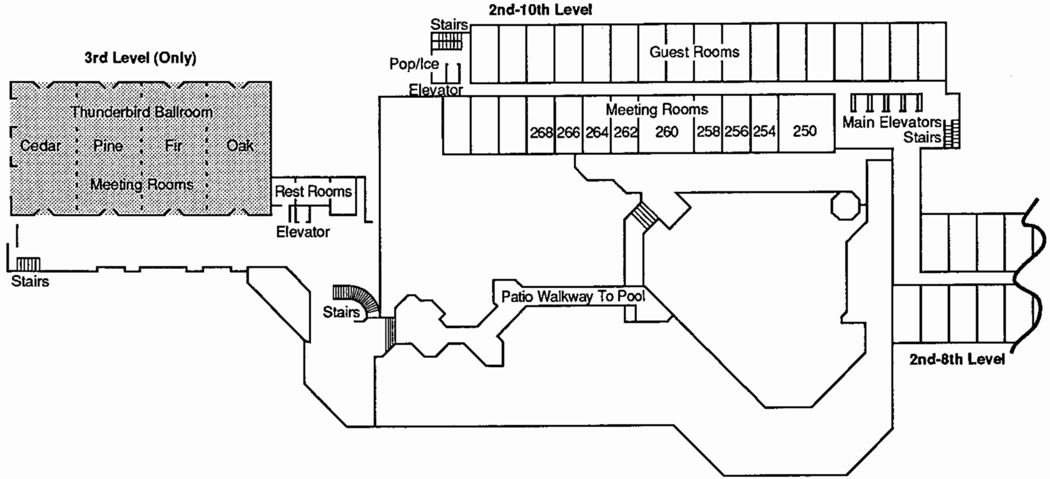
# Red Lion Inn

**1st Level**




3rd Level (Only)
Thunderbird Ballroom
Cedar
Pine
Fir
Oak
Meeting Rooms
Rest Rooms
Elevator
Stairs
Stairs
2nd-10th Level
Stairs
Pop/Ice
Elevator
Guest Rooms
Meeting Rooms
268
266
264
262
260
258
256
254
250
Main Elevators
Stairs
Patio Walkway To Pool
2nd-8th Level

## 1:15 - 5:00 PM

| | | | | |
|---|---|---|---|---|
| DONNER PASS POSTER | 1 Electromagnetic Theory (continued) | 24 Spacecraft Ant. Farms<br>25 Biomedical Applications | 48 Numerical Methods<br>49 Microstrip Antennas | |
| OAK | 13 Numerical Methods: Wire Antennas | 37 Parallel Computation Tech. for EM Scattering | 51 Numerical Methods: Iterative Methods | 73 Spacecraft Antennas |
| FIR | 14 Reflector Antennas I | 38 Scattering & Diffraction: Radar Cross Section | 52 Synthesis & Analysis of Reflector Antennas | 74 Numerical Techniques: Finite Element Methods |
| PINE | 15 Numerical Methods | 39 Microstrip Arrays | 53 Numerical Methods: FDTD II | 75 Adaptive Antennas |
| CEDAR | 16 Compact Ranges & Simulators | 40 MOM II | 54 Phased Arrays: Airborne, Space to Space & Patch Arrays | 76 Analysis of Microstrip |
| MONTEREY | 17 Antenna Analysis | 41 Shaped Reflectors | 55 Radiation & Scattering Measurements | 77 Layered Media |
| CARMEL | 18 Waveguides & T-Lines II | 42 Waveguides - Probes/ Transitions/Analysis | 56 Waveguides: Optical & Dielectric | 78 Millimeter Wave Antennas |
| SAN JOSE/ SANTA CLARA | 19 Phased Arrays: Pattern Control | 43 Phased Arrays | 57 High Freq. Diffraction I | 79 Radar & Antenna Measurements & Imaging |
| SAN CARLOS | 20 Surface Scattering & Clutter | 44 Measurements II | 58 Antenna Elements II | 80 Transient Scattering & Propagation |
| SAN JUAN | 21 Microstrip Antennas II | 45 Polarization Radar & Measurements | 59 Polarimetric SAR Imaging | 81 CommunicationThrough Atmosphere & Inosphere |
| SAN MARTIN | 22 Scattering & Diffraction: Integral Equation Methods | 46 Frequency Selective Surfaces | 60 Small Antenna Analysis | 82 High Frequency Diffraction II |
| SAN SIMEON | 23 Wave Generation by Particle Injection | 47 Propagation & Scattering in Random Media | 61 Microstrip Antennas IV | 6 Inverse Scattering & Imaging |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