

PIERS

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Proceedings

July 12-16, 1993

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA

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California Institute of Technology
Pasadena, California, USA**

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ABSTRACT

The third Progress In Electromagnetics Research Symposium (PIERS) was held July 12–16, 1993, at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. More than 800 presentations were made, and those abstracts are included in this publication.

 CONTENTS

Session 1A1	Inverse Problems of Low-Frequency Electromagnetism.....	7
Session 1A2	Antennas and Radiation.....	17
Session 1A3	Computational Electromagnetics I.....	27
Session 1A4	Current Topics in Scattering and Diffraction.....	37
Session 1A5	Field Effects of Moving Sources and Propagative Media.....	45
Session 1A6	Linear and Nonlinear Optical Properties of Surfaces.....	53
Session 1A7	Remote Sensing of the Earth.....	63
Session 1A8	Near-Field Microwave Imaging: Theory and Practice.....	73
Session 1A9	Remote Sensing of the Ocean.....	85
Session 1P1	Radar Clutter and Multipath Effects.....	93
Session 1P2	Antennas and Computation.....	105
Session 1P3	Computational Electromagnetics II.....	115
Session 1P4	Scattering and Diffraction of Electromagnetic Waves.....	127
Session 1P5	Electromagnetic Interaction With the Atmosphere, Ionosphere, and Troposphere.....	137
Session 1P6	Analytical Methods.....	149
Session 1P7	Remote Sensing I.....	159
Session 1P8	Electromagnetic Inverse Scattering Methods for Geophysical Applications.....	171
Session 1P9	Microwave Remote Sensing of Ocean Wind.....	185
Session 2A1	Radar Polarimetry: Basic Theory.....	193
Session 2A2	Synthesis of Antenna Aperture Distributions.....	205
Session 2A3	Computational Electromagnetics III.....	213
Session 2A4	Scattering and Diffraction I.....	223
Session 2A5	Inhomogeneous Media.....	235
Session 2A6	Bridges From Electromagnetic Theory to Circuit Theory.....	247
Session 2A7	Remote Sensing II.....	255
Session 2A8	Electromagnetic Inverse Scattering.....	265
Session 2A9	Electromagnetic Subsurface Sensing I.....	277
Session 2P1	Radar Polarimetry: Vector Scattering.....	289
Session 2P2	Microstrip and Printed Antennas.....	301
Session 2P3	Recent Advances in the Computation and Diffraction of Electromagnetic Waves.....	313
Session 2P4	Scattering and Diffraction II.....	321
Session 2P5	Electromagnetic Interactions With Special Media I.....	333
Session 2P6	New Trends in Electromagnetic Theory.....	341
Session 2P7	Devices and Circuits I.....	353
Session 2P8	Wave Propagation and Planar Structures.....	363
Session 2P9	Electromagnetic Subsurface Sensing II.....	375
Session 3A1	Radar Polarimetry: Metrology.....	383
Session 3A2	Microstrip Antennas and Structures.....	395
Session 3A3	Generalized Multipole Techniques—Comparisons and Combinations With Other Methods.....	407
Session 3A4	Surface and Volume Scattering: Rough Surface Scattering.....	417
Session 3A5	Electromagnetic Interactions With Special Media II.....	429
Session 3A6	Special Session Honoring Professor Charles Papas.....	441
Session 3A7	Devices and Circuits II.....	453
Session 3A8	Full-Wave Simulation of Waveguide Discontinuities.....	463
Session 3A9	Sea Ice Electromagnetics I.....	473
Session 3P1	Radar Polarimetry: Imaging.....	485

Session 3P2	Electromagnetic Interference and Antennas	497
Session 3P3	Efficient Methods to Solve Wave-Scattering and Propagation Problems	507
Session 3P4	Dense Media and Rough Surface Scattering	517
Session 3P5	Bianisotropic and Chiral Media	527
Session 3P6	Medical Applications	537
Session 3P7	Microwave/Millimeter Wave Instrumentation and Calibration	547
Session 3P8	Microstrip and Coplanar Lines.....	557
Session 3P9	Sea Ice Electromagnetics II	569
Session 4A1	Radar Polarimetry: Signal Processing Applications.....	581
Session 4A2	Antenna Arrays.....	593
Session 4A3	Advanced Computational Methods and Massive Parallel Computation	601
Session 4A4	Rough Surface Scattering	609
Session 4A5	Electromagnetic Propagation in Composite Materials: Electromagnetic Modeling	619
Session 4A6	Medical and Biological Applications of Microwaves.....	631
Session 4A7	Electromagnetic Compatibility in Equipment and Integrated Circuit Packaging Techniques	641
Session 4A8	Transmission Lines	653
Session 4A9	Microwave Radiometry for Remote Sensing.....	665
Session 4P1	Radar Polarimetry: System Application and Radar Meteorology	677
Session 4P2	Array Applications	687
Session 4P3	Physical Mechanism Extraction From Computational Methods.....	697
Session 4P4	Diffraction.....	707
Session 4P5	Electromagnetic Propagation in Composite Materials: Measurement Techniques	719
Session 4P6	Biomedical Applications of Computational Electromagnetics	731
Session 4P7	Microwave Applications of Ferroelectric Thin Films.....	741
Session 4P8	Waveguides and Waveguide Components	749
Session 4P9	Passive Microwave Remote Sensing for Spaceborne Applications	761
Session 5A1	Radar Polarimetry: Meteorological Applications	773
Session 5A2	Special Antennas and Applications	783
Session 5A3	Transient Radar	793
Session 5A4	Volume Scattering	805
Session 5A5	Passive Components I.....	815
Session 5A6	Electromagnetics in Biology and Medicine	823
Session 5A7	Quasi-Optical Electronics	831
Session 5A8	Interferometry I.....	843
Session 5A9	Radar Remote Sensing of Forests	853
Session 5P1	Radar Polarimetry: Gigahertz Wave Scattering	867
Session 5P2	Mobile Antennas and Intelligent Antennas for Earth Observation	879
Session 5P3	Computational Electromagnetic Methods for Electrically Large Problems	891
Session 5P5	Passive Components II.....	899
Session 5P7	Experimental and Theoretical Advances in Photonic Band Structure	907
Session 5P8	Interferometry II	917
Session 5P9	Radar Systems and Applications	925
Author Index		935

SESSION 1A1

Monday, July 12, AM 0820–1140, Beckman Institute Auditorium
Organizer: D. Lesselier

INVERSE PROBLEMS OF LOW-FREQUENCY ELECTROMAGNETISM

Co-Chairpersons: D. Lesselier, CNRS-ESE, Gif-sur-Yvette, France, and
H. Ermert, Ruhr—University Bochum, Bochum, FRG

0820	<i>Inverse Transformation From a Diffusive to a Propagative Field: Analytical and Numerical Solutions</i> D. Gibert and B. Tournier, Laboratoire de Géophysique Interne, Géosciences Rennes, Université de Rennes, France J. Virieux, Institut de Géodynamique, CNRS, Valbonne, France.....	8
0840	<i>Optimization of Power Devices: A Review</i> S. R. H. Hoole, Harvey Mudd College, Claremont, CA, USA.....	9
0900	<i>A Broadband Holographic Imaging Algorithm for Eddy Current NDT</i> H. P. Maier and H. Ermert, Ruhr—University Bochum, Bochum, FRG L. von Bernus, Siemens AG, Power Generation Group, Erlangen, FRG	10
0920	<i>Eddy Current Imaging of Defects in a Conductive Half-Space: Diffraction Tomographic and Generalized Solutions in a Wavefield Framework</i> R. de Oliveira-Bohbot, D. Lesselier, B. Duchêne, M. Nikolova, and A. Mohammad-Djafari, CNRS-ESE, Gif-sur-Yvette, France	11
0940	<i>Considerations on the Determination of the Spatially Varying Conductivity and Permeability of Metals from Eddy-Current Data</i> J. H. Rose, Center for NDE, Iowa State University, Ames, IA, USA	12
1000	Coffee Break	
1020	<i>Application of Markov Models for Inverse Problems in Eddy Current Nondestructive Evaluation</i> L. Udpa and W. Lord, Iowa State University, Ames, IA, USA	13
1040	<i>Parabolic Electromagnetic NDE Phenomena</i> W. Lord, S. Ross, L. Udpa, and M. Lusk, Iowa State University, Ames, IA, USA.....	14
1100	<i>An Introduction to Low Frequency (ULF/ELF/VLF) Radio Polarimetry and Some Applications to the Interpretation of Natural and Cultural Emission Signatures</i> J. Y. Dea and P. M. Hansen, NCCOSC, NRaD, San Diego, CA, USA W.-M. Boerner, University of Illinois at Chicago, Chicago, IL, USA.....	15
1120	<i>Low Frequency Inverse Scattering</i> P.-L. Shen and S.-M. Lin, Northwestern Polytechnical University, Xian, Shaanxi, PRC.....	16

**Inverse transformation from a diffusive to a propagative field:
analytical and numerical solutions.**

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Imaging the Earth interior is a major task in geophysics which involves many different techniques depending on both the nature and the depth of the targets to detect. For instance, long-period surface waves are an efficient tool to probe the upper mantle down to 700 km, while artificially created elastic waves constitute the preferred mean to image the first few kilometers of the subsurface in the context of petroleum exploration. For high-resolution imaging of the subsurface, the main operational techniques are seismic (elastic waves) and georadar soundings (electromagnetic waves).

Unfortunately, while the seismic methods can be adapted to any penetration depth, ohmic dissipation strongly limits the georadar penetrating power about 100 meters. Greater depths can be reached by using low-frequency electromagnetic fields which do not propagate but rather diffuse in the ground. This makes low-frequency electromagnetic probing a notoriously low-resolution imaging method. However mathematical links exist between the telegrapher equation, the wave equation, and the diffusion equation. For example, the transformation from a propagative to a diffusive field involves a Fredholm equation of the first kind¹. The purpose of our study is to document the inverse of this transformation.

An exact solution for the inverse problem is obtained by performing a spectral decomposition of the integral operator². This formal solution gives us a first glance at the ill-posedness of the transformation; in particular, the influence of noise is precisely evaluated. If formulated in the context of sharp reflector imaging, the inverse transformation benefits from strong *a-priori* information under the form of sparsity constraints. In this framework, the inverse problem takes a form similar to the well-known Prony model of spectral analysis. However, the standard numerical solutions of the Prony analysis strongly fail when faced with the low signal-to-noise ratio of our data. This comes from the fact that these solutions are linearized approximates. We present alternative numerical solutions designed to explicitly account for the strong non-linearities of the inverse problem. Although successful in the reconstruction of the reflectors, the simulated algorithm³ suffers slow convergence rates. A second approach uses a coupling of both the simulated annealing and the simplex algorithms, and allows for a better account of the continuum nature of the solution space. Finally, we present our first results concerning the neural network algorithm. All these solutions are tested in the context of two-dimensional magnetotelluric soundings with noisy synthetic data.

-
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Optimization of Power Devices: A Review

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Optimization in designing electromagnetic power devices is now increasingly better understood. As opposed to classical circuit models of magnetic circuits, today, gradient, stochastic and search techniques for mathematical optimization have been proposed and are used. These techniques, while being expensive, are exact. More recently, artificial neural networks have been suggested, but they work best only if the data set of parameter-set, performance pairs for training the network is close to the optimal solution we seek.

In this paper, the state of the art is reviewed and it is shown how all these methods may be used in concert to increase efficiency. The circuit model is used to generate an approximate inverse solution. Then direct finite element solutions are used to generate the required training set and this is used with the neural network to get a better solution. This solution is finally used as a starting point for the gradient optimization scheme which converges quickly because the starting point is close to the actual solution.

A Broadband Holographic Imaging Algorithm for Eddy Current NDT

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The use of eddy currents is a widespread method for nondestructive testing of electrically conductive materials. Applications are found in nuclear power plants, aviation industry, and in automotive industry.

We present a Broadband Holography Algorithm for imaging buried defects in electrically conducting materials as 2D-slices of the specimen. The change of conductivity is used as an indication of defects in homogeneous materials. The application of broadband elliptic polarized eddy current fields to nondestructive testing is investigated.

A coil or a system of coils located above the test region excites a broadband polarized eddy current field. The depth of penetration of the electromagnetic field is highly dependent on the frequency of excitation, the conductivity and the permeability. The diffusion equation gives an appropriate description of the field distribution in metallic materials. According to the so called skin-effect, these fields can be regarded as highly damped "skin-waves" which are penetrating the material along a limited range, and therefore testing is only possible in the near surface regions.

We use an imaging algorithm for synthetic apertures known from microwaves [1] or acoustic waves [2] for the reconstruction of buried defects. We adapt the algorithm to the specific properties of eddy current fields. In detail, for skin-waves the phase velocity is frequency dependent (dispersion), phase and attenuation constants are identical. The wavelength is larger than the penetration depth and consequently, measurable phase shifts are very small. Furthermore, the characteristic beam pattern of the probe has to be taken into account because the interaction of the fields with the defects takes place in the near field of the probe.

The reconstruction method can be explained by the theory of matched filtering. For this purpose the probe signal distribution in the receiving aperture is measured assuming that only one single scattering object is present (test function). Then the probe signal distribution in the aperture with a real defect is recorded. This result is correlated with the earlier performed test function, yielding a maximum value if the location where the test object has been assumed coincides with the position of a real scattering object. In order to reconstruct the whole image, the reconstruction algorithm needs the fictitious single scatterer to be moved across the whole object scene.

Eddy current fields, excited in the medium by an arbitrary probe, are determined experimentally. This distribution is needed for the reconstruction algorithm. In order to achieve radial resolution we extend the algorithm to broadband signals (pulses, stochastic process). The concept of phase multiplication, proposed in [3] and [4], is applied to the Broadband Holography Algorithm for compensation of small phase shifts and results in an improved radial and azimuthal resolution.

We report on numerical experiments with simulated and measured data. The measured data is recorded with a test fixture in which a manipulator moves a probe in a 1-dimensional linear aperture over a sample containing artificial defects of different form and size. The final result shows 2D-slices of the tested sample.

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Eddy Current Imaging of Defects in a Conductive Half-Space: Diffraction Tomographic and Generalized Solutions in a Wavefield Framework.

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With adequate corrections and extensions, solution methods of inverse scattering problems can be used for Nondestructive Testing of damaged metallic structures where eddy currents are generated by means of external low-frequency sources. The time-harmonic diffusion equation satisfied by the field in – non-magnetic – metal parts is taken as a Helmholtz wave equation whose propagation constant is complex-valued with equal real and imaginary parts inversely proportional with the skin depth. Huyghens-type sources located within the defects are the sources of the anomalous fields observed outside the structure under testing. When successful, inversion of such anomalous fields provides images of the defects. But there is one severe challenge: the problem at hand is strongly ill-posed due to exponential decay of the probing field in metal (skin effect) and corresponding evanescence of fields outside. In mathematical terms, an integral operator with damped kernel has to be dealt with at some point of the analysis. Also, at least in the first step, we are restricted to linearized solutions based on the Born approximation (which means testing of small defects at low frequency), the inverse problem being nonlinear with respect to the defects' conductivity.

Research on eddy-current imaging in a wavefield framework is going on since a few years now in our laboratory, in particular with the support of Departments of *Electricité de France, Direction des Etudes et Recherches* (EDF-DER). Present-day aspects of this research are outlined here with using a rather ideal two-dimensional test model: a cylindrical defect in a conductive half-space – a metal block in air – is illuminated by a planar source, the anomalous fields being observed at discrete frequencies ω on a line parallel with the block surface.

In the presentation the several algorithms that are currently studied are summarized and comparisons are carried out using results they yield from both synthetic and experimental data with emphasis put on their behavior vs. noise and model errors (the experiments have been led by N. Coutanceau at the *Retour d'Expérience, Mesures, Essais* EDF Department):

(i) Attenuation-matched Diffraction Tomography (DT) algorithms only account for part of the skin effect and provide approximate solutions but they maintain the Fourier formalism of the inverse scattering schemes they are issued from; DT is implemented using either data interpolation in the spectral space followed by fast Fourier inversion, or the method of Maximum Entropy Fourier synthesis, the latter being especially effective with sparse spectra.

(ii) A DT scheme may also be employed which fully cares for skin effect though at the expense of an analytic continuation of the fields in the complex ω plane – this operation somewhat replaces an inverse Laplace transform.

(iii) More computationally expensive inversion schemes aim at retrieving the conductivity in each cell of a cell-model of the defect and do not suffer from any neglect of the skin effect. They work in stochastic settings (e.g., Kalman filtering, simulated annealing) or in deterministic ones (e.g., ART, conjugate-gradient) with a priori information extensively used. Finally, new tools – wavelet-vaguelette decompositions (investigated with F. Brouaye) and Markov-random field based inversions – are introduced with first results possibly given.

CONSIDERATIONS ON THE DETERMINATION OF THE SPATIALLY VARYING
CONDUCTIVITY AND PERMEABILITY OF METALS FROM EDDY-CURRENT
DATA

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ABSTRACT

The determination of layered, one-dimensional conductivity profiles from eddy-current measurements has progressed rapidly in recent years. An in principal "exact" low-temporal-frequency method has been proposed that is based on an inverse Laplace transform of the impedance of an eddy-current probe as a function of the spatial frequency. Other, perhaps more practical methods, based on variational least-squares fits to the measured frequency dependence of the impedance, have also been proposed. The latter methods have been used by several groups to invert measurements of the impedance of air-core coils placed next to metals whose near-surface conductivity can be described by a single piece-wise constant layer (such layers might be generated by cladding or painting). Various groups have demonstrated the ability to determine the thickness and conductivity change for such single surface layer. More recently, I and other coworkers have successfully inverted measurements made with air-core coils placed near the surface of plates whose near-surface conductivity profiles vary in a smooth and continuous manner. We will briefly review these results for the one-dimensional case. Then we will discuss the prospects for two "two-dimensional" inversions. The first problem is to determine the magnetic permeability of a layered magnetic metal. This problem is two-dimensional since the permeability, $\mu(\omega, z)$, depends on both the depth and the frequency. We will also discuss the determination of the conductivity profiles of nonmagnetic metals that have two-dimensional spatial symmetries.

ACKNOWLEDGMENT: This work was supported by the Center for NDE at Iowa State University.

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Application of Markov Models for Inverse Problems in Eddy Current Nondestructive Evaluation

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Inverse problems in nondestructive evaluation (NDE) are involved with the reconstruction of defect shapes in materials, on the basis of information contained in the measured signal. A major difficulty in finding solutions to inverse problems in eddy current NDE lies in the quasi-static nature of the underlying physical phenomenon and the complex nature of the defect and test geometries, which necessitate the use of numerical models for solving the forward problem. Unfortunately these models do not provide a direct method for solving the inverse problem.

This paper presents an approach that uses the numerical model for the forward problem in an iterative scheme for reconstructing the defects in materials. Formulating the NDE procedure as a mapping from the defect space to the signal space, the inverse problem solution is first reduced to a search in the defect space for the optimal defect profile. Making use of a Markov model for the defect boundary, the search space is first represented by a tree structure. The search space is systematically constrained using appropriate transition probability matrices and the solution is arrived at using a simple tree search procedure.

Parabolic Electromagnetic NDE Phenomena

W. Lord, S. Ross, L. Udpa, and M. Lusk
Iowa State University

Defect characterization (imaging) capabilities of electromagnetic nondestructive evaluation (NDE) methods are rooted in the underlying electromagnetic field/defect interactions associated with the methods. Eddy current NDE phenomena are diffusive in nature and describable by the quasi-static or pre-Maxwellian field equations that lead to a parabolic governing partial differential equation (p.d.e.). This is in contrast to potential drop and flux leakage NDE phenomena which are static in nature and governed by an elliptic p.d.e., or microwave NDE phenomena which conform to Maxwell's equations and are governed by a hyperbolic p.d.e. type.

This paper discusses the imaging approaches that have been used for imaging elliptic, parabolic and hyperbolic NDE phenomena and introduces a new "q-transformation" between parabolic and hyperbolic domains, originally developed for geophysical applications, but that also shows promise for NDE studies.

AN INTRODUCTION TO LOW FREQUENCY (ULF/ELF/VLF) RADIO POLARIMETRY AND SOME APPLICATIONS TO THE INTERPRETATION OF NATURAL AND CULTURAL EMISSION SIGNATURES

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POLARIMETRY covers the entire electromagnetic spectrum and 'LOW FREQUENCY POLARIMETRY' applies to the polarimetric vector (polarization) field nature of the magnetic and the electric fields within the ULTRA-LOW-FREQUENCY (ULF: below 3 Hz), the EXTREMELY-LOW-FREQUENCY (ELF: 3 Hz to 3 KHz) and the VERY-LOW-FREQUENCY (VLF: 3 KHz to 30 KHz) spectral regions. The pertinent acoustic complementary spectral regions are identified as INFRASONIC (0.01 to 3 Hz), NEAR-INFRASONIC (3 to 20 Hz) and AUDIOSONIC (20 Hz to 20 KHz). These low-frequency vector electromagnetic and acoustic waves play an important role in coupled LITHOSPHERIC-IONOSPHERIC wave interactions especially in the upper ULF (above 0.01 Hz) to lower VLF (below 10 KHz) for which the radio waves display pronounced polarimetric effects, i.e., strong field-component dependence which may differ appreciably from one geographic (earth-magnetic) region to another.

In this paper, an introduction to this existing re-emerging field is presented, putting major emphasis on recent findings regarding the polarimetric behavior of natural and cultural emission signature observations of elevated electromagnetic noise including (i) Schumann resonances generated by electric storm discharges (8.6, 14, 21, etc., Hz); (ii) discrete VLF signatures (5.6, 11.2, 17.2/4/6 Hz) generated during space vehicle passages through the ionospheric D/E/F/ layers; and (iii) signatures peaking strongly in the 0.1-5 Hz spectral region during lithospheric stress build-up prior to earthquake and volcanic distress events. The polarimetric behavior of these signatures is interpreted with the objective of developing inversion methods for emission source localization which then may be implemented for Earthquake Hazard Mitigation measures.

LOW FREQUENCY INVERSE SCATTERING

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In order to recover the Rayleigh coefficient and the next high order nonzero coefficient from the backscattered signals, an inverse scattering method is proposed by Chaudhuri (IEEE Trans. on AP, Vol. AP-19, No. 3, 1981, P. 398). Now, We would like to point out that there are some mistakes in the above paper. So, the values of coefficients are not true. In this paper, we will present the correct answer.

Let $r(t)$ be the returned pulse response of the object to the incident pulse $E_i(t)$, and $f(t)$ is the backscattered impulse response of the object for the given orientation and polarization. For the case of low frequency ($ka \ll 1$), the Laplace transform of $f(t)$ can be expanded as follows:

$$F(s) = \sum_{n=0}^{\infty} a_n s^n$$

It is well known that $a_0 = a_1 = 0$, and $a_2 = V$, where V denotes the volume of scatterer.

Now, we can prove that

$$a_2 = c \int_{-\infty}^{\infty} t^3 r(t) dt / 6 \int_{-\infty}^{\infty} t E_i(t) dt$$

$$a_3 = \left[-c \int_{-\infty}^{\infty} t^4 r(t) dt + 12a_2 \int_{-\infty}^{\infty} t^2 E_i(t) dt \right] / 24 \int_{-\infty}^{\infty} t E_i(t) dt$$

$$a_4 = \left[c \int_{-\infty}^{\infty} t^5 r(t) dt + 60a_3 \int_{-\infty}^{\infty} t^2 E_i(t) dt - 20a_2 \int_{-\infty}^{\infty} t^3 E_i(t) dt \right]$$

$$\times \left[120 \int_{-\infty}^{\infty} t E_i(t) dt \right]^{-1}$$

where c is the velocity.

 SESSION 1A2

Monday July 12, AM 0820–1140, Baxter Lecture Hall

ANTENNAS AND RADIATION

 Co-Chairpersons: W. A. Imbriale, JPL, California Institute of Technology, Pasadena, CA, USA, and
 J. J. Lee, Hughes Aircraft, Fullerton, CA, USA

0820	<i>Necessary and Sufficient Condition for the Existence of an Inflection Point and Its Application to Reflector Antenna Analysis</i> M. H. Rahnavard, Shiraz University, Shiraz, Iran	18
0840	<i>Rapid Solution of Patch Resonators by a Combined Complex Image and Contour Integral Method</i> A. A. Omar and Y. L. Chow, University of Waterloo, Waterloo, Ontario, Canada	19
0900	<i>Method of Linearization for the Problem of Radiation Systems Synthesis</i> V. I. Dmitriev, Moscow State University, Moscow, Russia	20
0920	<i>Probe Compensation in Cylindrical Near-Field Scanning: A Novel Simulation Methodology</i> Z. A. Hussein and Y. Rahmat-Samii, JPL, California Institute of Technology, Pasadena, CA, USA	21
0940	<i>Biquadratic Programming and Antenna Design</i> K. Hirasawa, University of Tsukuba, Tsukuba, Japan	22
1000	Coffee Break	
1020	<i>Electromagnetic Radiation From a Series of Sharp X-Ray Pulses</i> R. L. Gardner, Phillips Laboratory, Kirtland AFB, NM, USA	23
1040	<i>Formulation of Time-Domain Planar Near-Field Measurements</i> T. B. Hansen and A. D. Yaghjian, Rome Laboratory, Hanscom AFB, MA, USA	24
1100	<i>Line Source Radiation in the Presence of Structures Formed by a Finite Number of Slotted Cylinders</i> V. Veremey, Institute of Radiophysics and Electronics, Ukrainian Academy of Sciences, Kharkov, Ukraine.....	25
1120	<i>FDTD Analysis of a Biperiodic Phased Array of Rectangular Apertures</i> J. Ren and O. P. Gandhi, University of Utah, Salt Lake City, Utah, USA L. R. Walker, J. Franschilla, and C. R. Boerman, Hughes Aircraft Company, Radar Systems Group, Los Angeles, CA, USA	26

**Necessary and Sufficient Condition for the Existence of an
Inflection Point and Its Application to Reflector Antenna
Analysis***

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In the study and analysis of surface curvature-induced shadow, which is encountered in dual-shaped reflectors, Glaindo-Williams surface and unstable optical resonator inflected point has an important role. In this paper, necessary and sufficient condition for the existence of inflected point is studied. The role of inflected point in analyzing an ideal cubic phase front is considered.

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Rapid Solution of Patch Resonators by a Combined Complex Image and Contour Integral Method

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Resonators of super-conductive microstrip patches are rapidly becoming popular because of their high Q -values ($\sim 10^6$). Two common analyses for such resonators are the point matching method [1] and the mode matching method [2]. Because the match is done over the large patch surface, the matrix equation resulted has frequently 180 to 400 unknowns.

A more efficient way is to match only around an assumed magnetic wall current at the (edge) perimeter of the patch with 3 to 10 fold reduction in unknowns. This is the 2-D contour integral method of Okoshi [3] and gives reasonable results. To improve the results further, the magnetic wall assumption is to be relaxed to include the edge fringe fields of the patch. Martinson and Kuester [4] proposed a fringe correction factor depending on the substrate ϵ_r . Such factor still neglects the dependence on the shape of the contour of the edges. Therefore, further improvement is possible. The alternative for such improvement is given below.

The resonator structure is divided into the interior and exterior regions. For the interior, we use the standard 2-D Okoshi formulation of [3] of magnetic current (electric voltage) on the patch perimeter. For the exterior, the recent 3-D complex image formulation [5] of magnetic current is used. The tangential electric and magnetic fields of the exterior and interior formulations are then matched over the patch perimeter to form a moment method matrix equation.

In the combined method, the influence of the fringe field from the exterior is actually quite small, but is enough to pull Okoshi's solution to nearly a perfect fit with experiment.

The studied examples are the rectangular and circular patch resonators of direct microstrip feed over a wide frequency range. It is evident from the formulation that the combined method can be applied to most patch resonators of arbitrary shape, with and without mode coupling stubs. The computer time is no more than 2 minutes per frequency point on a 33 MHz 80386-PC.

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Method of Linearization for the Problem of Radiation Systems Synthesis

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There is considered one multicriterial problem of the radiation system synthesis by the given radiation pattern. The problems of simple, optimal and quasi-optimal synthesis are investigated. There is developed a method of linearization for solving the problem of quasi-optimal synthesis for a discrete antenna lattice. It is shown how to design a computer system for discrete antenna systems with the given properties by means of the worked out method of the control parameters. Realization of such a system is described in detail and can be demonstrated on PC AT.