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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Analysis of source-excited time-harmonic and transient electromagnetic wave propagation in complicated environments, wave scattering by complicated targets, or wave penetration into complex structures generally requires decomposition of the incident field into elementary constituents, tracking each constituent through the environment or past the scatterer, and recombining at the observer. The elementary constituents are spectral objects such as plane waves, cylindrical waves, conical waves, modal fields, ray fields, etc. Under transient conditions, the recombination is conventionally performed first on the time-harmonic constituents, with frequency synthesis performed thereafter, but one may alternatively, by a less conventional approach, employ transient constituents (transient plane or cylindrical waves, etc.) and perform the remaining spatial synthesis thereafter. Viewed from this general perspective, there exists an enormous flexibility in the selection of the spectral objects, and of hybrid combinations, for analysis of a particular propagation or scattering problem.

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19. ABSTRACT (continued)

It is the objective of the proposed research to examine the various spectral options in their most fundamental terms, study the relation between them, and then assess which option best addresses a particular propagation or scattering phenomenon. The most elementary spectral object is a local plane wave, specified by three spatial wavenumbers corresponding to the three space coordinates, and by a temporal wavenumber corresponding to its frequency. The resulting synthesis involves a four-fold continuous spectrum superposition. This provides the substructure for all options. By rearranging the multiple spectra according to different constructive interference processes, one may eliminate one or more of the spectral variables and construct the variety of more compact spectral elements mentioned above. The long-term program proposed here is to determine systematically which spectral approach, for a given propagation or scattering problem, yields the most convergent representation. Being "most convergent," the desired representation should require the fewest number of elementary wave processes and thereby be the physically most transparent and, hopefully, computationally the most efficient. Specific applications to be addressed include: a) scattering by, and detection of, target **features** b) high-frequency penetration of complex structures c) propagation in non-uniform and tapered open waveguides.

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Spectral Methods for Electromagnetic Propagation and Diffraction

Final Report

L.B. Felsen

March 9, 1990

U.S. Army Research Office
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Abstract

Analysis of source-excited time-harmonic and transient electromagnetic wave propagation in complicated environments, wave scattering by complicated targets, or wave penetration into complex structures generally requires decomposition of the incident field into elementary constituents, tracking each constituent through the environment or past the scatterer, and recombining at the observer. The elementary constituents are spectral objects such as plane waves, cylindrical waves, conical waves, modal fields, ray fields, etc. Under transient conditions, the recombination is conventionally performed first on the time-harmonic constituents, with frequency synthesis performed thereafter, but one may alternatively, by a less conventional approach, employ transient constituents (transient plane or cylindrical waves, etc.) and perform the remaining spatial synthesis thereafter. Viewed from this general perspective, there exists an enormous flexibility in the selection of the spectral objects, and of hybrid combinations, for analysis of a particular propagation or scattering problem.

It is the objective of the proposed research to examine the various spectral options in their most fundamental terms, study the relation between them, and then assess which option best addresses a particular propagation or scattering phenomenon. The most elementary spectral object is a local plane wave, specified by three spatial wavenumbers corresponding to the three space coordinates, and by a temporal wavenumber corresponding to its frequency. The resulting synthesis involves a four-fold continuous spectrum superposition. This provides the substructure for *all* options. By rearranging the multiple spectra according to different constructive interference processes, one may eliminate one or more of the spectral variables and construct the variety of more compact spectral elements mentioned above. The long-term program proposed here is to determine systematically which spectral approach, for a given propagation or scattering problem, yields the most convergent representation. Being "most convergent," the desired representation should require the fewest number of elementary wave processes and thereby be the physically most transparent and, hopefully, computationally the most efficient. Specific applications to be addressed include: a) scattering by, and detection of, target features b) high-frequency penetration of complex structures c) propagation in non-uniform and tapered open waveguides.

I. Problem Statement

Analysis of source-excited time-harmonic and transient electromagnetic wave propagation in complicated environments, wave scattering by complicated targets, or wave penetration into complex structures generally requires decomposition of the incident field into elementary constituents, tracking each constituent through the environment or past the scatterer, and recombining at the observer. The elementary constituents are spectral objects such as plane waves, cylindrical waves, conical waves, modal fields, ray fields, etc. Under transient conditions, the recombination is conventionally performed first on the time-harmonic constituents, with frequency synthesis performed thereafter, but one may alternatively, by a less conventional approach, employ transient constituents (transient plane or cylindrical waves, etc.) and perform the remaining spatial synthesis thereafter. Viewed from this general perspective, there exists an enormous flexibility in the selection of the spectral objects, and of hybrid combinations, for analysis of a particular propagation or scattering problem.

It is the objective of the proposed research to examine the various spectral options in their most fundamental terms, study the relation between them, and then assess which option best addresses a particular propagation or scattering phenomenon. The most elementary spectral object is a local plane wave, specified by three spatial wavenumbers corresponding to the three space coordinates, and by a temporal wavenumber corresponding to its frequency. The resulting synthesis involves a four-fold continuous spectrum superposition. This provides the substructure for *all* options. By rearranging the multiple spectra according to different constructive interference processes, one may eliminate one or more of the spectral variables and construct the variety of more compact spectral elements mentioned above. The long-term program proposed here is to determine systematically which spectral approach, for a given propagation or scattering problem, yields the most convergent representation. Being "most convergent," the desired representation should require the fewest number of elementary wave processes and thereby be the physically most transparent and, hopefully, computationally the most efficient.

During this contract period, we have focused attention on developing and applying the following specific spectral options:

A. *Intrinsic modes* for propagation in *longitudinally varying closed and open waveguides*

B. *Gaussian beams* as basis elements for *radiation from large apertures* in the *presence of a perturbing environment*

C. *Hybrid ray-mode* formulation for *coupling into large waveguides*

D. *Complex ray* methods for *scattering from smooth concave-convex target* shapes.

E. *Spectral reconstruction* of waveguides from "skeletal" wave spectra

II. Summary of Results

The results achieved in problem categories A-E in Section I have been summarized in the semi-annual reports, and described in detail in the journal publications listed in Section III. The publication list has been arranged so as to place each paper into its proper category. In the summary below, references are identified by square brackets.

A. Adiabatic modes, intrinsic modes, adiabatic transforms

For nonhomogeneous closed and open guiding environments with weak longitudinal dependence, which legitimizes localizing assumptions, we have developed self-consistent field formulations that involve a) local normal (adiabatic) modes that adapt smoothly to the changing conditions; and b) intrinsic modes which correct failures of the adiabatic modes in cutoff transitions (closed waveguides), and in trapped-to-leaky mode transitions (open waveguides) [A1-A3].

In three-dimensional inhomogeneous waveguides, the *local modes* (adiabatic or intrinsic) follow *curved ray trajectories* in the lateral domain. To develop Green's functions in such inhomogeneous guiding environments by spectral synthesis, we have introduced *adiabatic transforms* which are localized versions of Fourier transforms [A4,A5; see also E1].

B. Gaussian Beams

Having extensively studied the propagation and diffraction properties of Gaussian beams (GB) in earlier investigations (but see also [B1]), emphasis during the contract period has been on the use GB as spectral basis elements in the representation of *arbitrary* radiated and diffracted fields. This can be done by embedding GB *self-consistently* in a configuration-wavenumber (phase space) lattice. This scheme has been applied with remarkable success to test cases involving a) radiation from large but truncated phased plane aperture distributions; b) transmission of these radiated fields through plane and curved dielectric layers. The results documented in [B2-B4] establish the GB method as a potentially important algorithm for high frequency propagation and scattering in complex environments (see also [D4]).

C. Hybrid ray-mode formulations

Our previously developed high-frequency theory for *self-consistent, rigorous* combination of ray fields and mode fields has been applied to the canonical problems of plane wave coupling into large plane parallel and circular waveguides. This has led to a detailed understanding of the spectral and computational implications in the hybrid scheme, and of the ability to generalize the concept to more complex environments [C1-C3].

D. Complex rays

Our previously developed complex ray theory has here been shown to explain in an entirely novel and computationally effective manner the high frequency scattering behavior of perfectly reflecting targets with smooth *convex-concave* shape. The novelty is that *all* observed phenomena in the scattered field, as a function of frequency, can be predicted by *ray theory* alone providing one incorporates *real and complex* rays into the algorithm. The complex rays explain *evanescent* field contributions generated by the concave portions on the target. The ray algorithms parametrizes in a simple manner time-harmonic as well as time-dependent conditions [D1-D3]. Complex ray fields have also been used for study of radiation from distributed aperture sources [D4].

E. Spectral reconstruction of high-frequency wavefields

In this study it is shown how a spectral continuum can be built around the (point spectrum) geometrical optics (GO) ray field in such a manner as to uniformize that field in transition regions near caustics, etc., where GO ray theory fails. In essence, this *novel* method generates GO ray transition functions *directly,* without going through the conventional route that requires solving a canonical problem. The method is shown to work not only for the conventional GO ray fields, but also for a class of ray fields embodied in the more general geometrical theory of diffraction (GTD). The method is also shown to construct intrinsic modes (see Sec. A) from the nonuniform adiabatic modes [E1; although this has been done for acoustic fields, the same procedure applies to electromagnetic fields].

III. Publications in Refereed Journals

(With acknowledgement to Contract No. DAAG-29-85-K-0180)

The list that follows is arranged according to problem categories.

O. Survey Papers (invited)

1. L.B. Felsen, "Real Spectra, Complex Spectra, Compact Spectra," J. Opt. Soc. Am. A3, pp. 486-496, 1986.
2. L.B. Felsen, "Target Strength: Some Recent Theoretical Developments," IEEE Journal of Ocean Engineering, OE-12, pp. 443-452, 1987.

A. Adiabatic modes, intrinsic modes and adiabatic transforms

1. L.B. Felsen, "Longitudinally Varying Ducts with Guiding to Antiguiding Transitions," Radio Science, Vol. 22, No. 7, 1204-1210, (1987).
2. M. Cada, F. Xiang and L.B. Felsen, "Intrinsic Modes in Tapered Optical Waveguides," IEEE Journal of Quantum Electronics, Vol. 24, No. 5, (1988).
3. M. Cada, F. Xiang, L.B. Felsen, "A Substantially Improved Treatment of Intrinsic Modes in Tapered Optical Waveguides," IEEE J. Quantum Electronics, 25, pp. 933-938 (1989).
4. L.B. Felsen, "Adiabatic Spectra for Tapered Dielectric Waveguides," AEU (Archives for Electronics and Communications) 40, pp. 258-262, 1986.
5. L.B. Felsen, "A Spectral View of Wave Propagation," Radio Science, Vol. 22, No. 6, 848-858 (1987).

B. Gaussian beams

1. I.T. Lu, L.B. Felsen, Y.Z. Ruan and Z.L. Zhang, "Evaluation of Beam Fields Reflected at a Plane Interface," IEEE Trans. on Ant. and Propagat., AP-35, pp. 809-817, 1987.
2. J. Maciel and L.B. Felsen, "Systematic Study of Fields Due to Extended Apertures by Gaussian Beam Discretization," IEEE Transactions Ant. and Propagation, AP-37, pp. 884-892 (1989).
3. J.J. Maciel and L.B. Felsen, "Gaussian Beam Analysis of Propagation from an Extended Plane Aperture Distribution Through Dielectric Layers: I-Plane Layer," to be published in IEEE Trans. on Antennas and Propagation.
4. J.J. Maciel and L.B. Felsen, "Gaussian Beam Analysis of Propagation from an Extended Plane Aperture Distribution Through Dielectric Layers: II-Circular Cylindrical Layer," to be published in IEEE Trans. on Antennas and Propagation.

C. Hybrid ray-mode formulation

1. L.B. Felsen and H. Shirai, "Hybrid Ray-Mode Analysis of High Frequency Wave Coupling Into Large Waveguides and Cavities," Optics Letters, 12, pp. 7-9, 1987.
2. L.B. Felsen, H. Shirai, "Rays, Modes and Beams for Plane Wave Coupling into a Wide Open-Ended Parallel Waveguide," Wave Motion, 9, pp. 301-317, 1987.
3. H. Shirai and L.B. Felsen, "Rays and Modes for Plane Wave Coupling into a Large Open-ended Circular Waveguide," Wave Motion 9, pp. 461-482, 1987.

D. Complex rays

1. H. Ikuno and L.B. Felsen, "Complex Ray Interpretation of High Frequency Reflection from the Illuminated Portion of a Smooth Target with Inflection Points," IEEE Trans. Ant. and Propagat., Vol. 36, No. pp. 1260-1271, 1988.
2. H. Ikuno and L.B. Felsen, "Complex Rays in Transient Scattering from Smooth Targets with Inflection Points," IEEE Trans. on Ant. and Propagat., Vol. 36, No. 9, pp. 1272-1280, 1988.
3. H. Ikuno and L.B. Felsen, "Real and Complex Rays for Scattering from Targets with Inflection Points," Radio Science, 22, pp. 952-958, 1987.
4. P.D. Einziger, Y. Haramaty and L.B. Felsen, "Complex Rays for Radiation from Discretized Aperture Distributions," IEEE Trans. on Ant. and Propagat., AP-35, No. 9, pp. 1031-1044, 1987.

E. Spectral reconstruction

1. J.M. Arnold and L.B. Felsen, "Spectral Reconstruction of Uniformized Wavefields from Nonuniform Ray or Adiabatic Mode Forms for Acoustic Propagation and Diffraction," J. Acoust. Soc. Am. 87.

IV. Personnel

Staff

Dr. L.B. Felsen, Institute Professor, Principal Investigator

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[1] Received 1986 R.W. P. King Young Scientist Award for best paper (co-author L.B. Felsen) in the IEEE Transactions on Antennas and Propagation

[2] Received Ph.D degree while on project; was awarded 2nd prize in 1988 URSI Student Prize Paper Competition for Gaussian beam papers [B3,B4] (co-authored by L.B. Felsen)