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14. ABSTRACT

(i) We developed numerical techniques for simulating radar returns from large realistic scenes composed of uneven ground, trees, and reflecting objects. The simulation includes effects of ionospheric dispersion on the radar pulses.
(ii) We developed an integral-equation code and performed numerical simulation of radiation for small-loop large-current antennas, with loops radiating in open space or partly shielded by enclosures of various material properties. The code implements regularization methods for handling of subwavelength electromagnetic radiation problems in the presence of materials.
(iii) We developed a fast integral-equation based solver for simulating propagation of thermo-acoustic waves induced by short microwave pulses in biological media, in particular in the human head. The code implements a matrix compression based on fast Fourier transforms (FFTs), as well a rescaling technique which allows us to treat problems with large contrasts of material parameters.
(iv) We analyzed propagation of infra-red (IR) radiation through dilute and dense media composed of discrete scatterers. In application to propagation of short IR pulses through atmospheric clouds we established conditions under which the waves may experience reduced attenuation. To allow simulation of propagation in dense media, we developed a fast integral-equation solver for a two-dimensionally periodic system modeling a laterally infinite slab of the medium.

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Contents

Summary

We give below Summaries of the individual parts of the Report. In each part of the Summary the references pertain to the given part of the Report.

Summary - Part I

Our effort covered the following subjects:

- Development of a computational framework allowing us to create a database with numerical simulations of returns from a realistic scene, which can be used in SAR imaging type analysis. The developed framework includes:
  - handling the numerous files containig scattering data for consecutive angles of incidence and for consecutive frequencies,
  - performing amplitude interpolation,
  - performing synthesis of the scattered pulse.
- Verification of the developed procedure by performing numerical simulations on an example of a scene of size $20\,\mathrm{m} \times 20\,\mathrm{m}$, composed of uneven ground, three trees with leaves and branches, and a perfectly conducting object of a pyramidal shape, 1 m in size.
- Performing analysis, implementation and numerical simulations involving the effects of ionospheric dispersion on the SAR returns.

Summary - Part II

The objective of this effort was to perform numerical simulations for large current, small loop antennas and to obtain predictions for the parameters associated with the antenna transmitting and receiving ports (such as the input and mutual impedances, coupling parameters, received voltage, radiated field, etc.) at the frequencies of the order of 1 MHz.

It is well known that antenna modeling requires simulations of a very high accuracy. Therefore, our analysis was performed in the framework of the integral equation, surface-current based formulation. To ensure further accuracy, the currents were expanded in Rao-Wilton-Glisson (RWG) basis functions, and the same set of basis functions was used as testing functions, resulting in the Galerkin discretization of the integral equations.

However, it is also known that electric-field integral equations, and other equation of similar structure, suffer from ill conditioning in the limit of small frequencies. This difficulty is due to the $\sim k^{-1}$ behavior of the "electrostatic" terms in the equation, i.e., terms involving divergence of the current (proportional to the charge density). A remedy, for perfectly conducting objects [1, 2], is to separate the solution into its solenoidal and non-solenoidal parts, and to rescale one of them in order to balance the magnitude of the individual terms in the equation.

Given the size of the antenna ($\simeq$ 1m) and the range of frequencies of interest ($\simeq$ 1MHz (wavelength $\simeq$ 300m)), one of the main challenges of this effort consisted of developing a computational framework capable of accurate simulation of low frequency, strongly subwavelength problems, i.e. problems involving geometries and geometry details of the order of $10^{-3} - 10^{-5}$ of the wavelength.

In our treatment of low frequency problems performed under this effort,

- we generalized the rescaling (regularization) procedure to general electrically/magnetically resistive surfaces (including impedance surfaces as a special case),
- we developed a general algorithm for the construction of solenoidal and non-solenoidal basis functions for arbitrary geometries of complex topology,
- we implemented the developed analytical and numerical procedures into the `vmax` code,
- we performed numerical simulations and obtained predictions for parameters characterizing the performance large current, small loop antennas of interest to the customer.

In Section II-2 we specify the notation, conventions, and units used in our formulation. In Section II-3 we briefly summarize our conventional integral-equation approach and delta-gap modeling of antenna feeds and loads. In Section II-4 we include definitions of the relevant antenna parameters. The results of numerical simulations are presented in Section II-5.

In Appendices we present the low frequency formulation generalized to arbitrary electrically/magnetically resistive surfaces (Appendix II-A), the algorithm for the construction of solenoidal and non-solenoidal basis functions (Appendix II-G), and, for completeness, other supporting information required for numerical simulations of small loop antennas.

Summary - Part III

The main incentives to study microwave-induced thermo-acoustic waves are two-fold:

1. Methods utilizing microwave-induced thermo-acoustic waves in biological tissues constitute a promising approach to medical diagnostics and imaging and, more generally, to the detection of inhomogeneities in the human body. The approach consists of irradiating the tissue with a short electromagnetic pulse of duration $\tau_0 \sim 1\,\mu$m), and detecting acoustic (or ultrasound) waves excited as the result of the thermoelastic expansion of the material. The method takes advantage of several facts:

   - In the frequency region $\lesssim 1$ GHz (or pulse durations $\sim 1\,\mu$s) various types of tissues and possible foreign objects differ significantly in their electromagnetic absorption properties [3, 4, 5, 6] and yet penetration depths in the tissue are at least several centimeters.
   - At the same time, the tissues show a relatively small acoustic (and ultrasound) contrast: the speed of sound in most soft tissues is $c \simeq 1.5\,\mathrm{mm}/\mu\mathrm{s}$ and the attenuation is also relatively uniform.
   - Further, the sound propagation speed given above implies that, for a pulse of $\sim 1\,\mu$s duration, the acoustic signal provides the spatial resolution of the order of a few millimeters, i.e., of the order of the acoustic wavelength, while a purely electromagnetic imaging at frequencies of a few GHz can achieve resolutions not better than a few centimeters (and electromagnetic signals of higher frequencies do not penetrate deep enough into the tissue).

   One of possible applications of thermo-acoustic waves, still in a preliminary stage of development, is the thermo-acoustic computed tomography [7, 8, 9, 10]. Resolutions of the order of 1 mm have been achieved in measurements of this type.

2. Other phenomena of interest are auditory effects caused by microwave-induced thermo-acoustic waves [11]. Conventionally, physical insight and numerical estimates of microwave-induced auditory effects were largely based on FDTD type computations [12, 13, 14].

The objective of our effort was to initiate development of numerical tools which would allow to solve, with high fidelity, the problem of generation and propagation of microwave-induced acoustic waves in biological media, with a specific application to acoustic waves generation in the human head.

The approach we adopted is based on integral equation formulation with a Fast Fourier Transform (FFT) compression scheme. The solution accuracy is the main advantage of the integral equations based methods. Our work built on the fast integral equation solver we had previously developed for large-scale simulations of electromagnetic scattering and propagation phenomena.

Our main results can be summarized as follows:

- **Extension of the fast, integral equation, electromagnetic solver to a volumetric acoustic solver with an interior source.** We extended our FFT- (AIM-)based fast integral-equation solver for electromagnetics to the Lippmann-Schwinger (L-S) volumetric equations of acoustics, with scalar fields described by piecewise constant functions supported on tetrahedra. In particular, we developed a formulation applicable to an *interior* acoustic source distributed throughout the volume of a scatterer. We note that problems involving microwave-induced acoustic fields involve *interior* sources and are quite different from more commonly considered scattering or propagation problems generated by a source *external* to the scatterer (e.g., a plane wave emitted by a distant source).

- **Development of solution procedure applicable to large-density contrast, interior acoustic source problems.** We formulated a solution procedure applicable to problems characterized large density contrasts (e.g., a human head immersed in air). It is well known that high-contrast problems lead to difficulties associated with the ill-conditioning of the resulting integral equations. Our approach utilizes the observation that, for high-contrast interior source problems, pressure near the object boundary is significantly smaller than pressure inside the object. The approach involves a rescaling procedure which alleviates the ill-conditioning and results in a significant acceleration of the convergence of the solution procedure.

- **Validation of the developed approach.** We derived the analytical solution for an acoustic sphere excited by an interior, volumetric, spatially constant pressure source, and compared it with the numerical solution. Also, we derived the analytical expression for an incident pressure wave induced by a constant pressure source and compared the

L-S integral equation solutions for the r.h.s.s defined both analytically and numerically. The results confirmed the accuracy of our solver.

- **Results of numerical simulations.** In our studies we chose a relatively simple model of a layered sphere with a cylindrical indentation (channel), immersed in air. The outer layer, with the material properties of bone tissues was meant to represent the skull, and the inner region with the material properties of soft tissues represented the brain. The sphere radius was about 0.07m. The geometry was composed of approximately half a million tetrahedra.

  We solved the electromagnetic problem for a plane wave of the frequency of 1.42 GHz and the incident field amplitude of 1 V/m. From the knowledge of the electromagnetic field intensities we computed the pressure source and, subsequently solved the acoustic problem for the frequency range from about 300 Hz to 12 kHz. We computed pressure distributions for the above range of acoustic frequencies, and, eventually the pressure time profiles.

In discussing the impact of our numerical simulations on the assessment of the effect of propagation of microwave induced acoustic waves in a human head, we should take into account both the simplifying approximation we made in our formulation and the simplified geometrical model we used.

Our numerical simulations indicate that the behavior of pressure waves in the head model induced by microwave radiation is primarily controlled by resonances in the acoustic problem solution.

In our computations did not take into account viscosity effects. Hence, we neglected attenuation of the acoustic waves, as well as the viscosity-induced shear waves. This effect is negligible in the audible range but may become significant at ultrasound frequencies.

Finally, we were considering an *isolated* head model immersed in air, hence we did not take into account any effects of energy flow from the head through the soft tissues of the neck and through the vertebral column to the rest of the body. As the result, the resonances we observed were relatively narrow (the only energy loss we accounted for was radiation of the acoustic wave into the surrounding air, and this, because of a large tissue/air density ratio (~ 1000) and thus a large impedance mismatch, is rather small).

A more realistic problem formulation should include (e.g., through matched impedance boundary conditions) a mechanism allowing energy transfer, by acoustic waves, from the head to the body. Such processes will increase resonance widths and cause a more rapid damping of the propagating microwave-induced pulse.

In summary, the quality of our numerical results and the associated code performance indicate that the approach, development of which we initiated under this effort, can provide a very accurate and reliable tool to assess the effects of generation of microwave induced acoustic pulses for arbitrarily shaped and arbitrarily inhomogeneous geometries (e.g., to reliably determine the resonance spectrum in a human head). We identified additional enhancements of the formulation which would allow us to carry out efficiently more realistic, large-scale simulations.

Summary - Part IV

The principal objective of this effort was to develop a set of algorithms and corresponding numerical tools

- to determine the effective electric permittivity of the cloud medium;
- to design and execute a relevant set of numerical simulations for modeling propagation of electromagnetic waves (pico-second and femtosecond laser pulses) through dense as well as dilute cloud medium, in the near infra-red region (i.e., for wavelengths of $1\,\mu\text{m} - 10\,\mu\text{m}$);
- to investigate conditions under which a reduced attenuation and an improved image quality can be achieved.

The results of our work can be summarized as follows:

- **Determination of the effective electric permittivity of a "dilute" atmospheric cloud.** We determined the effective electric permittivity $\hat{\epsilon}_{\text{eff}}$, of a "dilute" atmospheric cloud, composed of water droplets of the size of the order of $1\,\mu\text{m}$ and an average droplet separation of the order of $0.1 - 1.0\,\text{mm}$, corresponding to the volume fill factor f_{v} in the range 10^{-7} to 10^{-5}, in the framework of the Effective Field Approximation (EFA), known also as the Foldy approximation (see, e.g., Ref. [15], Chapter 6). We included dispersion effects caused both by the discrete nature of the medium and the frequency dependence of the permittivity of water. In evaluating scattering amplitude from individual water droplets we found it essential to use the exact Mie formula. In the wavelength range of interest ($1\,\mu\text{m} - 10\,\mu\text{m}$) and for droplets of the radius larger than $0.1\,\mu$m, the Rayleigh mixing formula tends to underestimate scattering on a single droplet, and can therefore underestimate the pulse attenuation in the medium (see, e.g., Figs. IV-8 and IV-10).

Since, in the effective-field approximation, the permittivity $\hat{\epsilon}_{\text{eff}}(n_0, a, \lambda)$ depends linearly on the medium density n_0, and on the "complex cross-section" $\hat{\sigma}_t(a, \lambda)$ (proportional to the forward scattering amplitude on a single droplet, $\hat{F}(a, \lambda)$), it is reasonable to tabulate the "complex cross-section" a function of two variables, the droplet radius a and the wavelength λ, and, in subsequent computations, interpolate its values.

We have created the effective electric permittivity $\hat{\epsilon}_{\text{eff}}$ data-base for a "dilute" atmospheric cloud in the range

$$0.1\,\mu\text{m} \leq a \leq 10.0\,\mu\text{m}\ , \quad 0.3\,\mu\text{m} \leq \lambda < \lambda_{\text{max}} \sim 10\,\mu\text{m}\ . \qquad (0.1)$$

- **Determination of the effective electric permittivity for a dense medium composed of discrete scatterers.** We developed and implemented (as an extension of our general-purpose fast integral-equation solver) a novel approach to large, dense systems of discrete scatterers.

  We modeled an ***infinite slab*** of a particulate medium as a laterally periodic system of large cells, each cell containing from several hundreds to about a million scatterers (see Fig. IV-15). Application of the FFT-based compression methods allowed us to solve scattering problems for such a slab at the computational cost approximately proportional to the number of unknowns per cell. Details of the approach are described in Section IV-5 and in Appendices IV-F, IV-G, and IV-H.

  We applied the implemented method to models of dense and strongly scattering media, and determined their effective electric permittivities in a way taking into account, rigorously, all multiple-scattering contributions. Some representative results, for a strongly scattering system, are shown in Figs. IV-16 and IV-17. In this case, in which the mean-free-path is comparable to the distances between the scatterers, the results show that the effective permittivity extracted from the multiple-scattering computation differs significantly from the prediction of the Effective Field Approximation.

  At present, the developed approach allowed us to carry out routine computations for periodic cells of moderate size – up to about $12.5\,\lambda \times$

$12.5\,\lambda \times 40\,\lambda$ and 300,000 unknowns, and to simulate media with the volume fill factor f_v of about 0.005 to about 0.05.[1] However, for the considered densities, the slab thickness $H \sim 40\,\lambda$ corresponds to only about one mean-free-path (say, l) in the medium. In order to quantify more precisely the multiple-scattering effects, it will be necessary to consider larger cells, in particular of larger thickness H, equal at least several mean-free-paths l. Simulations for such thickness are crucial if possible deviations from the exponential wave attenuation are to be detected.

We stress here that studying infinite periodic systems is essential in investigating wave propagation at slab thicknesses H exceeding few times the mean-free-paths l: even if it were possible to solve the propagation problem for a finite slab of a lateral size large compared to its thickness, the effects of the slab boundaries would make interpretation of the results difficult, if not impossible. The reason is that already at the thickness $H \gtrsim 2l$ the slab becomes so intransparent that diffraction from the boundary of the slab becomes important and it soon overwhelms the field which penetrated through the slab. These difficulties are avoided in simulations for an infinite periodic slab.

We found that, in our present implementation, the periodic cell size is limited not so much by the computational resources required by the relatively large numbers of unknowns per cell, but by the slowness of the iterative solution convergence. To improve the convergence, devising/implementation of a preconditioner containing far-field interactions is required. We stress that, to our knowledge, the issue of convergence of large (millions of unknowns per cell) periodic systems is new and has not been investigated before.

We expect that subsequent adaptation of the present code to more dilute media with smaller scatterers will allow us to model a realistic cloud with cell volumes exceeding 1000 cm^3 and containing more than 1,000,000 droplets. Such chunk sizes should be sufficient to obtain local effective medium parameters, in particular the wave attenuation rate, in the lower frequency part of the pulse spectrum, characterized by high penetrability (i.e., in the millimeter-wave range). Simulations of this type can provide information on the dependence of the local medium properties and scattering amplitude phases on the inhomogeneities, fluctuations, and spatial correlations of droplets. This

[1]For comparison, the fill factor for realistic atmospheric clouds is on the order of $f_v \sim 10^{-6}$.

information is essential, e.g., in assessing effects of medium turbulence on the signal integrity.

- **Propagation of ultra-short infra-red laser pulses in a dilute medium composed of discrete scatterers.** We carried out numerical simulations of propagation of short infra-red narrow-band ("sech"), as well as wide-band (harmonic, trapezoidally modulated) pulses through dilute media composed of discrete scatterers.

  Our results confirm the exponential attenuation of narrow-band pulses as the function of the penetration depth.

  Our results also indicate a significantly slower, power-like, attenuation of wide-band pulses of short enough rise time and, hence, large enough low frequency content. We ascribe this behavior to the nontrivial frequency dependence of the forward scattering amplitude on individual medium elements (droplets), as the result of which, the low-frequency part of the wide-band pulse spectrum becomes significantly less absorbed as the penetration depth increases. This low-frequency, weakly absorbed part of the spectrum starts to dominate the time profile of the pulse at large penetration depths and contributes to its weaker absorption.

  The numerical results of our analysis are presented in Section IV-6 and Appendix IV-I.

  In the last Section (Section IV-7) we discuss the feasibility of application/extension of the present research to active imaging through clouds, fog, and atmosphere. The atmosphere gives rise to additional absorption (due mostly to water vapor) in the lower-frequency part of the spectrum, except for several "atmospheric windows"; we estimate, for the considered short pulses, fractions of the total pulse power which can be transmitted through these windows.

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