ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

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The Electromagnetic System Initiative

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1-D Active radome based on Left-handed Material

We proposed designs to realize single-sided Left-handed Materials (LHM), which are easy to fabricate. With active lumped elements (varactors), the refractive indices of single-sided LHM samples become controllable. When EM plane wave incidents upon a prism made of the single-sided controllable LHMs, the transmitted beam is steered by changing the refractive indices of the LHMs. The incorporation of the LHM can reduce costs, weights as well as sizes of one dimensional (1-D) active radome devices.

Multi-Frequency resonator based on dual bands S shaped Left-handed Material

We experimentally realize a 1D RHM (Right-handed Material)-LHM (Left-handed Material) multi-frequency resonator based on LHM with dual negative bands. The resonator consists of dual negative bands LHM and air, which are arranged in an X-band waveguide. Multi-resonant frequencies for the resonator are observed within two left-handed bands of the LHM. The incorporation of LHM into the resonator design allows more flexibility to realize multi-resonance.

The experimental results show that the resonant frequencies are within the frequency bands, where the refractive indexes of the LHM sample are negative. Especially for the case that the resonator has two resonant frequencies, the two resonances happen in the two negative bands respectively. The resonator show that the LHM layer in the resonator can give the feasibility to choose the resonant frequency ranges, because one can simply choose the sizes of the rings of the S shaped multi-bands structure to decide the negative bands.

Imaging properties of finite-size left-handed materials (LHM) slabs

The ability of the Finite-Difference Time-Domain method to model a perfect lens made of a slab of homogeneous left-handed material (LHM) is investigated. It is shown that because of the frequency dispersive nature of the medium and the time discretization, an inherent mismatch in the constitutive parameters exists between the slab and its surrounding medium. This mismatch in the real part of the permittivity and permeability is found to have the same order of magnitude as the losses typically used in numerical simulations. Hence, when the LHM slab is lossless, this mismatch is shown to be the main factor contributing to the image resolution loss of the slab.

Finite-size left-handed material (LHM) slabs are studied both analytically and numerically. The analytical method is based on Huygens' principles and truncated current sheets that cover only the apertures of the slabs. It is shown that the main effects on the image's spectra due to the size of the slabs can be predicted by the proposed analytical method. Furthermore, the property of negative energy stream at the image plane is also investigated. We find that this unique property is actually due to the interactions between propagating and evanescent waves and can only occur with LHM slabs (both finite-size and infinite).

Metamaterial with Randomized Patterns for Negative Refraction of Electromagnetic Waves

Artificial metamaterials made to date are all periodic in structure. Yet, we have shown that by randomizing contour patterns deposited lithographically on circuit board materials, a metamaterial characterized by a constitutive relation with negative constitutive parameters is produced in solid-state form. We clearly demonstrate the phenomenon of negative refraction to show that it is not produced by periodicity. This underlines the importance of using constitutive relations for media characterization in electromagnetic theory and suggests that metamaterials could be realized with composite materials or fabricated with various techniques by using versatile hosting materials

Multifunctional Wide-Band RF Systems

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Antenna isolation

In communication systems, often times the receiving antenna and transmitting antenna are located close to each other so that there are couplings between the antennas which should be minimized. The couplings are mainly contributed by the surface waves. In literatures, people have been using electromagnetic band gap (EBG) structure to isolate the two antennas. The EBG has a good performance in the suppression of the surface wave but it is narrow band and lacks of tenability.

We investigated four cases of material: left-handed material, right-handed material, Mu negative material and Epsilon negative material as a material candidate to suppress the surface waves. Both analytical formulation and numerical simulation results are proposed. The guidance conditions for the surface wave propagating along material backed with PEC ground plane are obtained. We show significant improvements on the antenna isolation can be achieved by designing the slab's Mu to be in the range of [-1 1] while keeping Epsilon to be 1.

Equivalent circuit model for left-handed material

We report a general equivalent circuit model (ECM) to calculate the effective permeability of various configurations of split-ring resonators (SRR). In the proposed model, each column of the SRR units along the axis of the rings is modeled as a quasi-solenoid under magnetic induction. The inductance per ring of the infinite column of these rings is calculated, assuming all the rings in this column support the same current. The electromagnetic coupling between these individual columns of the rings is integrated into this circuit model, which is then applied to a two dimensional (2D) cross embedded split-ring resonator. The agreement between the predicted results and numerical simulations shows the efficiency of the model in predicting the frequency band of negative permeability.

Active radome in the antenna application

A controllable left-handed metamaterial based on a varactor-loaded S-shaped resonator structure is presented to realize an active radome. By controlling the phase properties of the radome, the antenna exhibits continuous scanning capability in a range of 40 degree, which is confirmed by theoretical analysis.

Full Body Prediction of Electromagnetic Scattering off Electrically Small Features

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In many scattering and radar cross section (RCS) problems, a subject of great concern is how electromagnetic waves behave when they scatter off large structures with electrically small features embedded on them, as well as how that can be effectively and efficiently modeled. Such small features may include cracks, grooves, or small projections or extensions off the main structure, and those are necessarily present when, for example, two component parts of a target are joined together. Such small features may contribute significantly to the scattering pattern and monostatic RCS of the overall large target, and thus understanding the contributions of these features becomes a critical step in the step of full-body prediction modeling.

We used RAM2D, a two-dimensional boundary integral equation code, to calculate the RCS of metal, dielectric, and impedance card structures in free space or in the presence of an infinite ground plane. Specifically, we simulated three different sized grooves, and compared the scattering pattern to that when a lossy dielectric coating is placed over the grooves. We show that the smaller the size of the target groove, the more difficult it is to accurately model the monostatic scattering pattern. In addition, RAM2D's prediction capability is general found to be inaccurate when the number of segments per wavelength is too large.

Phase Unwrapping and Denoising Techniques in SAR Interferometry

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Our study seeks to do some early investigation into the algorithms used to improve the accuracy of the critical phase unwrapping step. We seek to compare the different methods of unwrapping phases, especially when we have 3 baselines available, as is the case when there are 3 satellites. The primary method, and “reference” method to which we will compare other phase unwrapping methods to, is the Weighted Least Squares unwrapping technique. This technique makes use of the second derivatives of the wrapped phases to determine the best unwrapping procedure, with appropriate weights assigned to each pixel in accordance with how much we suspect that pixel is contaminated by noise. Another widely available phase unwrapping technique in literature today is the Branch Cut algorithm in tandem with “residues” present in noisy interferograms. These methods are meant for only one baseline (instead of multiple baselines), but they set up a solid framework for our multi-baseline study. In addition, we give a thorough treatment of the iterative dynamic programming approach that Ying, Munson, Koetter, and Frey used for both the single baseline and the multibaseline case. This Maximum a posteriori (MAP) estimation that they undertook is then compared with both the single baseline and multi-baseline cases that can be achieved using Weighted Least Squares or Branch Cut using weighted arithmetic averaging, and the merits of each discussed.

Since insufficient robustness to noise is probably the biggest factor in weak performances by different algorithms, we also look at ways to mitigate noise levels given that we have 3 interferograms instead of just 1. We propose 3-D projection as a technique to reduce the impact of noise during our phase unwrapping step. This makes use of fact that the geometry of the satellite configuration constrains the relationships among the 3 phases retrieved by the 3 satellites. The relative distances of the satellites from one another (baseline lengths) play a critical role in this, and we lay the groundwork as to how this can be exploited to retrieve more accurate phase values. We also present the increased retrieved height accuracy that 3-D projection achieves, and discuss some of the limitations that 3-D projection faces.

Ultra Wide Band Coherent Processing

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To resolve scattering centers that are closed together, people need an ultra-wideband (UWB) radar system. Since it is hard and expensive to realize in real life, there have been proposal of using different radar stations at different locations, each having its own operating frequency and bandwidth, to achieve a fusion of data such that as a whole, the range and cross-range resolution can be increased. We survey the different techniques used for the underlying technique of bandwidth interpolation, and look into the techniques of cohering two bands of radar data to form an ultra-wide band signals, from which we attain a 2D image with both range and cross-range resolution that is greater than the sum of bandwidth implied.

High-Definition Vector Imaging

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The goal of this research was to recreate the results of Gerald Benitz's paper 'High-Definition Vector Imaging' for a particular case of satellite configuration. A variation of Capon's technique, as presented in Benitz's paper, was implemented using the subspace constraint without the quadratic constraint. The results were satisfactory, but the processing time was prohibitively long. A different technique, using a reduced version of the MUSIC algorithm, was implemented. This technique produced results similar to the Capon's method results, but was significantly faster.

SVM Classification of UXO

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The Electromagnetic Induction (EMI) response from buried unexploded ordnance (UXO) has been studied with interest in recovering the attributes of the buried object. Utilizing the concept of the decomposing EMI signals into modes within a spheroidal coordinate system, the coefficients of those modes have been shown to be unique for unique objects. Therefore, these modes readily lend themselves for use in identifying and classifying the buried objects. With synthetic data generated by forward models, the appropriate coefficients were recovered and were processed using support vector machine (SVM). SVM, being a statistical learning algorithm which is able to identify trends in training data, was able to learn the association between the spheroidal mode coefficients and various appropriate classes into which UXO can be sorted. In particular, the interest lay in identifying body-of-revolution objects from non-body-of-revolution objects, homogeneous objects from non-homogenous objects, and large objects from small objects. These classification objectives are geared toward identifying UXO from clutter objects. In this study, SVM was successful in classifying various objects along these lines. Furthermore, a neural network was implemented to classify objects within a similar framework and produced comparable results.

Environmental Effects on UXO Identification

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This project seeks to understand the effect of environmental factors on electromagnetic induction (EMI) measurements of unexploded ordnance (UXO) and the associated inversion techniques applied on the noisy measurements. The environmental factors include clutter, since UXO sites are highly contaminated with metallic clutter, and ground effects, because soil may be slightly permeable. EMI measurements were taken of UXO overlaid by a surface dispersion of small metallic clutter pieces. Inversion was done to identify the UXO based on those noisy measurements. This was accomplished by optimizing the match between measured and modeled scattered magnetic fields, using a new generation of fast but accurate forward models. We used differential evolution (DE) to find the optimal match. Inversion is successful when the closest match originates from the correct UXO type out of the library of possible UXO types. Furthermore, measurements were also taken of UXO buried in soil. Through analytical approximations of spheres embedded in permeable half-spaces, it was found that for the range of realistic soil permeabilities, all halfspace effects are negligible except for a magnitude offset in the real part of the measured frequency domain EMI signal. We incorporated this offset effect in our forward models and did optimization inversion on the measurements. The inversion was successful for UXO buried at shallow depths. Lastly, clutter can be approximated as directional dipoles and their combined effect can be incorporated into our forward models along with the soil offset effect. Synthetic data was generated using this forward model. This improved forward model allows for Monte Carlo-type simulations to help understand the statistics of clutter noise and investigate ways of suppressing or filtering out that noise in measurements. Further research is also needed to enhance the robustness of our inversion techniques to overcome the environmental effects.

Electromagnetic Models and Data Analysis for UXO Discrimination

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Calculation of the H fields based on equivalent magnetic source

In the field test of UXO discrimination, detecting data of H fields on the surface are strongly affected by small clutters around the UXO and noises. We proposed an algorithm to reduce the effect of the clutters and the noises by calculating the H fields from the equivalent magnetic charges, which are extracted from the field test data of the surface. The obtained H fields on the plane above the surface show that undesirable factors are dramatically lowered.

PCA Analysis

Principal component analysis was applied to the task of discriminating unexploded ordinance from clutter in measurements made using the Geophex GEM-3 sensor. The goal of the investigation was to determine if the returned signal of a buried object would show up in a set of principal components separate from the returned signal of clutter objects. Unfortunately, the response from the object and clutter do not separate in principal component space.

Computations of Subsurface Equivalent Sources

UXO discrimination signal processing approaches to date assume particular models for subsurface objects that produce the signals. They then perform optimization calculations to estimate the location and type of these sources. This can be a very laborious procedure, even for very simple models of typical sources. And the models chosen are usually of limited validity or applicability. Further, the analyst rarely knows how many objects are contributing to the signal and how important each is. So, rather than assuming a model for each scatterer, we simply analyze the above-ground signals themselves and see where they lead below ground. Based on physically rigorous governing equations, the computations treat the above-ground data as an extended boundary condition, on the basis of which the algorithms will solve numerically for a complete source picture below ground. The completeness of the picture will only be limited by ill-conditioning and associated resolution constraints. To overcome this limitation, one beneficial approach may be to describe the source distribution using a set of basis functions. Instead of solving for source values directly, we are solving the coefficients of the basis functions. By using finite terms in the source expression we can both get a good picture of source distribution and help improve the condition number to some degree.

Electrostatic Phenomena from Moving Objects

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Sensors have been developed in recent years for the detection of electrostatic disturbances from slowly moving objects. Applications for these sensors are being developed in industry, but better models for their predicted behavior is needed to facilitate the design process. We investigate the theoretical considerations for the forward electrostatic problem and inverse problems of detection and estimation.

The solutions to analytic electrostatic problems were used to develop models for the object creating the electrostatic disturbance, as well as for the system used to detect the disturbance. A typical sensor used for detection generally consists of a band-pass amplifier with the input connected to an electrostatic electrode. To model the system, a mutual capacitance model that describes the physical interaction between source and electrode must be included in the amplifier equivalent circuit. Therefore, an analytic model for the mutual capacitance is highly desirable. We developed a potential averaging method based on the mean value theorem to give approximate analytic expression for the potential of a conducting electrode in a known incident field. Hence, due to a disturbance on known charge, an analytic approximation for the mutual capacitance can be used in the system circuit model.

The inverse problems of source localization and direction of arrival (DOA) are treated as estimation problems for a set of sensor measurements at known locations. We assume additive Gaussian noise for each sensor measurement and derive estimators for instantaneous source localization. We then compare with the theoretical optimal performance given by the derived Cramer-Rao Bound (CRB). It is shown that an iterative Maximum Likelihood estimator achieves the CRB in low noise. Ongoing work also considers DOA estimation from selective measurements in low signal-to-noise ratio. The fundamental goal is the determination of optimal sensor placement for various applications and environments.

Modeling trapping and binding forces between particles

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Modeling of optical binding and trapping effects

The Maxwell stress tensor and the distributed Lorentz force density are applied to calculate forces on media and are shown to be in excellent agreement. From the Maxwell stress tensor, we derive analytical formulae for the forces on both a half-space and a slab under plane wave incidence. It is shown that a normally incident plane wave pushes the transparent slab in the wave propagation direction, while it pulls the lossless half-space toward the incoming wave. In both cases, zero tangential force results, regardless of incident angle. The Lorentz force density is generalized to include magnetic media by applying the principle of duality to bound magnetic charges and currents. Agreement between the two methods is also demonstrated for the case of 2-D circular dielectric and magnetic particles subject to a plane wave incidence, multiple wave interference patterns, and Gaussian beams.

The momentum conservation theorem is derived from the Lorentz force law where the charges and currents are represented by field quantities via the Maxwell equations. Using the momentum conservation theorem, the force on a lossless material body is described by the divergence of the Maxwell stress tensor and is calculated by the integration of the stress tensor on any surface which completely encloses the material body. Thus, the radiation pressure on a three dimensional (3D) object is calculated from a surface integral with knowledge of the total fields external to the object.

The distributed Lorentz force is applied to bound currents due to the polarization of a medium and to bound charges at the material boundary. Contributions from magnetic current densities throughout a material body and magnetic charge densities at the surface are added to the standard Lorentz force on bound electric currents and charges to model the volume force density and the surface force density, respectively. The radiation pressure on a 3D object is determined by the combination of a volume integral with knowledge of fields and polarization inside the medium and a surface integral with contributions from fields on both sides of the boundary.

The Lorentz force density exists everywhere inside the media once the electromagnetic fields are present. In this regard, the Lorentz force density itself consists of complicated patterns inside media due to the interference of internally reflecting waves. This view is applied to precisely describe experimental observations of laser trapping and the fundamental aspects of optical momentum transfer in absorbing and dispersive media. This approach can also be applied to understand the details optical binding forces between particles, including the effects of complex material parameters.

We have applied the Mie theory and the Foldy-Lax multiple scattering equations to compute the scattered field of an arbitrary number of infinite dielectric cylinders of arbitrary size, subject to in-plane incidences. The Maxwell stress tensor has then been used to compute the force on each cylinder. Trapping and binding forces have been studied as function of particle size, number, permittivity and separation. We have applied this formulation to a system of 20 particles and the results show clear similarities with known experimental reports. To our knowledge, this is the first time that a simulation comes so close to explaining an optical trapping experiment. The formulation thus developed extends the capabilities of modeling particle interaction and optical matter beyond the simple cases of Rayleigh regime and two-particle systems.

As an application, we have studied the binding forces and we have defined an inverse problem as a way of controling them to shape the force distribution in space. We have proposed a new trapping regime based on the equilibrium between a scattering force and optical binding forces only. The trap is realized from the interaction between a single plane wave and a series of fixed small particles, and is efficient at trapping multiple free particles. The effects are demonstrated analytically upon computing the exact scattering from a
collection of cylindrical particles and calculating the Lorentz force on each free particle via the Maxwell stress tensor.

Image Quality Assessment of Laser Trapped Mirror

The radiation pressure exerted by an electromagnetic wave (such as light) on dielectric particles can be used to organize the particles in space and lock them in desired positions. An application of such property is to realize a very large parabolic telescope dish in space, also called a laser trapped mirror (LTM). Although the feasibility of an LTM is yet to be fully explored, it is already known that the experimental constraints and the harsh space environment will cause the irregularities on the dish. In this work, we investigate the influence of some reasonable surface roughness on the imaging capability of the LTM based on numerical simulations of electromagnetic scattering. We choose exact electromagnetic calculation (the method of moment is employed) and resort to small dishes (diameter up to 50 times wavelength). We first show that if the particles, with the diameter up to 1/10 of the wavelength, is aligned along parabola, the reflected wave focuses at the focal point. Then with roughness of few percent of wavelength it is shown that SNR (Signal to Noise Ratio) is reduced up to 4dB, but other than that the damage is moderate.

Experimental Methodology for Non-thermal Effects of Electromagnetic Radiation on Biologics

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MIT Auto-ID Lab

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Appropriate equipment is needed for research on the effects of radio-frequency radiation from radio-frequency identification (RF-ID) systems on biological materials. In the present study, a complete test system comprising assembled hardware and custom-built software was developed for a research project investigating whether RF-ID radiation produces significant effects in biologics. Furthermore, we document a method for determining specific absorption rate (S.A.R.) using vials containing 1.5cc of saline to represent biological samples. This methodology yielded S.A.R. values of approximately from 30W/kg to 150W/kg for 915MHz and 320W/kg to 450W/kg for 2.45GHz. Finally, the key system components – the transverse electromagnetic (TEM) cell, vial and saline solution – were modeled using CST Microwave Studio. Through modeling, we obtained values for the absorption as a percentage of the incident power. These values matched those from experiment, demonstrating a reliable setup for exposure studies.

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