ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

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Research on SAR Simulation Model

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Radar technology continues to find widespread use in the long range, all weather remote sensing of earth terrain. In this research, the use of polarimetric synthetic aperture radar (SAR) images in the remote sensing of various terrains is studied, from which the soil moisture content is predicted. The terrains studied range from idealized flat surfaces to locally tilted surfaces and real terrains covered by a tree vegetation.

Predition of soil moisture content is an important application in the area of microwave remote sensing. With the advances in Synthetic Aperture Radar (SAR) technology, high resolution active remote sensing of the earth terrain is now possible. We describe the proposed methodology for the determination of soil moisture content (SMC) from SAR data. We also evaluate the method by generating simulated SAR images based on a realistic electromagnetic scattering model. The soil moisture content retrieved from the proposed method is shown to have a statistical distribution which has its peak at the implemented soil moisture level. For a given terrain, the composition of the soil and the terrain information are assumed to be known. High resolution data of these parameters provide accurate inversion basis for the retrieval process, and it is possible to determine the reflection coefficients of the terrain facets using Physical Optics assumptions.

To model the tree vegetation, we use a well-known approach consisting of modeling a forest as being comprised of a crown layer, a trunk layer, and a rough-surface ground boundary. The crown layer is typically modeled as a collection of randomly oriented dielectric cylinders (branches) and flat discs (leaves). The crown layer can also be modeled as a continuous random medium. At L band frequencies, the main effect of the crown layer is a net attenuation of the electric field. At lower bands, this effect can be neglected, while at higher bands, the scattering due to the branches and leaves must be taken into account in addition to the attenuation. The trunk layer is modeled as a collection of dielectric cylinders that are placed over a flat and possibly tilted ground plane of arbitrary dielectric constant. The total scattering from the collection is approximated as the coherent sum of the scattering from each trunk.

While the backscatter coefficient is one metric used in the estimation of soil moisture content parameters, a second is the actual SAR image. To this end, an efficient SAR simulation program is used. This is accomplished by evaluating the cross-range focusing aspect of the matched filter correlation integral using a closed form analytic expression for the cross-range focusing sum. However, in this method, it is assumed that backscatter intensity of scatterers is independent of the azimuthal incidence angle. While for flat terrains with trunks, this approximation is valid, it does not hold for sloped terrains. In this case, it is important to take into account the wide-aperture effect in which the backscatter intensity due to a single trunk varies as the SAR antenna flies along track. This effect is modeled efficiently by breaking the cross range sum into a few sections in which the average backscatter return is used. In this way, the complexity of the cross range sum does not increase so dramatically.

Research on SAR Interferometry: application to STAP

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Airborne radars have long been used for the long-range, all weather sensing of remote targets. Future systems will be required to provide the detection of targets of increasingly smaller size. However, even though radar technology continues to become more powerful and sensitive, there is still a fundamental limit to the detection capabilities due to the presence of interference, either natural or man-made. The typical ground moving target indicator (GMTI) radar scenario is that of a small isolated moving target surrounded by strong stationary ground clutter and/or jammer signals. The purpose of STAP is to estimate, without any prior knowledge, the statistics of the noise plus interference and then adaptively cancel it. In this work, a review of the Space Time Adaptive Processing (STAP) and related algorithms is undertaken. In this development of the STAP theory and simulations, various clutter models are studied including those capable of modeling simple uniformly random terrains and other special cases of clutter such as wind-blown trees.

Before addressing full STAP, we first review other basic adaptive and non-adaptive radar techniques for clutter rejection. For example, the Classical Displaced Phase Center Antenna (DCPA) algorithm and its relation to STAP is accessed. Its functionality and limitations will are studied motivating the need for STAP techniques. Next, we will present a review of algorithms specifically related to STAP and apply them to some simple cases. In particular, the fully optimum (ideal) STAP algorithms will be presented and discussed, which will lead to the discussion of various performance metrics. A comparison between optimum and tapered fully adaptive STAP will also be covered. We shall then discuss the concept of pre-processing to reduce the degrees of freedom leading us to the development of partially adaptive STAP.

With this work, we have shown that the STAP method is not restricted to specific PRFs and antennas. However, it must be noted that the improvement capability of this technique comes in general at the cost of an increased antenna complexity and computational burden. In addition, the angle measurement precision may be degraded because of an inexact extraction of the angular location of the target returns in the antenna beam.

These drawbacks call for more capable signal processing architecture in future space-based radar systems. STAP has been extensively used in standard airborne and space-based radar systems with single apertures, and has been adapted to multiple aperture systems only recently (note that DPCA is not a viable technique in this case). This type of radar systems is nowadays studied to be implemented in the TechSat 21 program, based on three 150 kg satellites in 550 km orbit realizing a distributed aperture sensing. The advantages of distributed aperture are numerous, among other a better slow target detection, a better resolution, a possibility to dynamically reconfigure the antennas, etc. In the next phase of this work, we will examine more in details how STAP algorithms can be used in a TechSat21-type configuration, and show how the performances and detection are improved.

Multifunctional Wide-Band RF Systems

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Planarly layered media have been used to model a wide variety of environments, such as ground and vegetation for remote sensing applications, atmosphere for wave propagation or dielectric substrates for microstrip devices. When an integral equation approach is used, the proper analysis of planarly layered media requires the knowledge of the associated Green's functions in their dyadic form. It is known that these Green's functions are expressed in the spectral domain as the product of a Hankel function for transverse variables and exponential functions for the longitudinal variables

In this work, we have extensively studied the Green's functions associated to single-layer media and have drawn numerous conclusions on their behavior. First, we concentrated mainly on the spectral expressions of the Green's functions and their thorough study. Since Mixed Potential Integral Equation is often preferred because of its less singular kernel than standard Electric Field Integral Equations or Magnetic Field Integral Equations, we have concentrated on the Green's functions for potentials. After providing all the components for all cases of source and observation position, we use these expressions to study the continuity of the fields, check analytically the reciprocity, and study the various modes (propagating and leaky) that are launched in single-layer substrates backed by ground planes. For the sake of illustration, spatial results for all the components are also given.

In a second step, we have studied the asymptotic behavior of the potentials, and therefore of the fields, at small and large distances. For large distances, i.e. in far-field, the contribution of the surface waves is shown to be dominant, with the known square-root of r decay. For small distances, equivalent to static and quasi-static cases, we show that the two components of the electric potential Green's function, inherent to Sommerfeld's choice for the magnetic vector potential Green's function, have a Taylor expansion which first terms in k (k being the wave number) are similar. This analytical result shows that the two components merge into one in the static limit, which is in agreement with fundamental electrostatic theory.

On the Electromagnetic Scattering by Left-Handed Media Spheres

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The study of left-handed (LH) media, first introduced by Veselago in 1968, has recently received much attention in the literature, both from a theoretical and an experimental point of view. Theoretically, such materials have been predicted to have a number of unique properties, including a negative index of refraction. Although naturally occurring materials with simultaneously negative permittivity and permeability are not known, one left-handed material has been artificially realized as a periodic lattice of metallic rods and split-ring resonators. Theoretically, the rods have been shown to have an effective negative permittivity, while the split-ring resonators have been shown to have an effective negative permeability. Experimentally, this meta-material has been built and measured to have a negative index of refraction, consistent with theory.

To study the propagation through LH media, there are two approaches. The first one is a macroscopic approach where the assumption of isotropic homogeneous media is made. Although this more theoretical approach is of foremost importance to properly understand left-handed materials, they are based on the assumption that these materials are homogeneous; however, this is not the case since left-handed properties are obtained from a complex arrangement of rods and split ring resonators (SRRs). Thus, the second approach is a microscopic approach where the actual structure of the meta-materials is modeled. In this work, we take both approaches in order to better understand both the theoretical and practical issues related to LH materials**.**

Macroscopic Studies

More recently though, all previous theoretical predictions and experimental observations have been questioned by Valanju et al (Phys. Rev. Lett., 88-187401, 2002), wherein the authors claim that the presence of dispersion prevents power transmitted at a RH medium-LH medium interface from refracting at a negative angle. However, Valanju et al draw their conclusions based solely on the electric field and neglect to calculate the Poynting vector, which is in the power flow direction for both non-dispersive and dispersive media. We have therefore studied wave and power transmission at a boundary between two homogenous and isotropic regions, one of which is a right-handed medium (permittivity and permeability both positive) and the other of which is a frequency dispersive left-handed medium (permittivity and permeability negative over a certain bandwidth). In order to account for the dispersion of the second medium, two types of signal spectra are considered. The first, for simplicity, consists of two discrete frequencies, while the second is Gaussian, which contains a continuum of frequency components. In both cases explicit expressions for the time-domain electric and magnetic fields are obtained, from which the Poynting vectors are calculated. Upon calculation, we have shown that negative refraction is possible for multi-frequency signals by explicit calculation of the Poynting vector in LHM. In the case of two discrete frequencies, we have shown that the direction of the time-averaged Poynting vector is in the average direction of the time-averaged Poynting vectors for each frequency treated separately, implying that negative refraction is possible. Using a Gaussian signal spectrum, we have confirmed this conclusion after also determining the power refraction angle to be negative, without violating causality. The angle of refraction was found to be in agreement with that predicted by Snell's law, with the LHM having a negative index of refraction.

Another macroscopic approach studies including using analytic techniques based on the Green's function methodology. In particular, we determine the electromagnetic field expressions due to a linear antenna, i.e. infinite line source, located outside a slab of LHM. The case of a dipole antenna can be treated in an analogous manner. As an example, we derive and study the integral expressions for the fields arising under the conditions necessary for producing a perfect image. We find that for certain regions of space, the integral expressions diverge exponentially and can not be evaluated in the usual sense. Yet, using an analytic continuation argument, a closed form expression for the fields at all spatial points can be found. Remarkably, we find that inside the slab there is a convergence of power, formed at the first image point while in the transmitted region an equivalent source forms at the second image point. While this source-sink-source solution is non-intuitive, it satisfies Maxwell's equations, the boundary conditions, and the radiation conditions. Still, experimental proof of this perfect lens effect has not been demonstrated. In order to understand current experimental results, frequency dispersive models for permittivity and permeability, which include losses, are introduced into the simulations. The effects of loss are studies and comparisons with experimental results are made.

Finally, we have also performed extensive work on the calculation of Cerenkov radiation in Left-Handed media. In this work, we have considered both dispersion and dissipation. Our conclusion corroborates Dr. Veselago's conclusion that both forward power and backward power exist when a particle moves in LH media.

Microscopic Studies

In addition to macroscopic studies, we have studied LH meta materials from the microscopic point of view. Our work in this area so far has given us the theoretical understanding as well as the modeling capabilities to study these meta-materials. Therefore, along with the development of the current geometries and their engineering applications, we are investigating new designs that exhibit LH properties. The figures of merit to consider are increased bandwidth, lower loss, and smaller size with respect to the currently achievable ones. As part of the research, we are exploring further the optimization of the LHM properties. One approach we have successfully used is a full three-dimensional analysis of both the split-ring resonators (SRR) and the rods. This has yielded good results in terms of our understanding of the materials as well as our ability to design them.

Due to the complexity of these media, one of the main approach we use is based on numerical FDTD simulations. The purpose of this work is to use a three dimensional FDTD method to study the transmission characteristics, phase propagation, and index of refraction of metamaterials to unambiguously determine their left-handed or right-handed property. Two macroscopic configurations of metamaterials are used towards this purpose: a slab to calculate the transmission coefficient and phase propagation, and a prism to study the index of refraction. The configurations of the metamaterials are based on a periodic arrangement of rods (for negative permittivity) and split ring resonators (SRRs, for negative permeability) embedded in a parallel plate waveguide. The results of this work conclusively demonstrate that fields propagating inside the metamaterial with a forward power direction exhibit a backward phase velocity and a negative index of refraction. Methods for extracting the constitutive parameters of metamaterials are also demonstrated. New SRR geometries are also investigated to find optimal metamaterial designs.

A second approach we are working on is a hybrid approach wherein we model SRRs embedded in a homogeneous frequency dispersive electric plasmas (to simulate effect of rods) using the two-dimensional FDTD method. This hybrid approach is useful because it turns out that the SRR structures are the most difficult to model and understand from analytical and effective media arguments. In addition, using a 2D FDTD based method would allow for shorter simulation times enabling more optimization possibilities. Eventually, the goal would be to develop structures much smaller than those currently achievable that have LHM bands at microwave frequencies (X-band). The reduction in size would enable the realization of more applications.

Currently, there are two methods being used to determine whether a particular medium has LHM properties. The first is a prism-based experiment, which measures the angle of peak power and then uses Snell's Law to determine the effective index of refraction. The second method is to measure the transmission and reflection coefficients of the slab. A transmission band reflects a similar sign of the permittivity and the permeability, which is taken to be negative if the transmission peak appears in an otherwise transmission-free region. Yet, this last conclusion may be erroneous, and the sign of the permittivity and permeability could as well be positive, as we have verified in our simulations. From an experimental point of view, it is much easier to realize and measure a slab of meta-material rather than a prism. Yet, as already mentioned before, the sole transmission characteristic of a material cannot unambiguously determine the sign of the index of refraction, and more processing is needed. For this reason, we are also working on the prediction of the index of refraction (as a complex value) from the reflection and transmission coefficients (complex values). The purpose of this work is to immediately identify the frequency band(s) over which the material exhibits NRI properties. Further work in this area includes the study of the robustness of the retrieval algorithms to noisy input data.

Polarimetric Passive Remote Sensing

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It has long been recognized that sea foam has a disproportionately strong effect on thermal emission from a wind-driven ocean surface. An empirical formula due to Stogryn for sea foam emission which was based on early experiments is still widely used today. Recently, attempts have been made to derive a physical model of foam emission where the foam is idealized as a collection of air bubbles with sea water shell.

The foam layer is typically assumed to overlay a flat ocean surface. Therefore, the effects of the rough ocean surface are not taken into account in such models. In this work, we want to introduce the roughness of the ocean surface by incorporating the large scale variations included in the commonly used two-scale model. Hence, a realistic Cox-Munk slope distribution is used to characterize the slope distribution of the random sea-foam surface.

The solution to this problem is obtained in two steps. First, the dense medium radiative transfer theory is used to compute the thermal emission from a foam layer on a flat interface. Second, the emission from a tilted foam layer is calculated using coordinate and polarization transformations. In doing so, it is assumed that dominant effects of the rough ocean surface on foam emission is the geometric tilting of emission vectors.

Using this approach, we examine polarimetric foam emission for different sea surface foam parameters as well as wind speed and direction. We will present results of brightness temperatures as a function of looking angles and frequencies. When combined with the commonly used two-scale theory of thermal emission from plain ocean surface, one can arrive at a simple but physics-based description of foam-covered ocean emission that can be used as a basis of parameterized inversion from real data.

Detection of Ships over large ocean surfaces

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The US Navy has for long been trying to understand and predict radar cross-section of various types of ships on the ocean surface, in particular in the GHz band. Towards this purpose, we have continued our work on the development of the Mode Expansion Method (MEM), and have seeked ways to accelerate it, in order to be able to model realistic ocean surface sizes.

In particular, our emphasis has been on the study of the integral equation governing the scattering of electromagnetic waves and the effort to relate the surface current representation to the Fourier theory. A unique mode distribution representing the amplitude of surface-to-surface inter-acting waves has been obtained, providing guidance for selecting dominant interacting waves, thereby minimizing the number of unknowns in the matrix equation. In this way, the number of unknowns achieved for HF-MEM has been reduced to less than 10% of that of traditional MoM technique. In addition, in order to speed up the evaluation of the matrix elements (written in terms of integral relations), we have implemented the steepest descent path (SDP) method. The total computation time for a large scale (1300 wavelengths) rough ocean surface has been analyzed in about 5 minutes, while keeping the accuracy in a satisfactory range. The method is therefore very helpful to solve 2-D rough surface scatterring problems in very large scale.

Time Domain Electromagnetic Models for UXO Discrimination

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The detection and removal of buried unexploded ordnance (UXO) is an expensive and difficult task. In the United States, an estimated 11 million acres of land may be contaminated with UXO. The problem is more acute in European countries, where millions of buried UXO remain from two world wars. The overwhelming task of finding and removing these UXO is hampered by the fact that almost three-quarters of the costs and efforts are expended digging in response to sensor false-alarms caused by metallic clutter. Hence, accurate discrimination techniques are an area of active research. A promising technique is EMI, which is carried out at frequencies where the soil and natural environment are transparent. Measurements of the EMI field from buried objects are taken in both the time domain (TD) and frequency domain (FD). Common practice is to use a static magnetic primary field, which is turned off periodically, while one measures the EMI response of the target. The profile of the EMI response may reveal characteristics about the target such as its dimensions, permeability and conductivity. Hence, EMI scattering simulations are valuable for predicting target responses and developing inversion processes.

For a time domain (TD) EMI response from a step function primary field, a small skin depth exists for very early time, corresponding to the high frequency response. Numerical methods generally have poor accuracy in early time because the skin depth can be extremely small and difficult to resolve. This work focuses on a numerical solution of the TD EMI response from axisymmetric targets for arbitrary skin depths. A boundary integral (BI) method is used for the exterior region, and two separate formulations are used for the interior region. When the skin depth can be resolved on a reasonable mesh, a standard finite element (FE) method is used to solve the interior diffusion equation for the magnetic vector potential, leading to an FE-BI formulation. When the skin depth is small, the divergence equation for the magnetic field is implemented in the interior. A new method is then developed in which the normal derivative of the magnetic field is calculated using a physics based thin skin depth approximation (TSA), so that no interior mesh is required. This is referred to as the TSA-BI method. The numerical method's accuracy is validated over the entire TD response with analytical solutions for canonical targets. Remarkably, the TSA-BI method is shown to be more accurate and faster than a standard FE-BI method in much of the TD. Using both methods, various typical target geometries can then be studied to identify important characteristics in the entire TD response. Furthermore, objects with simple material inhomogeneities (such as aluminum and steel parts) can be examined for any identifiable characteristics in the TD response.

Electromagnetic Models and Data Analysis for UXO Discrimination

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The Electromagnetic Induction (EMI) response from prolate spheroids and spheroidal shells under axial excitation in the asymptotic regime (large size parameter c) has been studied in the past. It is therefore known that previous solution became unstable for relatively small size parameters (around $|c|=30$).

In an effort to extend the range of validity of the full analytical solution of both the spheroid and the spheroidal shell to larger size parameters, asymptotic forms for the angular and radial spheroidal wave functions as well as the characteristic values of the spheroidal wave equation have been investigated for large c. For moderate size parameter (c>n+10), the angular prolate spheroidal wave functions, Smn, may be approximated by an expansion of alternately parabolic cylinder functions and associated Laguerre functions. Appropriate normalizations have been derived for all cases of m, n, and c. Using these expressions for Smn, together with approximation found in the literature for the radial function, the region of validity of the full analytic solution is extended far enough in c to overlap with the region of validity of the small penetration approximation (SPA). Thus a dependable, broadband solution is achieved. Using this broadband EMI solution inversion techniques for current frequency domain instruments are in development.

These results have been prepared for publication in a report entitled, "Asymptotic Expansions of the Prolate Spheroidal Wave Functions for Complex Size Parameter c" The principal conclusion of this publication is that no new asymptotic expansions are necessary in order to calculate the spheroidal wavefunctions when considering complex size parameter. Rather, combinations, governed by the m, n, and the ratio c_r/c_i govern which expansion type, prolate or oblate, is applicable. Previously discovered theory of prolate and oblate asymptotic expansions for the spheroidal wavefunctions may be applied after accounting for normalizations and ordering.

X-Band Radar Propagation over Mountainous Terrain

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MIT Lincoln Laboratory

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The goal of this work is to develop an accurate model to study the effects of terrain on the performance of ground based radar and communication systems. To account for all the surface scattering phenomena, the method of moments (MoM) formulation is used which leads to an exact solution of the electromagnetic problem. Furthermore, a layer is included on the terrain to incorporate the effects of a geophysical medium such as foliage, sea ice, or ocean foam. Effective permittivity representations for the geophysical medium are calculated using various homogenization techniques. In the past, modeling of the geophysical layer has often been neglected, and the terrain (or ocean) surface was simply treated as a perfect conductor or impedance surface. Due to the terrain size under study, the exact formulation requires a prohibitively large number of unknowns, so fast techniques must be implemented to solve the problem. In particular, we use the Forward-Backward Method as an iterative solution, combined with the Novel Spectral Acceleration Method. These fast techniques result in huge reductions of memory requirements and computational cost, although their efficiency decreases as the surface roughness increases. Both fast techniques are adapted for the layered media formulation. The tools developed in this work are general and can be applied to many problems such as radar cross section studies of ships on a rough ocean surface, or the prediction of propagation losses of microwave communication systems.

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