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 forest regions is studied. Specifically, we are interested in using polarimetric SAR data to determine the parameters of the forest such as the stem volume density and the average radius of the collection of trees. Our approach, similar to that used in the past, is to use an electromagnetic model of the forest to study the effect of various forest parameters on the backscattering coefficient. In addition, the polarization phase difference is used to determine the radius. While much work has been done for flat terrains, relatively little work has explored the effect of sloped terrains. Retrieval of forest parameters is a much more difficult problem in this case due to the lower power returns.

In the literature, forest regions are often modeled 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. Studies have shown that the primary contribution to the radar backscatter is due to the interaction of the ground with the trunk (and vice versa). To accurately and efficiently model the dihedral reflectors a double bounce model based on the scattering matrix formalism is used to include the contribution of the interaction between the ground surface and the tree trunk.

As a first step, a parametric study of the backscatter coefficient's dependency on the trunk radius, height, permittivity, and the forest's stem density was done using several Monte Carlo simulations, with realizations on the order of 200, where the position of the trunks was uniformly distributed over a fixed area. As expected, these simulations of the trunk layer indicate that the backscatter intensity is a smooth monotonically increasing function of stem volume. After calibration, such curves could be used for the retrieval of forest density from measurement data. Calibration consists of measuring the backscatter intensity of strong well-known scatterers such as corner reflectors and comparing the result to theoretical predictions.

To determine the radii of the tree trunks, the polarization phase difference between the HH and VV SAR components is used. This effect arises to the double bounce and has a strong dependency on the radius for electrically small trunks. Thus, it is easier to discriminate with a lower band SAR. It should also be noted that the phase difference has no dependency on the trunk height. To apply this method to a SAR image, a histogram of the phase difference for each pixel is formed. In a collection of trees with the same radius, the histogram will show a sharp peak at the one particular phase difference, which can be used to determine the radius of trees. However, in the case of a non-uniform forest, the statistics of the phase difference can be used to determine the statistics of the trunk radius for the region analyzed.

While the backscatter coefficient is one metric used in the retrieval of forest 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.

Multifunctional Wide-Band RF Systems

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Utilizing the surfaces of a moving vehicle, such as an airplane, smart skin antennas were originally designed to establish an advanced antenna system for communication and/or remote sensing. As a result, the smart skin antenna achieves many-fold increases in communication range, reduces the size and weight of the hardware and aerodynamic drag, and simplifies the maintenance of the electronics. Recently, interests have been focused on extending and improving the performance of the smart skin antenna. For instance, to use the same geometrical design to operate on several radio frequencies simultaneously or selectively, and to form scanning beams with low-level sidelobes. As a large bandwidth of the operation frequency is required, an ultra-wideband antenna element is needed. The UWB antennas have the properties of maintaining a good impedance matching and radiation pattern over a wide frequency range. In particular, the impedance matching is often required such that the return loss is less than 10 dB at the input port of the antenna.

Several kinds of antenna elements, including fractal antennas, bow-tie antennas, spiral antennas and log-periodic antennas, are investigated. The theoretical limit on the bandwidth of an electrically small antenna is used as a guideline for comparing the bandwidth performance against the normalized size of the antenna. The properties of ultra-wideband (UWB) performance, with a fractional bandwidth greater than 100% is attributed to the complementary and self-similar structure of the antenna elements.

For instance, to achieve an UWB response from an antenna element, frequency independence based on the principles of self-similarity and self-complementary can be used. Fractal, bow-tie, spiral and log-periodic can all reach bandwidths in excess of 1:4 provided that the electrical size is reasonably large. With the exception of the log-periodic antenna where the total array size is relatively large, fractal, bow-tie and spiral antennas have a characteristic length approximately equal to the wavelength of the central frequency. The different implementations of these antennas are compared by plotting the inverse of the bandwidth versus the normalized size of the antenna. They are found to follow a trend that is parallel to the inverse of the limiting half power bandwidth.

The Sierpinski Gasket monopole antenna achieves good bandwidth with tuning and stacking; however, recent implementations are not conformal in the sense that the antenna is perpendicular to the ground plane. Also, while non-fractal wideband antennas may utilize complementary structures to achieve continuous wideband impedance matching, the multiband behavior of the fractal antenna is very distinct and may offer a better return loss for each particular band. The use of transmission line models correctly explain the position of multiband through the adjustment of the attenuation parameters.

In general, a log-periodic antenna has a good polarization and bandwidth performance; however, it also has a large overall size that compromises its performance. The spiral antenna, despite the fact that it can only have circular polarization, is very compact and has been extensively studied. The advancement in tapering the current in the spiral arms by various means extends the bandwidth attainable by the spiral elements. Like the spiral antenna, the bow-tie antenna also has a compact size, a wide bandwidth, and a simple structure, but it produces linear polarization.

On the Electromagnetic Scattering by Left-Handed Media Spheres

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Left-handed media, so called due to the anti-parallel nature of the wave vector and the Poynting vector arising from simultaneous negative permittivity and permeability, were first given theoretical consideration by Veselago in 1968. A number of remarkable and potentially useful electromagnetic properties exist for left-handed media including backward waves, reverse Doppler shift, reverse Cerenkov radiation, near field focusing phenomena, and a negative index of refraction. Recently, a two dimensional meta-material consisting of split ring resonators printed on dielectric sheets was shown to exhibit left-handed media properties in the microwave regime (X-band). Motivated by this demonstration and in anticipation of possible applications of LHM, we have studied the properties of various electromagnetic scattering phenomena in left-handed media.

In this work, the electromagnetic properties of a sphere composed of a homogeneous and isotropic left-handed medium (LHM) are studied and compared to those of a right-handed medium (RHM) sphere. We begin by briefly reviewing the derivation of the Mie scattering coefficients based on the Debye potential formulation. Although these coefficients have been derived by many authors in various textbooks and papers, the details of the derivation are presented to illuminate one small subtlety in the case of a left-handed medium. In particular, in an LHM, there is an ambiguity in the choice of sign for the wavenumber, which if not properly accounted for, could lead to incorrect scattering results. However, as we will show, the fields are independent of the choice of sign since the complete solution contains both inward and outward traveling waves inside the sphere. Still, care must be taken in simplifying the Mie coefficients. As has been shown, certain simplifications of these coefficients, often presented in textbooks, implicitly assume a certain sign for the wavenumber of the LHM. Accordingly, care must be taken to choose the correct sign for this wavenumber when these references are used directly.

After deriving the Mie scattering coefficients, the scattering properties of the LHM sphere can be studied. As previously mentioned, a LHM exhibits a negative index of refraction, so that from a geometrical optics or ray-trace prospective we would expect field distribution near a RHM sphere to be very different from the distribution near a LHM sphere. As we have shown, based on the exact Mie solution, there exist different points of focusing for a LHM versus a RHM sphere. The LHM sphere bends the incoming wave inward due to the negative index of refraction to converge at a point inside the sphere. On the other hand, a wave impinging upon a RHM sphere will tend to form a focusing point in forward scattering region.

For a more quantitative comparison, the near-field patterns for a LHM sphere and a RHM sphere are compared and found to be quite distinct, especially in the forward scattering region. In contrast, the far-field patterns are found to be similar in the forward scattering region. The extinction and absorption efficiencies are also calculated. For spheres in the resonant regime (roughly one wavelength in radius), the behavior of a RHM sphere is quite different from the behavior of a LHM sphere, however for larger radii, both the extinction and absorption efficiencies of a RHM sphere and a LHM sphere approach the same optical limit.

The Electromagnetic Fields of an Elementary Source Located Below a Layer of Left-Handed Medium

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Left-handed media, so called due to the anti-parallel nature of the wave vector and the Poynting vector arising from simultaneous negative permittivity and permeability, were first given theoretical consideration by Veselago in 1968. In this work, the electromagnetic fields of an elementary source located below a slab of negative medium are calculated using a layered media approach. We consider the case of a line source or equivalently an infinite linear electric antenna, noting that the case of a dipole antenna can be treated in an analogous manner.

For this study, we locate the source below a slab of finite thickness composed of homogenous isotropic left-handed media. The general solution is found by expanding the cylindrical wave source into a set of plane waves, both propagating and evanescent, with unknown amplitudes. Enforcing the continuity of the tangential electric and magnetic fields, allows for the determination of these unknown amplitudes so that the fields in each of the three regions can be expressed in terms of infinite integrals over the tangential frequency spatial components. As discussed in other works, there is some ambiguity in the choice of sign for the perpendicular frequency spatial component for the negative media region, however, since both the upward and downward waves solutions are included, is can be shown that the resulting integral expressions are independent of this sign choice.

As an example, the integral expressions for the fields arising under the conditions necessary for producing a perfect image, as introduced by Pendry, are studied. Under these conditions, based on a simple ray-tracing argument, we would expect to find one image of the source formed inside the slab and another image of the source in the transmitted region. For this case, we find that the integral expressions can be evaluated exactly for part of the slab and part of the transmitted region, in terms of cylindrical wave functions, which in accordance with the ray-trace argument originate from the image points. However, we find that the integral expressions diverge exponentially in the other regions leaving the fields in these regions undefined. Yet, based on the argument that the fields are physical quantities and hence analytic, it is possible to analytically extend the previous cylindrical wave functions into the regions where the integral expressions are not well defined. 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, there is a question of whether it is a unique and hence a physical solution since the medium under study in this case is lossless.

To explore the uniqueness of the above solution, losses are introduced into the slab. In this case, it can be shown that the integral expressions will always converge and represent a unique physical solution. The results of various cases with loss illustrate an interesting behavior, similar to the source-sink-source solution, including that of the net power flow in the direction of the reflected field, which is unexpected in cases where the reflection coefficient from one region to the next is very small. However, it is not clear in the limit of vanishing loss, that the field distribution will approach that of the source-sink-source configuration.

SAR Interferometry Preprocessing

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Phase unwrapping in interferometric synthetic aperture radar (InSAR) system has inherent noise from the decorrelation of the constituent images. The noise level can be so high that renders part of the interferogram useless in obtaining a digital elevation map (DEM). In order to increase the usability of the interferogram, different preprocessing techniques are used in a modular fashion to generate an accurate terrain map.

The first preprocessing technique deals with the orbit instability and hence the incoherent baseline over a finite portion of the orbit. Ground Control Points (GCPs) are used in the non-linear optimization of baseline and baseline orientation angle retrieval and a preliminary inversion of baseline based on simulated interferogram reveals the correlation between baseline uncertainly and inverted height error.

On the development of unwrapping algorithms, regular least square method fails to take into account that the rewrapped image of the unwrapped phase differs from the original interferogram, and can be improved by using that difference in the iteration. A preliminary study shows that the convergence rate improves with the new method. Convergence is reached for a preset residue level of 10-3 in 17 iterations instead of 28 iterations. By taking into account the difference between the rewrapped image of the unwrapped phase differences and the original interferogram, the solution yields a higher digital elevation map (DEM) which compensates for the underestimation of the least square method.

To alleviate the existence of local inconsistencies of the data, referred to as residues, which slows down the convergence of typical unwrapping algorithms and introduces inaccuracies into the height inversion, the computationally efficient Donoho wavelet denoising technique is applied. With the complex interferogram as input, by preserving the lines of phase discontinuity, the rewrapped image demonstrates a significantly better quality. We evaluate the height retrieval accuracies of this algorithm using simulated X-band InSAR system as well as real SAR data (Mt. Fuji) from JERS-1.

For a simulated Gaussian mountain, the improvement of the unwrapping accuracies is very distinct, from 3% to 1% rms error. The height inversion of the simulated SAR interferogram based on the Grayling data shows that, with preprocessing, the height inversion is less susceptible to noise corruption. For the Mt. Fuji data, assumption of the system parameters have been made and the error figure on the 512 by 512 interferogram is 118 m of rms height (standard deviation). More accurate system data is needed to aid the inversion for further comparison of different unwrapping schemes used in combination with the preprocessing technique.

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.

Electromagnetic Models and Data Analysis for UXO Discrimination

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Cold Regions Research and Engineering Laboratory

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The Electromagnetic Induction (EMI) response from prolate spheroidal shells under axial excitation has been studied. For a conducting and permeable spheroidal shell the EMI response has been calculated exactly assuming the background medium (both outside and inside the shell) is nonmagnetic and only weakly conducting. This response is important for broadband (0 ~200 KHz) EMI detection and discrimination devices targeted primarily at Unexploded Ordinance (UXO). The prolate spheroidal shell is a canonical shape and was chosen due to its flexibility in describing spherical and needle-like shells. When extended to the oblate case, these models will include disks as well.

Inside the shell, the magnetic field must be expanded in spheroidal wave functions, while outside, the magneto-quasistatic (MQS) magnetic fields are described by Associated Legendre and sinusoidal functions. These spheroidal wave functions have been studied and Fortran codes which compute the spheroidal wave functions of the first and second kinds have been developed. These codes have been tested and compare favorably to all known sources.

The Sparse Matrix/Canonical Grid (SMCG) method is extended to 3-D random media scattering applications by finding the scattering properties of a random medium containing randomly positioned and oriented discrete dielectric spheroids contained in a cubic test volume. The SMCG method reduces the complexity for each matrix-vector multiply an iterative solver normally requires ($O(N^2)$) to $O(N \log N)$. Interactions are decomposed into “strong” and “weak” interactions by defining a neighborhood distance, r_d (specified in terms of gridpoints). Strong interaction terms are calculated directly with no approximation requiring $O(N)$ complexity for each iteration. Weak interaction terms are approximated by a multivariate Taylor series expansion around the nearest gridpoint to gridpoint distance for any given pair of particles. The multilevel block Toeplitz (MBT) structure inherant in weak interaction matrices allows a 1-D FFT of complexity O(N log N) to replace the dense matrix-vector multiply in the iterative solver. Greater accuracy may be achieved by increasing r_d, a higher order expansion, and/or a finer grid at the cost of more interaction terms, more FFTs, and/or longer FFTs respectively. Results indicate the SMCG method achieves a substantial reduction in complexity compared to the standard full method.

X-Band Radar Propagation over Mountainous Terrain

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The goal of this work is to develop accurate models to study the effects of terrain on the performance of ground based radar and communication systems. The types of terrain in these problems are extremely large, both in distance (typically 25 km) and height variation (up to 500 m), although we limit the scale of the local roughness to no less than a few wavelengths. Usually, a terrain profile is defined by large, flat patches that can be many hundreds of wavelengths long, and the entire geometry must take into account the spherical earth. To fully account for all surface scattering phenomena, we use an integral equation formulation which leads to an exact solution of the electromagnetic problem. Due to this terrain size, this exact formulation requires a prohibitively large number of unknowns, so we incorporate fast techniques to make the problem tractable. In particular, we use the Forward-Backward Method as an iterative solution, accelerated by a variant of the Fast Far-Field Algorithm as well as an FFT matrix-vector multiply for the self terms. These fast techniques result in huge reductions of memory requirements and computational cost, although their efficiency decreases as the surface roughness increases. The resulting algorithm that is a combination of these techniques is an approximation, and we verify the accuracy through comparison with the basic Forward-Backward Method.

Furthermore, we include a layer of random medium on the terrain to incorporate the effects of foliage (although it could be a different geophysical medium, such as snow or ocean foam). The random medium is created using Strong Fluctuation Theory to model the discrete scatterers (such as leaves in foliage), obtaining values for the effective permittivity. 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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