ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

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Research on SAR Simulation Model

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In this work, we develop an image processing scheme to generate synthetic aperture radar (SAR) images from a rough surface terrain, which is specified by a digital elevation map (DEM), with large dihedral reflectors (e.g. tree trunks). Important in the analysis of such SAR systems is a knowledge of the electromagnetic characteristics of the target being studied. In order to determine the electromagnetic characteristics of the region being analyzed, the rough surface and dihedral reflectors are modeled as a collection of triangular facets. The backscattering response is then obtained using the Physical Optics (PO) method. A closed form solution to the PO integral for flat polygonal plates is used to quickly calculate the response from each facet. Although the PO method is based on high-frequency approximations, it is found, based on comparisons with exact MoM results, to be a valid approach for relatively smooth surfaces where the correlation length is greater than a few wavelengths. To accurately 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 rough surface and the dihedral reflector.

The SAR image is then obtained by using a matched-filter approach which incorporates both range and cross-range focusing. In comparison with frequency-domain, or Doppler based algorithms, the matched filter approach allows for simple and accurate SAR signal processing of band-limited signals. The matched filter approach works by correlating the received signal with a reference signal, which is defined to be the response from a point scatterer at a given position along the ground. Regions of high correlation correspond to the locations of the scatterers with strong backscattering responses. This correlation process can be performed in either the time or spectral domains, the two approaches are equivalent. In this work, the spectral domain representation is used since the scattering coefficients are calculated as a function of frequency.

The model for the received signal that the SAR receives is determined by convolving the scattering response with the incident pulse shape, which is assumed to be a band-limited chirp signal multiplied by a Gaussian footprint function. Previous work included the development of an efficient SAR image simulation scheme for non-dispersive scatterers, which allowed the correlation integral to expressed in a closed form solution yielding a highly efficient algorithm. However, in this work we allow for the presence of dispersive scatterers while maintaining computational efficiency. This is accomplished by evaluating the range focusing aspect of the matched filter correlation integral using a linear interpolation scheme in which the fast varying part of the received signal is accounted for analytically. This in turn allows the cross-range focusing sum to be computed analytically in closed form. The resulting efficient algorithm allows for the modeling of large terrains. Several test cases have been modeled such as rough surfaces with tree structures, and flat surfaces with building and ditch structures.

Wideband Antenna Element

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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.

Smart skin antennas were originally designed by utilizing the surfaces of a moving vehicle, such as an airplane, 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.

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.

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. 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.

Evaluation of SAR Interferometry using Wavelet Denoising

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Obtaining a digital elevation model (DEM) with the help of synthetic aperture radar (SAR) interferometry requires 2-D phase unwrapping known to be sensitive to noise. In particular, the existence of local inconsistencies of the data, referred to as residues, slows down the convergence of typical unwrapping algorithms and introduces inaccuracies into the height inversion. To reduce the effect of noise, some sort of preprocessing of the interferogram is desired. This suggests applying the computationally efficient Donoho wavelet denoising technique, with the complex interferogram as input, that preserves the lines of phase discontinuity (fringes) yielding filtered images of good visual quality. We evaluate the height retrieval accuracies of this algorithm using simulated SAR data, and 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.

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 DEM which compensates for the underestimation of the least square method.

Polarimetric Passive Remote Sensing

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Recently there has been significant interest in using polarimetric passive remote sensing measurements from wind-roughened ocean surfaces to deduce wind vector information. However, the presence of foam on the ocean surface complicates such analyses. Even though only a small portion of the sea surface is covered with foam, the foam has a very high emissivity compared with open sea surface and must be accounted for correctly.

We model the foam as a layer of densely packed air bubbles. Each bubble is taken to be spherical with a thin outer layer of sea water. Because the bubbles are packed closely together, coherent multiple scattering effects must be properly included. Thus we use the theory of quasi-crystalline approximation (QCA) to compute the collective scattering response from the foam particles. The QCA allows us to incorporate the correlation property of the particle positions and its effects on multiple scattering. In contrast to the traditional dense medium approach which assumes small particles, we formulate QCA using the T-matrix coefficients that are applicable to particles of general sizes. The extinction coefficient and scattering phase matrix obtained using QCA are then used as inputs to the dense medium radiative transfer (DMRT) equation. The polarimetric brightness temperatures from a foam-covered ocean surface are obtained by solving the DMRT equation with appropriate boundary conditions. Our model provides a rigorous basis to relate bubble characteristics to foam emission that is applicable for any bubble size and concentration.

Computational Method in Multiple Scattering by Spheroidal Scatterers

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The Sparse Matrix/Canonical Grid (SMCG) method is applied to 3-D random media scattering simulations. The random medium consists of 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 from $O(N^2)$ to $O(N \log N)$. Interactions are decomposed into “strong” and “weak” interactions by defining a neighborhood distance (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 inherent 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 the neighborhood distance, 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 that the SMCG method achieves a substantial reduction in computational complexity compared to the standard full method.

A new method to realize matrix-vector multiplies involving Multilevel Block Toeplitz (MBT) matrices occurring in 3-D electromagnetic scattering was developed. This method extracts only the unique terms from the MBT matrix into an auxiliary vector, thus reducing computer memory requirements. The matrix-vector multiply is then realized as a convolution, or equivalently as an outer product in the Fourier domain, requiring only O(N log N) complexity. Implementation into the SMCG method showed a substantial speedup when compared to the full dense method.

Electromagnetic Models and Data Analysis for UXO Discrimination

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Broadband electromagnetic induction (EMI) sensors are promising in the detection and discrimination of subsurface unexploded ordnance (UXO). However, theoretical modeling of EMI responses from nonspherical objects has been lacking. In this work, we obtain the quasi-magnetostatic solutions for conducting and permeable spheroids under arbitrary primary field excitation. The problem is solved analytically using the separation of variables method in spheroidal coordinates. In this method, the interior magnetic field is expanded in terms of vector spheroidal wavefunctions. On the other hand, because the medium surrounding the spheroid is poorly conducting, we can expand the exterior magnetic field simply in terms of the magnetostatic (Laplace) solutions. The unknown expansion coefficients are solved by imposing the appropriate boundary conditions at the surface of the spheroid. This formulation is exact; however, the solutions break down at high frequencies due to numerical problems in the computation of the spheroidal wavefunctions. Since a broadband response is desired, we also develop an approximate theory known as the small penetration-depth approximation (SPA). The SPA is based on the observation that at high frequencies, the primary field decays rapidly as it penetrates the spheroid. This allows us to reformulate the system equations in terms of the exterior fields only and circumvents the numerical difficulty associated with the spheroidal wavefunctions.

Even though the SPA is motivated by the high frequency behavior of the interior magnetic field, we find that the method is in fact capable of yielding accurate results over all frequencies for highly permeable spheroids. This case is of practical significance because many UXO have high permeability material components (e.g., steel). For such objects, SPA gives us a computationally efficient method for calculating their broadband EMI responses, without any limitation in terms of frequency and aspect ratio. The corresponding numerical code is therefore ideally suited as forward model in a systematic inversion for some of the parameters of a given configuration. Even though our investigations focus on spheroids only, it should be noted that prolate and oblate spheroids provide a very general and versatile model for nonspherical geometry that ranges from long needle to sphere to flat disc.

Since multiple UXO as well as substantial amount of debris are likely to be located in the same area, we also calculate the broadband EMI response from multiple objects. Preliminary study shows that mutual interactions are generally negligible. We investigate the effects of orientation averaging as well as multiple sizes on the broadband EMI response. It is found that responses from individual objects could overlap and make target discrimination more difficult.

Finite Difference Techniques for Body of Revolution Radar Cross Section

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A number of radar cross section prediction techniques have been developed which exploit body of revolution (BOR) symmetry, reducing computational requirements and enabling calculations for electrically larger objects. These approaches include both frequency domain Method of Moments (MoM) BOR algorithms, and more recently, Finite-Difference Time-Domain (FDTD) BOR implementations. In cases where the signature is desired over an extended bandwidth, FDTD BOR techniques have the advantage of calculating the entire frequency extent simultaneously. However, the FDTD simulation still must be repeated for each incident angle of interest, and as the target size becomes large, and wideband signatures become necessary at many incident directions, additional reductions in computation are desirable. The purpose of this work is to examine three finite-difference approaches to determine their accuracy and potential for further relaxing computational requirements for particular body of revolution geometries.

The first approach reduces the overall computational burden by lowering the number of angles at which calculations must be performed. A single FDTD BOR simulation is used to calculate the monostatic signature for one incident angle, as well as bistatic signatures for adjacent observation directions. The bistatic equivalence theorem is then used to approximate monostatic signatures for other angles near the incident direction of the actual FDTD BOR simulation. In contrast, the second approach reduces computational requirements for BOR objects of large electrical radius, using a hybrid FDTD and Geometrical Optics formulation. Individual scattering centers such as surface gaps, protrusions, or slope discontinuities are identified, and integral expressions derived for the scattering of each. These expressions are evaluated by the method of stationary phase, in which the contribution is assumed to arise from a stationary phase point in the plane of incidence. A two-dimensional scattering problem is created by a local tangent plane approximation through the stationary phase point, and this is solved via a two-dimensional FDTD approach. Finally, the third approach reduces computer memory requirements by simplifying the finite difference equations used in the solution. Explicit phase dependence is introduced for propagation of the incident wave over the BOR object, producing a parabolic wave equation (PWE). As with the BOR FDTD approach, symmetry is exploited to decouple the three-dimensional PWE problem into a sequence of two-dimensional problems, which are solved by an efficient marching in space approach. For each of these results are compared with standard FDTD and MoM BOR approaches, high frequency physical theory of diffraction approximations, and measurements or Analytical results where available. From these comparisons, the accuracy and computational requirement tradeoffs possible with this collection of finite-difference signature tools are determined.

Inverse Scattering Models for Recognition of Targets in Random Media

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A Three-dimensional FDTD simulation is used to compute the scattered field of an object in or beneath a random medium. The FDTD computational domain contains three layers: free-space, and two layers of random media that may also contain an object. The random media can be used to describe many types of physical media, such as snow, soil, or vegetation. Here we use them to model soil, with ground penetrating radar applications in mind. The soil is modeled as a random permittivity that fluctuates from cell to cell, described by a correlation function that is Gaussian in the horizontal direction and exponential in the vertical direction. Parameters such as the mean and variance of the soil permittivity are determined by experimental data. Both the homogeneous and the random layers are lossy, so a modified PML with stretched coordinates is used to terminate the computational domain. The simulation assumes a TE or TM plane wave incidence, and uses a total scattered field formulation for stratified media. The near to far field transformation is performed by enclosing both the object and random media in a Huygens' surface, and integrating the equivalent frequency domain electric and magnetic currents with the layered Green's function. The targets modeled are metal and dielectric cylinders, created with a conformal mapping technique. Our interest lies in cases where the scattered fields of the target are much smaller than the clutter of the random medium. Monte-Carlo analysis is performed using an ensemble of random media whose parameters appropriately model various soil types. Each realization of the random medium is generated in the spectral domain by filtering random numbers (with zero mean and normalized variance) with the Fourier transform of the correlation function. A three dimensional Fast Fourier Transform is then used to generate the spatial fluctuation, which is mapped into the FDTD computational domain. The statistical properties of the scattered field are studied using the numerical simulation technique described above. In addition to Monte-Carlo analysis, frequency averaged radar cross section and the Angular Correlation Function are applied to determine their effectiveness in detecting the object.

X-Band Radar Propagation over Mountainous Terrain

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Christopher Moss

In this project, we are concerned with accurately modeling the effects of terrain on the performance of X-band ground based radar. The type of terrain in question is extremely large, both in distance (typically 50 km) and height variation (up to 500 m), although we limit the scale of the local roughness to no less than a few wavelengths. 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, the exact formulation requires a prohibitively large number of unknowns, so we incorporate a Fast Multipole Method to make the problem tractable. We also use basis functions that are optimal for given surface profiles, such as wavelets for areas with local roughness and Natural Basis set for smoother portions of the terrain. These fast techniques result in huge reductions of memory requirements and computational cost, although their efficiency decreases as the surface roughness increases. Furthermore, we include a layer of random medium on the terrain to incorporate the effects of foliage (although it could be another geophysical medium, such as snow). The random medium is created using Strong Fluctuation Theory to model the discrete scatterers (leaves) in the foliage, obtaining values for the mean (effective) and variance of the permittivity. Ultimately we will add a target to the simulation, placed up to 50 km from the source, to study the complete radar system performance for given terrain profiles.

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