ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

Academic and Research Staff
Professor Jin Au Kong, Dr. Tomasz M. Grzegorczyk, Dr. Bae-Ian Wu, Dr. Robert T. Shin, Dr. Y. Eric Yang

Visiting Scientists and Research Affiliates
Dr. Arthur K. Jordan, U.S. Navy, Naval Research Laboratory, Washington, DC.
Dr. Kevin O'Neill, U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
Dr. Michael Tsuk, Digital Equipment Corporation, Tewksbury, Massachusetts.
Dr. Akira Itoh, Tokyo National University of Science and Technology, Tokyo, Japan.
Dr. Yih-Min Chen, Yuan-Tze University, Chung-Li, Taiwan.
Dr. Chien-Chin Chiu, Tam-Kang University, Tam-Shui, Taiwan.
Dr. Leung Tsang, University of Washington, Seattle, Washington.
Dr. Tarek M. Habashy, Schlumberger-Doll Research, Ridgefield, Connecticut.
Dr. L.W. Li, Singapore National University, Singapore.

Graduate Students
Benjamin E. Barrowes, James Chen, Xudong Chen, Brandon Kemp, Jie Lu, Christopher Moss, Madhusudhan Nikku, Joe Pacheco, Zachary Thomas, Weijen Wang.

Technical and Support Staff
Zhen Wu, Bin Hu, Xiaozhi Shen, and Qing Wan

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Sponsor
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Project Staff
Professor Jin Au Kong, Dr. Tomasz Grzegorczyk, Dr. Bae-Ian Wu
Xudong Chen, Chrisopher D. Moss, Joe Pacheco, Madhusudhan Nikku

Study and characterization of left-handed metamaterials

Many of the basic properties of left-handed (LH) media are in constrast to those typically encountered in right-handed media. For example, using a rigourous plane wave analysis of propagation and transmission into a dispersive LH medium from a RH medium, we show that power refracts at a negative angle, without violating causality. Second, the perfect lens concept is studied through a Green's function analysis. It is shown that under the perfect lens requirement, that a single source outside a LH media slab will generate two perfect images. Interestingly though, the time-averaged power flow inside the slab forms a sink. However, it is shown that while the introduction of loss eliminates this behavior, the lens becomes imperfect. It is seen that even a small amount of loss can destroy the imaging properties of the LH media lens. In terms of scattering, the Mie solution for plane wave scattering by a LH medium sphere is examined. It is shown that where applicable, care must be taken in choosing the appropriate algebraic signs of the wavenumbers in the evaluation of the Mie coefficients. In addition, it is then shown that a sphere composed of a LH medium will focus incoming energy into a spot inside the sphere. Finally, the effects of aniostropy on reflection and transmission are examined.

Various tools for understanding and characterizing left-handed metamaterials are presented. First, the accuracy of approximate analytic models of the rods and split-rings is investigated by using two-dimensional FD-TD simulations to compare transmission characteristics. It is shown that the rods tend to agree more favorably with their analytic model than the split-rings do. Next, in order to better understand the behavior of the rods and rings separately, numerical simulations of rods (or rings) embedded in homogeneous magnetic (or electric) plasma media were performed. Using the transmission characteristics, it is shown that in order to obtained left-handed features, the plasma in the immediate vicinity of the rods or rings needed to be removed, which shows that the electromagnetic fields surrounding the metamaterial are not homogeneous. To further verify left-handed features, a phase-tracking method is used to retrieve the bulk index of refraction. In addition to the phase-tracking retrieval method, a more precise retrieval method that utilizes the complex S-parameter results is also investigated. Using this method, and S-parameters results from three-dimensional FD-TD and MoM simluations, it is shown that metamaterials composed of rods and split-rings can be characterized by a negative permittivity and negative permeability.

Two potential applications of LH media are explored. The first application is to use left-handed media as a radar absorber. These absorbers are designed by using a genetic algorithm, which determines a set of material parameters and layer thicknesses that minimizes the reflected power over a given frequency bandwidth or angular swath. In the design process, the frequency dispersive bulk media Drude and Lorentz models were used to model the ring and rod metamaterials. It is shown that LH media can be used to reduce the backscatter RCS, although its applicability is somewhat limited. The second application explored is that of using metamaterials in the design of a light-weight directive antenna substrate. By Snell's law, if a source is embedded in a substrate that has a small index of refraction compared to air, its source rays will be transmitted near the normal of the substrate. Since left-handed metamaterials are frequency dispersive, there exists a frequency where its index of refraction is zero. Unaltered, the metamaterial will have a narrowband of operation where it is highly directive. In order to design a wideband directive antenna, the plasma and resonant frequencies of the metamaterials are adjusted to achieve minimum beamwidth. Additionally, it is found that certain anisotropic metamaterials, which in practice are simpler to build, will actually perform better in terms of beamwidth than their isotropic counterparts. In conjunction, the perfomance tradeoffs between beamwidth, gain, and substrate thickness are dicussed.

Retrieving the constitutive effective parameters of metamaterials

We propose an improved method to retrieve the effective parameters (index of refraction, impedance, permittivity, and permeability) of metamaterials from transmission and reflection data. The estimation of effective parameters is not a trivial problem, which leads sometimes to rather controversial results. We propose a robust method to solve this problem. The successful retrieval results for various metamaterial structures show the effectiveness of the method. The main conclusions are as follows:

The first boundary and the thickness of the effective media can be determined by matching impedance through all sample frequencies for different lengths of slabs in the propagation direction. For symmetric 1D metamaterials, we have drawn the empirical conclusion that the first boundary coincides with the first boundary of the unit cell facing the incident wave, and the thickness of the effective medium is approximately equal to the number of unit cells multiplied by the length of a unit cell. For 2D and asymmetric 1D metamaterials, the effective boundaries have to be determined by optimization.

The requirement $Real\{z\} \geq 0$ cannot be used directly for practical retrievals when $Real\{z\}$ is close to zero because the numerical or measurement errors may flip the sign of $Real\{z\}$, making the result unreliable. In this case, we have to determine the sign of z by the value of its corresponding refractive index n so that $Imag\{n\} \geq 0$.

There is a resonance band characterized by the fact that the requirement $Imag\{\varepsilon\} \geq 0$ and $Imag\{\mu\} \geq 0$ cannot be satisfied at those frequencies. On each side of the resonance, the branch of $Real\{n\}$ can be obtained by a Taylor expansion approach considering the fact that the refractive index n is a continuous function of frequency. Since the refractive index n at the initial frequency determines the values of $Real\{n\}$ at the subsequent frequencies, we determine the branch of the real part of n at the initial frequency by requiring that $Imag\{\varepsilon\}$ and $Imag\{\mu\}$ are non-negative across all the frequency band.

Due to the noise contained in the S parameters, the retrieved n and z at some specific frequencies are not reliable, especially for thicker metamaterials at lower frequencies. In spite of this, the fact that S_{11} and S_{21} for multiple cells of metamaterial calculated from the retrieved ε and μ for a unit cell metamaterial match the S_{11} and S_{21} computed directly from numerical simulation confirms that the metamaterials can be treated as effective homogeneous materials.

Refraction at a boundary between half-spaces and slabs of metamaterial

We show that anisotropic metamaterials in which some components of the permittivity and permeability tensors can have negative real values (thus associated with left-handed metamaterials) call for a reconsideration of the common concepts of critical angle and Brewster angle. By studying the reflection coefficient for isotropic and biaxial half-spaces and slabs, we show that a metamaterial for which the Brewster angle appears beyond the critical angle is realizable. In addition, we also show that the Goos-Hanchen shift induced by left-handed isotropic slabs is not necessarily negative but could be positive when the second interface of the slab supports a surface plasmon. Finally, upon studying a bianisotropic metamaterial, we show that propagation at a negative angle can occur, although it would not if only the permittivity and permeability tensors were considered. All the results have been obtained using a generalization of a known eigenvalue method to general bianisotropic media.

Antenna Design Using Left-Handed metamaterials

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Project Staff
Professor Jin Au Kong, Dr. Tomasz Grzegorczyk, Dr. Bae-Ian Wu
Joe Pacheco, Weijen Wang

Left-handed (LH) metamaterials are typically realized artificially as composite structures that are composed of periodic metallic patterns printed on dielectric substrates. These materials affect the macroscopic properties of the bulk composite medium and exhibit a negative effective permittivity or permeability for a certain frequency range only. Using a commercially available software (CST Microwave Studio), simulations are done on the radiation of a monopole antenna embedded in metamaterial substrates.

Metamaterials under consideration are composed of a periodic collection of rods, of rings, and of both rods and rings. The metamaterial is the starting point of the analysis and is usually composed of periodic structures of metal and dielectric for the microwave region. We can build the structure and do experiments to see what its performance is for antenna substrate, or we can do numerical simulations or we can do theoretical studies assuming the substrate is homogeneous. Experiment is the most expensive and time consuming, so we use numerical simulation and theoretical studies first to design a metamaterial structure good for antenna substrate, then use experiments to verify our prediction. Since simulating the real size structure requires a lot of memory and takes a long time, we will put a slice of metamaterial in a parallel plate waveguide to approximate the radiation effect. We can also simulate the metamaterial in a waveguide and extract the S-parameters to find the effective μ and ε for all frequencies. With the effective permittivity and permeability, we can calculate the corresponding S-parameters and compare with the ones we obtained from simulation. Furthermore, we can use analytic formula to obtain farfield results with μ and ε. This theoretical farfield results is faster to acquire than the ones from simulating in a parallel plate waveguide. Therefore, for optimizing, we will use theoretical method to find the optimized structure first, then simulate it in the parallel plate, and lastly, fabricate and test it. Far field radiation data are collected and examined between substrates with different type of ground planes. The metamaterial is shown to improve the directivity, power, and bandwidth.

Study and applications using metamaterials with left-handed properties

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Project Staff
Professor Jin Au Kong, Dr. Tomasz Grzegorczyk, Dr. Bae-Ian Wu
James Chen, Jie Lu, Chrisopher D. Moss, Madhusudhan Nikku, Joe Pacheco

Radiation pattern due to composites of S-shaped metallic structures

Conventional Left-handed materials have been fabricated using a composite of metallic rings and rods. The rings, commonly known Split Ring Resonators (SRR) lead to a resonant effective permeability (μ). And, the rods, which are thin metallic wires, lead to a plasma type effective permittivity (ε). In the overlapping frequency band, where ε and μ are both negative, a negative refractive index is observed leading to the well-known Left-Handed (LH) behavior of the composite material. It was recently demonstrated that S-shaped metallic structures (S-rings) exhibit LH characteristics equivalent to an SRR-rod combination. And, negative refraction in a prism made of such structures was experimentally verified, in the frequency band roughly between 15GHz-20GHz, depending on the physical dimensions of the setup.

In the present research, the radiation characteristics of composites of such S-shaped structures are studied in detail. Numerical simulations using the High Frequency Structure Simulator (HFSS) numerical package and Method of Moments (MoM), lead to an understanding of the currents induced on a single element due to a plane wave excitation. The incident plane wave was a TEM mode at 17GHz, with the Electric Field vector in the plane of the ring and the magnetic field vector perpendicular to the plane of the ring. The current density observed along a single ring is expressed as a periodic function of a parametric variable denoting position along the S-ring. The constants of this function are determined from the physical dimensions of the ring. The current density thus obtained is used to determine the vector current moment due to the ring. The far field radiation due to the ring is then determined using this vector current moment. The radiation pattern to a single S-ring is found to be symmetric in nature and resembles a radiation pattern due to a combination of dipoles stacked along the segments of the S-ring.

In order to determine the far field radiation due to a composite made up of S-rings, the array factor specific to the composite structure is determined first. This array factor coupled with the radiation pattern due to a single ring gives the pattern due to the composite. A prism of S-rings with a prism angle of 26.6^{o} is used in the present study, with 10 elements on the longer side and 5 elements on the shorter side. It is observed that the characteristic negative refraction of the composite is observed considering the edge elements of the prism, and use a negative progressive phase shift. On the other hand considering all the prism elements leads to substantial diminution of the distinct lobes and a radiation pattern concentrated parallel to the incidence direction is observed, showing no LH behavior whatsoever.

Study of loss mechanism in left-handed metamaterials

An important loss mechanism when realizing left-handed metamaterials based on a succession of split-rings is the coupling between the scattered field and higher order waveguide or Bloch modes which may be cutoff. In addition to standard dielectric and metallic losses, these coupling losses can also be very large and should therefore be minimized, which can be accomplished by optimizing the geometry of the split-rings.
In this work, we propose a metamaterial in which the ring has been adapted from infrared applications and we show by a succession of arguments that the metamaterial thus realized not only exhibits left-handed properties but also very low losses into higher waveguide or periodic modes. The arguments are based on transmission measurements, phase tracking inside the metamaterial, as well as a numerical prism experiment. Results are obtained using both a two-dimensional periodic Method of Moments and a three-dimensional Finite-Difference Time-Domain technique.

Lateral Goos-Hanchen (GH) shift with Left-handed material (LHM) slab

It has been known that LH slabs exhibit either a negative lateral GH shift when the slab is sandwiched by the same right-handed material (RHM) on both sides, or a positive shift when the slab is matched with a right-handed material. In this study, we found that with a LHM slab, the lateral GH shift can change from a positive to a negative shift even at different incident angles, with the slab configuration unmodified. This is a property that can not be observed with a RHM slab. The analytical conditions for different GH lateral shift, therefore, have been derived for both LHM and RHM slab for all possible cases. The potential of using this unique property from LHM slab for waveguide applications are also investigated.

Sub-wavelength imaging

The poles of the electric field inside a slab having a negative permittivity and a negative permeability are analyzed. The analytical solution shows that there is a pole on the integral path which moves toward infinity along the imaginary k_z axis as the permittivity and permeability both approach the real value of -1. The resolution ability of the slab is shown to be determined by this pole, and the left-handed material slab behaves like a special parallel plate dielectric waveguide which can guide the evanescent waves. Therefore the guided component can propagate through the slab without loss of amplitude. A quantum explanation is also given to show the limitation of the resolution ability of the slab, and the predictions are shown to be consistent with numerical results.

Multifunctional Wide-Band RF Systems

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Project Staff
Professor Jin Au Kong, Dr. Tomasz Grzegorczyk, Dr. Bae-Ian Wu
Madhusudhan Nikku, Joe Pacheco

Polarizing Capabilities of Uniaxial Metamaterials

Polarizers are one of the most widely used components in optical applications. Traditional polarizers are sheet polarizers, which are essentially membranes of submicroscopic dichroic crystals. A dichroic crystal is a uniaxially anisotropic molecular assembly. An unpolarized wave entering such a medium is split up into linearly polarized ordinary and extraordinary waves. Correspondingly, two types of polarizers are possible, *O*-type and *E*-type. *O*-type Polarizers transmit the ordinary wave, whereas *E*-type polarizers transmit the extraordinary wave. Conventional sheet polarizers are *O*-type polarizers. A typical *O*-type polarizer has a complex permittivity along the optic axis with a large imaginary part. This leads to an attenuating extraordinary wave, while the ordinary wave is transmitted. Recently, *E*-type polarizers have also come into existence. These polarizers transmit the extraordinary waves while attenuating the ordinary waves. *E*-type polarizers that are in use today have been found to be better than *O*-type polarizers.

This present work studies the performance characteristics of a metamaterial polarizer vis-a-vis those of existing *O*-type and *E*-type polarizers. The proposed metamaterial polarizer has a uniaxial permittivity tensor with a negative permittivity along the optic axis and a positive isotropic permeability. The characteristics used as a basis for comparison are: 1. Leakage of light (transmittance) through a pair of crossed-polarizers, and 2. Fresnel coefficients of a single polarizer. The expressions for the transmittance and the Fresnel coefficients were obtained analytically using the kDB method. A novel procedure to determine the angles of transmission of the ordinary and extraordinary waves through a uniaxial slab is developed, along with the procedures for validation. The procedure allows convenient analysis of wave propagation through a uniaxial slab, at any incidence. The viability of enhancing the performance of polarizers by using metamaterial media is investigated. The performance of such a polarizer is compared to that of typical *O*-type and *E*-type polarizers.

The configurations of the permittivity and permeability tensors of such a uniaxial medium, with negative permittivity along the optic axis, are studied along with the limits of the ordinary and extraordinary refractive indices. With the recent advances in thin film manufacturing technologies, the thickness of the polarizers have been considerably reduced, to nanometers, and the coating techniques have developed greatly. There has also been a significant increase in the durability of the dichroic sheets, owing to high performance requirements of applications like Liquid Crystal Displays. Nevertheless, polarizers still face some basic problems, like, leakage in crossed polarizers, losses due to attenuation, etc. It is demonstrated that if a medium with the proposed constitutive properties is achieved, then some of the very common problems of present day polarizers can be mitigated.

Research on SAR Simulation Model -- Physical Sparse Array Beamforming

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Project Staff
Professor Jin Au Kong, Dr. Tomasz M Grzegorczyk, Dr. Bae-Ian Wu
James Chen

We are concerned in this work with the physical shaping of a beam emitted by three antennas in space. The purpose of this study is to use the three antennas and realize a footprint on the ground that has variations of less than 5 dB within the mainbeam and a sidelobe level of no more than -13 dB down from the peak power. We show analytically that the maximum and minimum power from three satellites will occur within a footprint size of 10 km by 10 km. Therefore, to satisfy the design requirements, the peak power within footprint would be ~ 2 dB with variation less than 5 dB. We demonstrate a case in which the proposed result can be achieved (the configuration is not unique) . The satellite parameters are presented. In this case, satellite #1 and #2 radiates a footprint on the ground with amplitude 1 and 0.25 respectively, while satellite #3 has negligible power contribution to the footprint (panel's amplitude is set to 0.25 however the phase distributions cancel out the footprint power).

Research on SAR Interferometry: application to STAP

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Project Staff
Professor Jin Au Kong, Dr. Tomasz M. Grzegorczyk, Dr. Bae-Ian Wu
Zachary Thomas

Moving target detection (MTD) has been a fundamental radar application since radar's conception. By detecting Doppler shifts in returned radar signals, moving targets can be differentiated from stationary targets. For a ground based stationary radar configuration, only targets moving toward or away from the radar will have Doppler shifts. The return from stationary objects will be at the radar's center frequency. When the situation is such that the radar is moving relative to the ground, stationary ground clutter will have a Doppler shift that is related to the look angle of the radar platform. Because the relative Doppler shift for stationary ground clutter is predictable, MTD can be achieved by various techniques including displaced phase center antenna (DCPA), and the more robust space-time adaptive processing (STAP). The research investigates the prospect of STAP in the spaceborne arena. The goal is to use a sparse spaceborne radar array to detect ground moving targets (GMTD). The array is assumed to consist of three satellites each approximately fifty meters apart. The formation flying satellites introduce many challenges considered by the research. The investigation considers the effects of spatial under sampling, limited accuracy in relative radar position knowledge, and extremely sparse element spacing.

Research on Coherent Change Detection (CCD)

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Project Staff
Professor Jin Au Kong, Dr. Tomasz M. Grzegorczyk, Dr. Bae-Ian Wu
Jie Lu

We investigate a signal processing technique named Coherent Change Detection (CCD) that uses the multi temporal interferometric SAR images to detect subtle geophysical changes in terrains, which may not be detectable by observing SAR images only. We thoroughly reviewed the method itself and possible applications of CCD, and performed numerical simulations on the electromagnetic wave scattering by rough surface to evaluate the method and study the sensitivities of CCD to different factors, such as grass height, ground type, baseline, and noise. The results show that CCD is sensitive to the height change of the ground. In our simulations, with a resolution in the SAR image of 5 m $\times$ 5 m, and a standard deviation of the ground height of 3.52 m, a height change of $\Delta z = \lambda/4 = 6.25$ cm is detectable

Time Domain Electromagnetic Models for UXO Discrimination

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Cold Regions Research and Engineering Laboratory

Project Staff
Professor Jin Au Kong, Dr. Kevin O'Neill, Dr. Tomasz M. Grzegorczyk
Christopher Moss

The detection and removal of buried unexploded ordnance (UXO) is an expensive and challenging task. In the United States, an estimated 11 million acres of land may contain buried UXO. The problem is more widespread in European countries, where millions of buried UXO remain from two world wars. The overwhelming task of finding and removing these UXO is exacerbated by the fact that almost three-quarters of the costs and efforts are expended responding to sensor false-alarms caused by metallic clutter. Hence, accurate detection and discrimination techniques are a popular area of active research. A promising technique is electromagnetic induction (EMI) sensing, which uses frequencies at which the natural environment is transparent (generally less than 500 kHz). In time domain EMI sensing, targets are saturated in a static primary magnetic field that is then shut off. The transient primary field causes currents to flow in the target, inducing a secondary magnetic field that is measured with a receiver coil. These currents, and the secondary field, eventually decay to zero due to the finite conductivity of the target. Depending on the instrument, the receiver coil takes sample of the decaying secondary field anywhere between 50 us and 0.1 s after the primary field transient. The time domain profile of the scattered field reveals characteristics of the target such as dimension, permeability, and conductivity.

Standard numerical methods can only calculate the EMI secondary field for low frequencies (usually a small portion of the total frequency band of interest), due to the extremely small skin depths of UXO type targets. Recently, a new numerical method called the Thin Skin Approximation (TSA) was developed to model the high frequency EMI response, and accurate results were obtained. However, one cannot obtain a complete time domain response from a frequency domain model that is only accurate at either low or high frequencies. In this work, a time domain TSA method was developed and combined with standard numerical methods to obtain a solution that is accurate for any skin depth (or equivalently for any time or frequency of interest). A method of moments (MoM) was used to solve the boundary integral (BI) for the exterior region, while two separate formulations were used for the interior region, depending on the skin depth. When the skin depth can be resolved on a reasonable mesh, a finite element method (FEM) was used to solve the interior problem for the magnetic vector potential. The technique is referred to as the FE-BI method. When the skin depth is small, the divergence equation for the magnetic field was implemented in the interior. A new method was developed in which the normal derivative of the magnetic field is calculated using a type of TSA, so that no interior mesh is required. This second technique is referred to as the TSA-BI method. The two approaches, FE-BI and TSA-BI, can both be solved separately in their regimes of validity to obtain the entire time domain response. The method's accuracy was verified by comparison to analytical solutions for spheres and spheroids, as well as experimental results. Various typical target geometries can now be studied to identify important characteristics of the time domain response that may be useful for inversion algorithms such as a Support Vector Machine or the Linear Least Squares method. Furthermore, objects with simple material inhomogeneities (such as aluminum and steel parts) can be examined for identifiable characteristics in the time domain response.

Electromagnetic Models and Data Analysis for UXO Discrimination

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Project Staff
Professor Jin Au Kong, Dr. Kevin O'Neill, Dr. Tomasz M. Grzegorczyk
Benjamin E. Barrowes, Xudong Chen

The Electromagnetic Induction (EMI) response from prolate and oblate spheroids under arbitrary excitation in the asymptotic regime (large and complex size parameter c) has been studied. Realistic primary fields from existing instruments have been modeled and our predicted EMI response has been shown to agree remarkable well with measured data. These results have been prepared for publication in a report entitled, "Broadband Analytical Magnetoquasistatic Electromagnetic Induction Solution for a Conducting and Permeable Spheroid" and has been submitted for consideration to IEEE Transactions on Geoscience and Remote Sensing.

We present studied the solution for the induced electromagnetic induction (EMI) response from multiple permeable and conducting spheroidal objects in close proximity under time harmonic excitation. The exact formulation for the induced EMI response is based on magnetic field boundary conditions. The internal magnetic field of each spheroid is represented in terms of an infinite sum of the vector spheroidal wave functions. The external magnetic field is composed of the primary field and the induced secondary field from each spheroid, each expressed as an infinite sum of solutions of the first and second kinds of the Laplace equation in the spheroidal coordinate system. The total external secondary field summation coefficients are solved for simultaneously thus including all multiple body interactions. This analytical solution is shown to be in agreement with a numerical solution based on the finite element method (FEM). This solution is also compared to magnetic field measurements from machined steel and aluminum spheroids taken with the GEM-3 broadband EMI instrument and found to be in good agreement as well.

The detection and removal of buried unexploded ordnance (UXO) is an expensive and challenging task. We present some new modeling methods for use in EMI inversion applicable to UXO discrimination. Our innovative optimization and inversion methods attack this problem by exploiting new analytical solutions for scattering in the magneto-quasistatic (MQS) regime. We solve for the magnetic field in spheroidal coordinate system, and express it as a linear superposition of basic modes. Previous work has shown that even geometrically complicated elongated metallic object can often be represented effectively in the MQS realm by a spheroid. Thus in one approach we attempt to process ultra-wide band (UWB) MQS data to infer the properties of an equivalent spheroid, thereby characterizing the material properties, general shape, and location of a subsurface object. Objects too complicated to be represented by a single spheroid can often be constructed from combinations of spheroids. Beyond this, the response of any discrete scatterer can be represented in terms of fundamental solutions in spheroidal coordinates, which are particularly well-suited for elongated objects. Therefore, in our second approach, we address the more general case by using as discriminators an object's scattering coefficients for each spheroidal mode, although the object itself need not be a spheroid. We compare the measured data with the signatures of each candidate UXO, and rule out or identify it according to the goodness of fit. In both inversion schemes, the optimization algorithm employed is differential evolution (DE), which shows good convergence properties and is easy to use.

Modular Antenna Tiles for Conformal Array Architectures

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Project Staff
Professor Jin Au Kong, Dr. Tomasz M. Grzegorczyk, Dr. Bae-Ian Wu
Zachary M. Thomas

Conformal antennas are needed in ground based and airborne applications where the antenna is to be mounted on the exterior of a curved or doubly curved surface such as the hull of an airplane. In order to minimize the design, manufacturing, and installation costs, modular antenna panels can be constructed. These modular units can be used to tile the surface where the antenna is needed. Such a method not only reduces the setup costs, but also allows for easy, economical replacement of tiles that have been damaged or destroyed while in service. In tiling a curved surface, gaps are introduced along the edges of contiguous tiles. An aberrant array pattern will result due the additional diffraction from the tile edges and cavities. These effects can be significant and must be considered during tile design. The research focuses on modeling the effect of tile gaps, and proposing methods to mitigate the resulting interference. We consider geometries such as a slit or wedge shaped gap and treat the gaps as additional source elements in the antenna array. The gap radiation pattern is determined and the total interference pattern is formed by treating the gaps as elements in a phased array. To determine the radiation pattern of the entire antenna (true elements and gaps) we first find the radiation of the gap free structure. We consider this to be the baseline pattern of the antenna and add the interference pattern to the baseline radiation pattern. The resulting total radiation patterns for a line of elements are in good agreement with simulation. By understanding the radiation of different gap models we can propose adjustments to the design of the modular tiles such that the gap radiation will be minimized. The research thus far has demonstrated that tile thickness and termination of the gap play an important role in shaping the resulting interference pattern. Proper tile design can substantially minimize the gap radiation such that the resulting radiation approaches the baseline situation. Ongoing research focuses on realistic gap geometries, and larger tile structures.

Electrostatic Phenomena by Moving Objects

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Project Staff
Professor Jin Au Kong, Dr. Tomasz Grzegorczyk, Bae-Ian Wu,
Brandon Kemp

Charges moving at a velocity near the speed of light of the host medium emit electromagnetic waves, which can be detected by existing sensors. Such occurrences have been extensively studied. Objects moving at slow velocities disturb the surrounding fields in a different way. Sensors for the measurement of electrostatic field disturbances have been developed, but extensive investigation of the phenomenology has not been previously reported. This work focuses on the forward problem of understanding the fundamental physics describing the electrostatic phenomenon of moving objects and the inverse problem of determining a physical description of a moving object from sensor data. The research involves developing models of electrostatic disturbances induced by various moving objects, predicting how various moving objects register as signatures in sensor data, and including sources of external noise that can interfere with the interpretation of measurement data.

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