

Section 3 Electromagnetics

Chapter 1 Electromagnetic Wave Theory and Applications

Chapter 1. Electromagnetic Wave Theory and Applications

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1.1 SIR-C Polarimetric Radar Image Simulation and Interpretation

Sponsor

National Aeronautics and Space Administration
Contract 958461

Project Staff

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This project investigates the use of spaceborne polarimetric radar measurements for monitoring, mapping, and retrieving the aboveground vege-

tation biomass. Fully polarimetric radar data obtained from the SIR-C/XSAR missions over the Landes Forest in Southwestern France have been analyzed in detail. In our investigation of the application of SIR-C data to vegetated terrain classification and biomass inversion, the measured backscattering coefficients, the derived complex correlation coefficient of HH and VV polarizations as well as the ratio between cross- and co-polarization ratio are fully utilized. A validated pine forest scattering model, which is based on the radiative transfer theory with the specific branching structure of pine trees taken into account, is used to interpret the SIR-C/XSAR polarimetric backscattering measurements from the Landes forest. From the analysis of measured data and the model results, the cross-polarization backscattering coefficients at L-band and the correlation between HH

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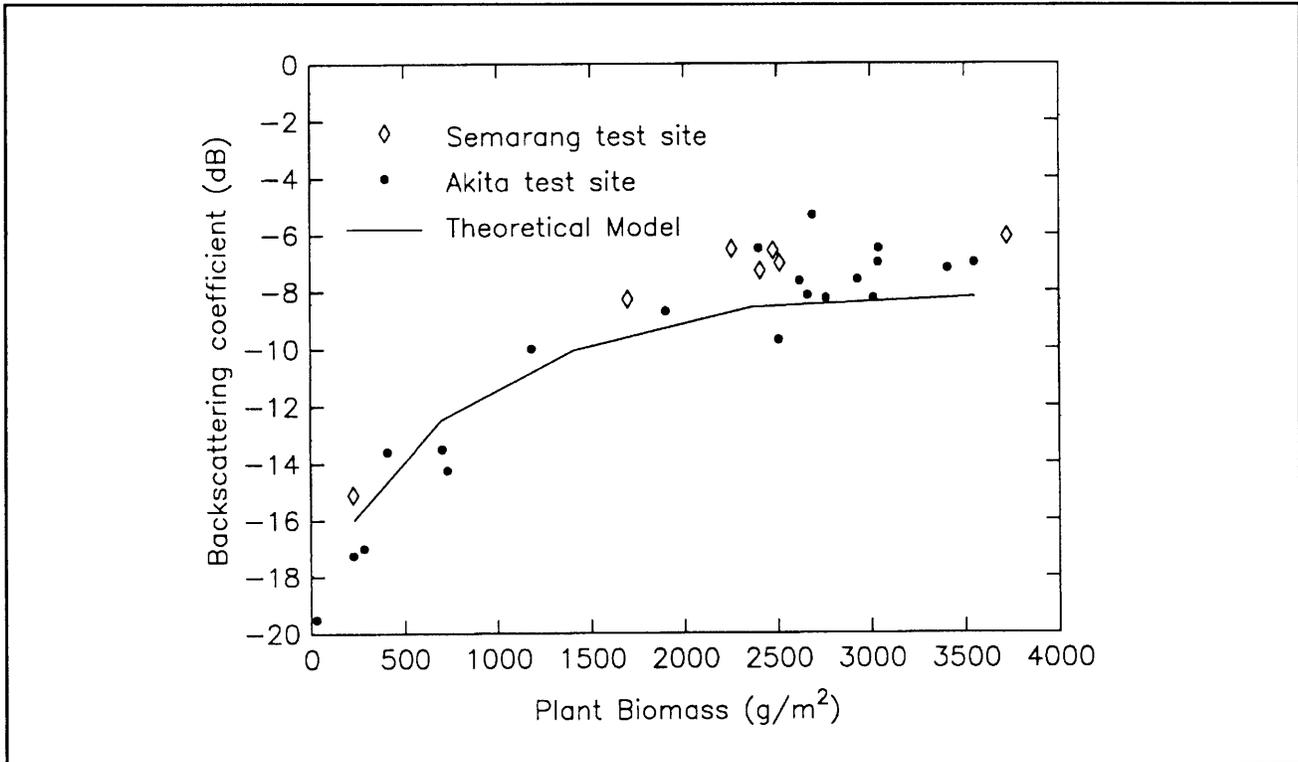


Figure 1. The backscattering coefficient versus plant biomass: comparison of theoretical model and experimental data.

and VV backscattering returns at both L- and C-band are found to be useful for the biomass retrieval. Bayesian classifications using data with known ground truth and with theoretical simulation are applied to classify the forest for biomass up to 50 tons per hectare with the available data. With the use of the pine forest scattering model, biomass inversion has been shown to be feasible over a wider biomass range (up to 100 tons per hectare) for angles of incidence around 45. In addition to the analysis of SIR-C/XSAR data, we have refined our forest scattering model by taking into account the double scattering mechanism between trunk and branches which shows more effects on the cross-polarized backscattering return.

Recently, there have been some pilot studies that use ERS-1 data to estimate rice crop acreage and monitor rice growth at several places in Asia. Through this project, we also develop a theoretical scattering model for the rice canopy to analyze the temporal variation of radar backscatters from different rice growth stages observed by ERS-1. The scattering model takes into account the cluster structure of rice plants, a flooded ground surface, and coherent wave interactions between scattering components. The effects of attenuation on the coherent wave caused by inhomogeneities are taken into account using the Foldy's approximation. The Monte Carlo simulation algorithm is employed to compute the scattering return from rice field.

The simulated backscattering results at different growth stages are in good agreement with the ERS-1 data (figure 1). Simulations are also performed to explain some phenomena observed from the JERS-1 data and SIR-C data. A similar model is further developed for the sunflower field with rough soil ground. The scattering from rough ground surface is obtained using Kirchhoff approximation. The simulated backscatters at different growth stages of sunflower are in good agreement with the experimental data obtained from the Montespertoli test site in Italy during the airborne Remote Sensing Campaign Mac-Europe 91. The model is then utilized in the inversion of sunflower biomass with the neural network technique.

1.2 Polarimetric Passive Remote Sensing

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Project Staff

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The principal goal of this project is to obtain a better understanding of how the third Stokes brightness parameter, U , is related to ocean wind direction. This brightness parameter, which is not measured in conventional passive remote sensing, has recently been shown to respond to the azimuthal anisotropy of the observed medium and thus should give information on ocean wind direction. The calculation of the polarimetric brightness temperature of the ocean requires the use of rough surface scattering theory and a statistical model of the ocean surface. Our approaches include the use of analytic rough surface scattering theories, such as composite surface scattering model, and numerical methods, such as the method of moments. Monte Carlo simulations based on exact numerical methods are used for randomly rough surfaces to insure accurate calculation of the polarimetric brightness temperature.

Experimental verification of our models is an important part of the process. The growing interest in polarimetric passive remote sensing of the ocean has resulted in a number of ongoing and future experiments in which we plan to participate and compare our model results with the experimental results. The use of polarimetric passive techniques for ocean remote sensing from a realistic satellite borne radiometer will be studied. Atmospheric effects on the measurements will be investigated using radiative transfer theory; and other potential effects, such as breaking waves and foams under high wind conditions, will also be studied. A variety of retrieval techniques for wind speed and direction from polarimetric passive data will be examined to determine the most advantageous sensor configuration and retrieval method.

The results of this project to date are favorable for the application of polarimetric techniques in future air- or space-borne passive sensors. Theories and experiments involving one-dimensional periodic surfaces have demonstrated that U responds to surface azimuthal anisotropy. These results indicate that use of U can enhance retrieval techniques for physical properties of azimuthally asymmetric media. Models for prediction of polarimetric brightness temperatures of one- and two-dimensional periodic surfaces have been developed and applied in theoretical studies. Properties of U for one-dimensional surfaces have been examined through both theory and experiments. A study of two-dimensional periodic pyramidal surface polarimetric thermal emission has indicated that properties of U observed in the one-dimensional surface case remain similar for two-dimensional surfaces. Furthermore, a study of the response of U to level of medium anisotropy was performed, and it was

found that U brightnesses saturate relatively quickly as azimuthal anisotropy increases.

Models for prediction of polarimetric brightness temperatures of one- and two-dimensional randomly rough surfaces have been developed and applied in Monte Carlo simulations of ocean-like surfaces. Sensitivities of polarimetric brightnesses to various ocean properties have been investigated. Monte Carlo simulations of one-dimensional randomly rough surfaces have demonstrated that U again responds to surface azimuthal anisotropy and that U is insensitive to the polar angle of observation and to the permittivity of ocean-like surfaces at K_u band. However, the magnitude of the U return from ocean-like surfaces was observed to be small (less than 5 K). Thus, although U has desirable properties for air or space borne passive ocean remote sensing, sensitive radiometers must be employed to ensure accurate measurements. This same Monte Carlo model has been validated through comparison with bistatic scattering measurements of fabricated very rough two-dimensional Gaussian surfaces.

A model for the prediction of polarimetric brightness temperatures of foam or spray covered ocean surface has been developed. The foam cover is modeled as a layer of randomly distributed dielectric particles overlying the rough sea surface. Radiative transfer theory is applied to calculate the fully polarimetric brightness temperatures. The small perturbation method is used to compute the scattering from rough ocean surface. The thermal emission from ocean surface is included as its boundary conditions. The effect of coupled volume and surface interaction on the polarimetric thermal emissions from foam covered ocean surface is investigated. The model results with the foam contribution are validated by comparing with WINDRAD data.

The positive results of this project are expected to generate further interest in polarimetric techniques for passive remote sensing and to lead to the development of future polarimetric passive systems for Earth remote sensing. Application of polarimetric techniques in passive remote sensing of the ocean has shown potential for more accurate space-borne measurements of global wind vectors in the future. In addition, surface scattering models developed in this project can also be applied in other studies of rough surface scattering, including studies of active remote sensing of the ocean and should provide very accurate predictions by which the validity of other approximate methods can be assessed. A better understanding of rough surface scattering phenomenology should result, as well as the potential development of future extended analytical theories.

1.3 Development of an Atmospheric Attenuation Model

Sponsor

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The intensity of emitting electromagnetic energy of ocean depends mainly on the roughness of its surface. Ocean surface characteristics are generally affected by local meteorological conditions such as wind speed and direction. One important application of using passive polarimetry is to retrieve the wind speed and direction above the ocean surface. Both experimental and theoretical studies have shown that the Stokes parameters varied as a harmonic function of azimuth angles over the rough surface. In the past, most theoretical studies did not take into account the atmospheric effects on the microwave passive polarimetry of ocean surface. However, the atmosphere can not be treated as a vacuum. The thermal radiation from the ocean is attenuated due to absorption of atmosphere. On the other hand, the atmosphere, which is composed of thermally agitated gaseous molecules, also contributes to the brightness temperature. The real observations are not only functions of ocean surface characteristics but also influenced by the atmospheric conditions, temperature, pressure, and moisture above the surface. In addition, the atmospheric effect varies with frequencies.

The objective of this study is to investigate the effect of atmosphere on the measurement of polarimetric brightness temperatures of ocean surface. The atmosphere is modeled as a stack of horizontal layers above the ocean surface which is modeled as an one-dimensional periodic rough interface. Both the extended boundary condition method and the method of moment are used to calculate the emission from the rough ocean surfaces. The simulation results are compared. The millimeter-wave propagation model is used to evaluate the absorption constants of atmosphere for various frequencies and atmospheric conditions. Atmospheric parameters are specified according to the U.S. Standard Atmosphere (1976). The brightness temperature observed is then obtained by solving the coupled model of rough surface scattering with atmosphere layer using the radiative transfer approach. Thermal emission from the

ocean surface is included as its boundary conditions.

Simulations are carried out to interpret the 1995 NASA WINDRAD data set. The effects of frequency, polarization, observation angle, and atmospheric conditions are studied. The simulation results indicate that in atmosphere T_h and T_v are higher while U is lower than the values in free space. This atmospheric contribution is the largest at 22 GHz among four frequencies 17 GHz, 19.35 GHz, 22 GHz and 37 GHz. The more humid or warmer air has more atmospheric contribution.

1.4 Electromagnetic Modeling of Snow with Microstructures

Sponsor

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Research and Engineering Laboratory
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Seasonal snowcover is one of the major environmental factors over the earth's surface. Snowcover imposes an impact on the radiation and energy budget between atmosphere and surface. For hydrologic applications, snow is also a major contributor to runoff in rivers and to groundwater resources. On the ground, snow is generally inhomogeneous and stratified. Furthermore, the affects of snow metamorphosis typically cause the grain size, shape, density, and liquid water content of snow to vary from one stratigraphic layer to another.

The time-varying snowpack structure greatly complicates the analysis of electromagnetic interactions with snow-covered terrain. Generally, the ground truth measurements of snow characterizations are laborious and thus very difficult to acquire as time series. Although several investigations have indicated that the millimeter wave-backscatter of snowcover is strongly influenced by the presence of liquid water, electromagnetic modeling of snow undergoing internal changes, due to metamorphism and phase change, still needs to be studied systematically.

In this project, we investigate the temporal variation of the millimeter-wave backscatter signature of snowcover based on a dense medium radiative

transfer (DMRT) theory and a one-dimensional mass and energy balance model of snow, named SNTHERM. In the previous DMRT models of snowcover, the ice particles are assumed to have no bonding with each other, and the effects of reflection and refraction between the strata of snow are not considered. In our study, we apply a model of adhesive spherical particles to account for the clustering feature of snow grains.

Our study demonstrated that the aggregation of scatterers greatly affects the electromagnetic properties of densely packed media. The multilayer DMRT scattering model of snowcover developed in this work takes into account the reflection and refraction at the snow-snow interfaces. Appropriate boundary conditions, quadrature points and weights are selected for using the discrete-ordinate eigenanalysis method to solve the multilayer DMRT equations. It shows that the inclusion of reflection and refraction at the snow-snow interfaces may affect the model prediction. To model the time-varying behavior of snowcover, SNTHERM is employed to simulate the aging process of snow. SNTHERM provides pertinent snow parameters, such as grain size, density, liquid water content, and stratification with a high resolution in time and depth. These snow properties are then used in modeling the temporal radar signatures of snowcover. The comparisons of temporal model responses with time series polarimetric backscatter data at 35 and 95 GHz are presented. Good agreement is demonstrated between model and measurements in both timing and magnitude. The results indicated that the coupled DMRT and SNTHERM model can be useful in studying the electromagnetic interactions with time-varying snow microstructure.

1.5 Study of SAR and SCANSAR Interferometry

Sponsor

Mitsubishi Corporation

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In spaceborne synthetic aperture radar (SAR) interferometry, the terrain elevation information is obtained from the phase difference of two SAR images gathered by the same sensor in repeated passes. With the advantage of large swath width, SCANSAR would cover a wider area with the tradeoff of coarse azimuthal resolution. However, when the SCANSAR mode is used to derive interferometry, decorrelation due to the mis-alignment in the scanning cycle of twopass would be serious. In order to compare various processing methods systematically, the SAR simulator can be used to analyze the performance of various SCANSAR processing algorithms.

An SAR interferometry simulator has been developed and implemented based on the electromagnetic modeling of scattering applied to remote sensing (EMSARS) model. The GIS database—including a digital elevation map (DEM) and feature map—is used to create synthesized SAR images (figure 2). The real SAR simulation involves calculation of received field for each time step and frequency component, which is a time consuming process. We choose instead to start from the simulated range compressed data, in which the scattered field for each azimuthal step is calculated by summing up scattering field from individual cells that are within the specified azimuthal beamwidth and range resolution. K-distribution statistics are used to simulate the speckle inherent to the radar data. The scattering fields obtained from two repeat passes are combined to form the interferogram. The Doppler part of the commonly used range-Doppler algorithm is used to synthesize images under various misalignment conditions. Using the simulator, decorrelation effect due to the angular difference can be studied. It is found that the correlation coefficient of two images is decreased with increasing misalignment. This decorrelation effect can be shown to improve with the proper azimuthal filtering.

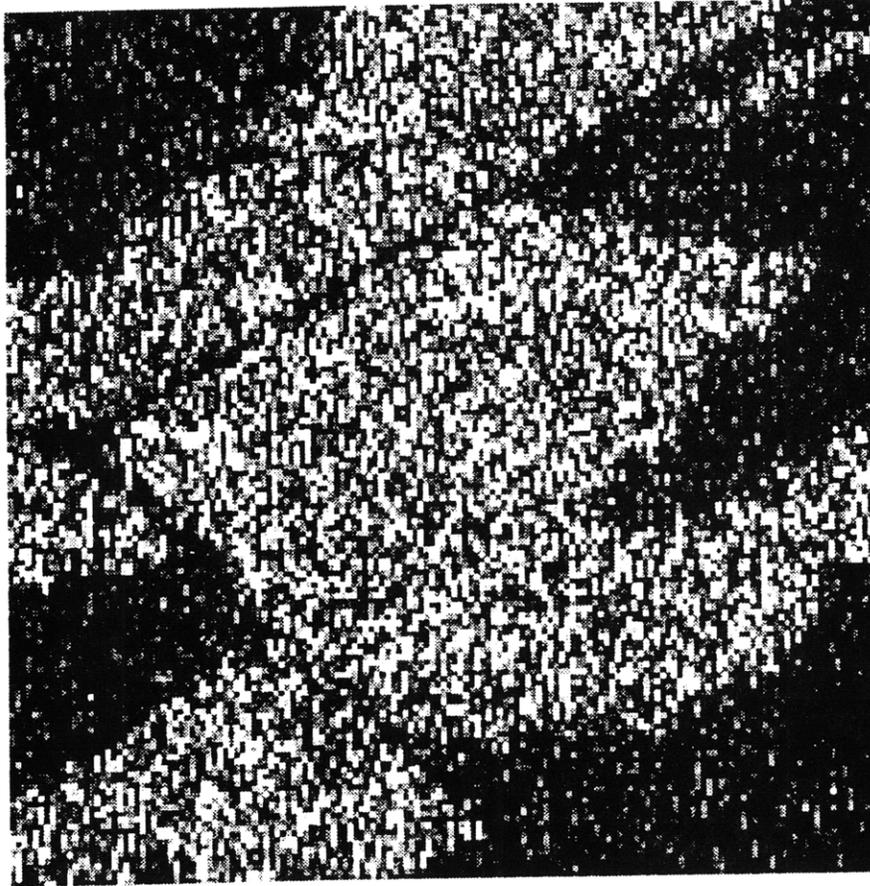


Figure 2. Simulation of the synthetic aperture radar (SAR) image with electromagnetic scattering application to remote sensing (EMSARS) module.

1.6 Inversion of Sea Ice Parameters

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Project Staff

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The large expanse of sea ice in polar regions has a great impact on the Earth's climate system. The thickness of sea ice is an important factor in understanding the dynamics of sea ice cover and the heat exchange between the ocean and the atmos-

phere. In the past, several sea ice direct scattering models had been developed and verified by various experiments. However, these models are usually complicated and are difficult to find closed-form solutions for direct inversion. To utilize these developed scattering models for ice thickness retrieval, the parametric estimation method offers a greater flexibility in the choice of direct scattering models, the parameters to be inverted, and the data to be employed. However, such an approach usually comes with the problems of non-unique solutions and inversion stability with noisy data. Although it is possible to reduce the effects of these uncertainties by using diversified data like multifrequency, multi-angle, and polarimetric data, the cost of making such extensive measurements may be prohibitive for satellite remote sensing of sea ice. On the other hand, the orbited satellites will repeat their passes at a fixed time interval, it is natural for them to make timely sequential observations. With these

time-series measurements, more data become available which may be helpful for resolving the non-uniqueness and stability problems, and useful for the geophysical parameter reconstruction.

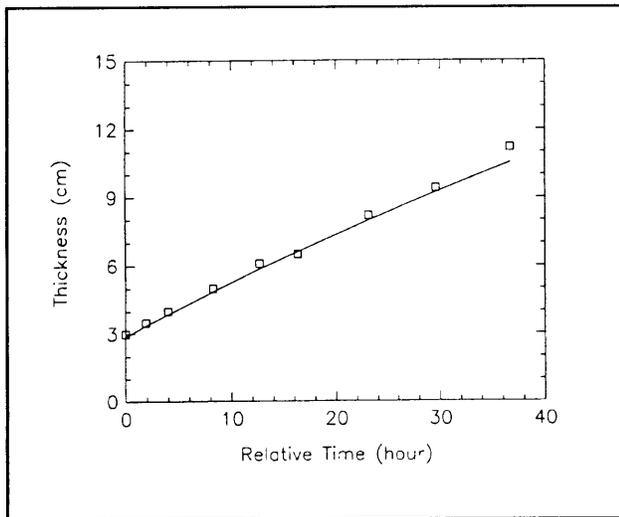


Figure 3. Saline ice thickness retrieval using polarimetric time-series data. Squares represent the measured ice thickness. Solid curve indicates the evolution of reconstructed ice thickness using measured time-series data at 25 degree incident angle.

The application of time-series radar measurements to accurately invert the thickness of saline ice is presented in this study. We develop a thickness retrieval algorithm based on a dynamic-electromagnetic scattering model of saline ice and the time-series active remote sensing data. This direct scattering model consists of a saline ice physical model describing the dynamic variation of ice characteristics coupled with an electromagnetic scattering model accounting for the wave propagation and scattering in random medium. The interpretations of experimental data are demonstrated, which show good agreement with observations. It also indicates that the volume scattering of brine inclusions is an important contribution to the backscatter response of saline ice. The inversion algorithm is constructed based on a parameter estimation approach where the radiative transfer equation is used as the direct scattering model to calculate the backscattering signatures from ice medium, and the Levenberg-Marquardt method is employed to retrieve ice thickness iteratively. Additional information provided by the saline ice thermodynamics is applied to constrain the electromagnetic inverse problem to achieve a more accurate reconstruction. This inversion algorithm is then applied to retrieve the growth of a sheet of thin saline ice by using the set of C-band polarimetric radar sequential measurements from CRRELEX 93 and 94 experiments (figure 3) The demonstrated

accurate thickness retrieval suggests the potential usage of this algorithm for the satellite remote sensing of sea ice.

1.7 Study of Radio Interference on ILS Category III Operations

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Federal Aviation Administration

Project Staff

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Automatic landing system was developed in the 1960s to allow an airplane to conduct "zero decision-height/zero runway-visual-range" final approach procedure on Category III instrument landing system (ILS) equipped runways. These systems are designed to meet not only the accuracy limits but also stringent requirements in reliability measures such as availability, continuity of service, and integrity failure rates. Ideally, clean ILS signals must be maintained in the vicinity of airports where automatic landing mode will be engaged. In reality, interference from other RF sources might be possible because the frequency bands the ILS components operate are heavily populated. For example, FM broadcasting stations, which transmit right below the ILS localizer band, have proliferated in metropolitan areas with major airports. There are also increasing number of industrial, scientific, and medical (ISM) equipment radiating in various RF bands, some of which can create high power harmonics in the localizer band. All of these developments are of great concern to the aviation authorities.

We studied ILS autoland system integrity and continuity risk under various RF interference conditions. Generic simulation models of the autoland system are developed for typical airliner transports, with varying landing weights and different extent of inertial smoothing in the control system. The autoland model is combined with the ILS receiver response model, ILS signal-interference model, and wind disturbance model, to form a full simulation model for the final approach process. Monte Carlo simulations over hundreds to thousands of landings are conducted to assess the total system risk. The continuity risk is defined to be the probability of CDI current exceeding 20 microamps during the final 30-second period, the condition which will normally cause the autoland system to "disconnect." The integrity risk is defined by the probability of key system performance measures exceeding certain

boundaries at the touch down point even though the autoland system does not disconnect during the final 30-second period, i.e., without detectable alarms. The key measures defining a successful landing include aircraft lateral displacement, banking angle, and sideslip rate. We found from the simulation that continuity risk appears to dominate integrity risk, and that present standard of RF interference immunity for ILS receiver provide sufficient margins to control the continuity risk. The study also shows that control systems with inertial smoothing has lower integrity risk than those without.

1.8 MMW Model for Three-Dimensional Radar Scattering from Targets and Background

Sponsor

DEMACO

Project Staff

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We have extended the iterative radiative transfer theory to the second-order and applied it to three-dimensional radar scattering of isolated trees. In the surface scattering aspect, we developed Monte Carlo simulation model to study radar return from randomly rough surfaces at near-grazing incidence angle. We also finalized the scanning radar image simulation package based on EMSARS scattering model. The followings are highlights of our work:

1.8.1 Three-Dimensional Radar Scattering Model of Isolated Trees

With the advance of radar technology, high-resolution imaging of terrain and target with millimeter wave radar has been of great interest in terms of both application and theoretical development. In the effort to develop an electromagnetic model of scattering applied to remote sensing (EMSARS) background scattering model, a discrete scatterers model based on the radiative transfer theory is developed for the simulation of radar scattering from isolated trees with fine range resolution at low grazing angles.

In this model, a tree is treated as combination of trunk and crown where the scattering power is calculated separately. Trunks are modeled as circular cylinders with random rough surfaces where

Kirchhoff approximation is used to calculate the radar return power. The attenuation caused by the crown is also considered. The crown is modeled as a collection of discrete scatterers embedded in a random medium with fixed shape. To calculate the scattering from the crown, radiative transfer theory is used. Branches and coniferous leaves are modeled as circular cylinders. Deciduous leaves are modeled as elliptical disks. Finite cylinder approximation and physical optics approximation is used for the calculation of scattering from cylinders and disks, respectively. The radiative transfer equation is solved iteratively to the second order which includes the double scattering among scatterers inside crown. Range profiles of copolarization and cross-polarization backscattering coefficients are obtained by superimposing the returns at equal path length. Theoretical prediction of the range profile is compared with the measurement data by the Army Research Laboratory using a 94 GHz FM-CW radar for various coniferous and deciduous trees. It is found that the double scattering is important in the copolarization return at farther range. Theoretical simulation also shows the importance of double scattering for cross-polarization return.

1.8.2 Monte Carlo Simulation of Scattering from Randomly Rough Surfaces

Numerical analysis of electromagnetic scattering by random rough surfaces has been investigated using both integral equation and the finite-difference time-domain techniques with Monte Carlo simulation. It was noted, however, that the simulation technique becomes very time consuming at low grazing incidence angles. This is mainly because the input radar beam illuminates over a large surface area. Thus the computational domain expands significantly compared to near-normal incidence. As a result, computational time and storage requirement could grow out of portion. In practice, it is also difficult to obtain controlled measurement results, which requires the radar beam to illuminate only one type of surface over a long range, to validate theoretical predictions.

Recent advances in signal processing hardware have made high-resolution imaging radar reality. One important feature of these imaging radar systems is that since range resolution is determined by the signal processing algorithm, the effective illuminated area corresponding to an image pixel is limited, even at very low grazing angles. This work is motivated by this type of radar applications. The rough surface is assumed to have fixed size, as determined by the limitation of the computational technique.

For each randomly generated surface, we obtain the range-gated scattering return using pulse-compression technique. The effective pulse width is chosen to fit within the range direction of the surface so that the edge effect can be minimized. To do this, backscattering cross sections at multiple frequency steps will be calculated and processed with weighted Fourier transform. Finally, the results from different surfaces are averaged to obtain the mean normalized radar cross section.

This technique would be very useful for the physical simulation of high resolution radar images. Because of memory constraint, we currently are able to study the case of one-dimensionally rough surface, i.e., the surface height only varies in one direction. A modulated pulse plane wave is synthesized by multiple frequency steps. For each frequency, scattered field is obtained by using the method of moment technique. The complete time response is synthesized in the same fashion as the input pulse. Finally, a time gate is applied to the solution. Therefore, the edge diffraction effect can be isolated out from our consideration. The program has been validated with the small perturbation approximation solution in the low-slope, small roughness limit.

1.9 Electromagnetic Waves in Complex Media

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Project Staff

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This research is focused on theoretical studies of electromagnetic phenomena in complex media that will lead to applications in the modeling and analysis of realistic electronic systems. We are concentrating our efforts on those characteristics that have major impacts on system behavior, in particular on electromagnetic interaction with detailed geometrical features and material properties.

Modeling of small apertures in an electronic system enclosure is an important element in determining the amount of electromagnetic emissions. These simple geometrical features, typically found as air vents in computer boxes, can create difficulty for modelers since smaller spatial "cells" usually need to be set up around the apertures to get accurate

results. We avoided this problem by investigating the electromagnetic interaction around the aperture and developing a technique for maintaining larger spatial grids around the aperture. The method replaces a small aperture in a perfectly conducting screen with pairs of oppositely directed electric and magnetic dipoles on either side of the short-circuited screen. Equations are derived which determine the electric and magnetic currents induced by arbitrary fields within the FDTD computational domain. These currents are induced by the short-circuit fields, at the apertures. To determine the short-circuit fields it is necessary to subtract out the fields of the electric and magnetic dipoles. An analytical solution for dipole radiation is used to determine the dipole fields, and it is shown that the FDTD dipole fields deviate from the continuum dipole fields at distances close to the dipole. It is shown that a very accurate solution for the power transmitted through small circular aperture can be obtained using the proposed method. Thus our hybrid technique improves the efficiency of numerical modeling.

Our other work on numerical computation model centered around the FDTD method. An analytical study of the FDTD formulation for various transmission line geometries was conducted. Both closed and open transmission lines were considered. It was found that the accuracy of solution depends upon the fine details of the gridding scheme. For example, for a microstrip center conductor modeled with n nodes, the effective width was found to be approximately $w = (n - 0.25)\Delta$, which is three quarters of a grid cell greater than the heuristic width, $w = (n - 1)\Delta$.

1.10 Publications

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