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RETRIEVAL OF SOIL MOISTURE AND ROUGHNESS FROM THE POLARIMETRIC RADAR RESPONSE

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1 Introduction

The purpose of this final report is to summarize our accomplishments over the period May 93 to October 1996 for the investigation entitled "Retrieval of soil moisture and roughness from the polarimetric radar response" supported by the Terrestrial Ecology Program of NASA Headquarter. The main objective of this investigation was the characterization of soil moisture using imaging radars. In order to accomplish this task, a number of intermediate steps had to be undertaken. In this proposal, the theoretical, numerical, and experimental aspects of electromagnetic scattering from natural surfaces was considered with emphasis on remote sensing of soil moisture. In the general case, the microwave backscatter from natural surfaces is mainly influenced by three major factors: (1) the roughness statistics of the soil surface, (2) soil moisture content, and (3) soil surface cover. First the scattering problem from bare-soil surfaces was considered and a hybrid model that relates the radar backscattering coefficient to soil moisture and surface roughness was developed. This model is based on extensive experimental measurements of the radar polarimetric backscatter response of bare soil surfaces at microwave frequencies over a wide range of moisture conditions and roughness scales in conjunction with existing theoretical surface scattering models in limiting cases (small perturbation, physical optics, and geometrical optics models). Also a simple inversion algorithm capable of providing accurate estimates of soil moisture content and surface rms height from single-frequency multi-polarization radar observations was developed. The accuracy of the model and its inversion algorithm is demonstrated using independent data sets. Next the hybrid model for bare-soil surfaces is made fully polarimetric by incorporating the parameters of the co- and cross-polarized phase difference into the model. Experimental data in conjunction with numerical simulations are used to relate the soil moisture content and surface roughness to the phase difference statistics. For this purpose, a novel numerical scattering simulation for inhomogeneous dielectric random surfaces was developed. Finally the scattering problem of short vegetation cover above a rough soil surface was considered. A general scattering model for grass-blades of arbitrary cross section was developed and incorporated in a first order random media model. The vegetation model and the bare-soil model are combined and the accuracy of the combined model is evaluated against experimental observations from a wheat field over the entire growing season. A complete set of ground-truth data and polarimetric backscatter data at L-, C-, and X-band over a wide range of incidence angles were collected. Also an inversion algorithm for estimating soil moisture and surface roughness from multi-polarized multi-frequency observations of vegetation-covered ground is developed.

In what follows a summary of major accomplishments with pertinent references are provided.

2 Summary of Major Accomplishments

The following tasks were accomplished during the past year:

1. Development of a polarimetric calibration technique for distributed targets:
   Quantitative analysis of the measured backscatter from rough surfaces required the use of a very precise radar calibration procedure. Traditionally, calibration of distributed targets is performed using calibration methods developed for point targets and using the illumination integral to calculate the backscattering coefficients. Using this method, possible phase variations or antenna cross-talk variations (between orthogonal polarization channels) across the beam are totally ignored, which may compromise the calibration accuracy. To rectify this deficiency of existing calibration techniques, a new technique was developed with which the radar polarization distortion matrix is characterized completely by measuring the polarimetric response of a sphere over the entire mainlobe of the antenna, rather than along only the boresight direction [1].

2. Development of a Semi-Empirical Scattering Model:
   At microwave frequencies many natural surfaces do not fall into the validity regions of the theoretical models, and even when they do, the results based on these models fail to agree with the measurements. To circumvent this difficulty, we took a rather unique approach to the problem. Using our calibrated polarimetric radar system, extensive backscatter measurements covering a wide range of surface roughness and moisture conditions were conducted. The statistical parameters of the surfaces were determined by a laser profilometer and soil moisture was measured by taking samples and using dielectric probes. Using the polarimetric data and the expected asymptotic behavior of backscattering coefficients in limiting cases, a semi-empirical model (SEM) was developed and its accuracy was tested [2, 3, 18]. item Development of a fully polarimetric hybrid model for bare soil surfaces:
   The semi-empirical model for bare soil surfaces which was developed in the first phase of this investigation was improved. The improved model is made fully polarimetric by including the phase difference statistics [19, 20].

3. Development of a Level-1 SAR image classifier:
   A radar image classifier was developed for the purpose of identifying statistically homogeneous distributed targets in the imaged scene. This task was important it bears directly on to the soil-moisture estimation objective. Basically it is mandatory to identify the cover class of a given pixel before any algorithm is applied to it. This classifier operates on calibrated L- and C-band data and segments the image into four categories: (1) Bare surfaces, (2) Short vegetation, (3) Tall vegetation, and (4) Urban. The accuracy of the classifier was tested using independent images acquired in different seasons [4].

4. Development of a dielectric probe for measuring the soil moisture:
   Traditionally coaxial probes have been used for measuring soil moisture in fields. These probes are very sensitive to pressure and have a very small contact area. Accurate measurement using these probes require a large number of sample measurements which is very time consuming. To rectify this problem we designed and completed a prototype soil probe based on microstrip resonators that is not only very accurate, but also very convenient to use. With this new probe it is also possible to predict the soil type to some extent [5].

5. Development of in situ and in vivo vegetation dielectric measurement technique:
A waveguide technique for measuring the dielectric constant of vegetation needles was developed. Basically the dielectric constant of the sample is calculated from the measured reflection coefficient using a novel inversion algorithm based on an eigen-analysis of the impedance matrix of the method of moments solution [6].

6. Development of bistatic scattering measurement facility:
In order to characterize soil moisture and roughness parameters of a surface covered with randomly oriented particles (as in the vegetation case), the bistatic scattering character- istics of the surface are required. The specular direction is the most important bistatic direction in this type of problems because the mean-field (coherent scattering) is not zero. For this purpose a fully polarimetric bistatic scattering system was designed and tested. The Bistatic Facility is currently configured to perform bistatic measurements in the 8.5-10 GHz and 34-35 GHz frequency range [7, 8].

7. Development of scattering model for inhomogeneous rough surfaces:
One major problem with existing theoretical models for rough surfaces as applied to soil surfaces is their inability to treat inhomogeneous dielectric profile. Recently we developed a theoretical model that can take into account the effect of vertical inhomogeneity. For the first time a complete second order fully polarimetric scattering model for stratified rough surfaces with relatively small rms height. The model was experimentally verified using careful controlled experiments [9, 21].

8. Development of a numerical technique for rough surfaces:
Numerical simulations are necessary to indicate the trend of the scattering behavior, par- ticularly where theoretical solutions and/or controlled experimental data do not exit. In specific three different approaches addressing different problems in numerical evaluation scattering behavior of rough surfaces were considered:

   - One problem in numerical computation of scattering from rough surfaces is related to the fact that the scattering is usually computed from finite samples of rough surfaces. In order to eliminate the edge effect of finite samples, the magnitude of the incident wave is tapered. In these methods, the dimension of surface samples must be chosen large enough so that the backscatter becomes independent of footprint size [22]. To rectify this problem, we developed a novel numerical method that can be illuminated by plane waves. To eliminate the effect of edges, tapered resistive sheets are used. It is shown that the new method is numerically more efficient than the traditional methods [12].

   - The numerical techniques available in the literature are limited to perfectly conduct- ing surfaces. However, the dielectric properties of soil surfaces are very much differ- ent from those of perfect conductors. Due to moisture variations and inhomogeneity among the constituent particles, the soil medium usually behaves as an inhomo- geneous dielectric. The numerical simulation developed here has the capability of handling inhomogeneous dielectric surfaces. This simulation was used to evaluate

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the effect of moisture profile and correlation function on the backscatter data. It was found that both the correlation function and the dielectric inhomogeneities play a very important role [10, 11].

- One limitation of existing numerical methods is their lack of efficiency. To improve the computation time wavelet basis function are used to produce spars impedance matrices which are easily invertible [23, 24].

9. Retrieval of soil moisture form vegetation covered surfaces:
Under this task some basic studies were carried out. We developed forward scattering models for characterizing the dependence of radar backscatter to soil moisture in the presence of short vegetation. The following models were developed:

- Conducting of field measurements for surfaces covered with short vegetation:
A complete set of ground-truth data and polarimetric backscatter data were collected. A wheat field was chosen as the test field and radar measurement was conducted over the entire growing season. The backscatter data collected on the wheat field was calibrated and processed completely. This data was collected in summer 1993 during the whole growing season (mid-April to mid-September) at 6 incidence angles and 3 frequencies (L-, C-, and X-band). The experimental results show a significant backscatter sensitivity to soil moisture for all three frequencies and under different vegetation biomass conditions [15].

- Development of scattering model for grass blades:
A analytical scattering model for grass-blades of arbitrary cross section was developed. Closed form expressions for the polarizability tensor elements are derived. This model is valid when the all cross section dimensions are small compared to the wavelength [13].

- Generalization of Rayleigh-Gans model:
A theoretical scattering model for long, thin dielectric cylinders of arbitrary cross section and electrical length was developed. This is an extension of our previous model for electrically long cylinders. Using this solution we are able to model scattering from grass blades of arbitrary cross section and curvature very accurately [14].

- Coherent Scattering Model for Short Vegetation :
A coherent scattering model with high fidelity was developed. In this model, the effects of coherence among the scatterers as well as non-uniform illumination are taken into account. The scattering formulation for the grass components accounts for fine geometrical features of the grass blades such as curvature and cross section. [16, 17]

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3 Students

3.1 Ph.D. Students

1. Yisok Oh
   Dissertation Title: Microwave Polarimetric Backscattering from Natural Rough Surfaces.
   Graduation date: December 1993 Position: Assistant Professor, Hong-IK University, Seoul, Korea

2. Roger Dean De Roo
   Dissertation Title: Theory and Measurement of Bistatic Scattering of X-band Microwaves from Rough Dielectric Surfaces.
   Graduation date: December 1996. Position: Post Doctoral Fellow, Radiation Laboratory, The University of Michigan.

3. James Norman Stiles
   Dissertation Title: A Coherent Microwave Scattering Model for Grassland Structures and Canopies.
   Graduation date: January 1996
   Position: Assistant Professor, University of Kansas

4. Tesn Chie Chiu
   Dissertation Title: Electromagnetic Scattering from Rough Surfaces Covered with Short Vegetation.
   Graduation date: December 1997.

3.2 M.S. Students

1. Neil Peplinski

2. Andrew Zambetti

4 Publications

1. Sarabandi, K., Y. Oh, and F.T. Ulaby, "Measurement and calibration of differential Mueller matrix of distributed targets," *IEEE Trans. Antennas Propagat.*, vol. 40, no. 12, 1524-1532, Dec. 1992.

2. Oh, Y., K. Sarabandi, and F.T. Ulaby, "An empirical model and an inversion technique for radar scattering from bare soil surfaces," *IEEE Trans. Geosci. Remote Sensing.*, vol. 30, no. 2, March 1992.

3. Oh, Y., "Microwave Polarimetric Backscattering from Natural Rough Surfaces," Ph.D. Dissertation, The University of Michigan, 1993.

4. Pierce, L.E., F.T. Ulaby, K. Sarabandi, and M.C. Dobson, "Knowledge-based classification of polarimetric SAR images," *IEEE Trans. Geosci. Remote Sensing.*, vol. 32, no. 5, pp. 1081-1086, Sept. 94.

5. Sarabandi, K., and E. S. Li, "A microstrip ring resonator for non-invasive dielectric measurements," *IEEE Trans. Geosci. Remote Sensing.*, accepted for publication (Dec. 96).

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7. De Roo, R.D., R. Hartikka, N. Peplinski, and A, Zambetti, "Bistatic Measurement Facility User's Manual", The University of Michigan, Ann Arbor, MI", 031163-F, Aug. 1994.

8. De Roo, R.D., and F.T. Ulaby, "Bistatic Specular Scattering from Rough Dielectric Surfaces", *IEEE Trans. Antennas and Propagat.*, vol. 42, no. 2, pp. 220–231, Feb. 1994.

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10. Sarabandi, K., Y. Oh, and F.T. Ulaby, "A numerical simulation of scattering from inhomogeneous dielectric random surfaces," *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no.2, 425-432, March 1996.

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12. Oh, Y., and K. Sarabandi, "An improved numerical simulation of electromagnetic scattering from perfectly conducting random surfaces," *IEE Proceedings- Microwave, Antennas and Propagat.*, accepted for publication.

13. Stiles, J.M., K. Sarabandi, and F.T. Ulaby, "Microwave scattering model for grass blade structures," *IEEE Trans. Geosci. Remote Sensing*, vol. 31, no. 5, 1051-1059, Sept. 1993.

14. Stiles, J.M., and K. Sarabandi, "A scattering model for thin dielectric cylinders of arbitrary cross-section and electrical length," *IEEE Trans. Antennas Propagat.*, vol. 44, no.2,260-266, Feb. 1996.

15. Stiles, J.M., "A Coherent Microwave Scattering Model for Grassland Structures and Canopies" Ph.D. Dissertation, The University of Michigan, 1996.

16. Stiles, J.M., and K. Sarabandi, "Scattering from cultural grass canopies: a phase coherent model," *IEEE Trans. Geosci. Remote Sensing*, submitted for publication, (March 97).

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17. Stiles, J.M., K. Sarabandi, and F.T. Ulaby, "Scattering from cultural grass canopies: measured and modeled data," *IEEE Trans. Geosci. Remote Sensing*, submitted for publication, (March 97).

Conference Papers

18. Oh, Y., K. Sarabandi, and F.T. Ulaby, "An inversion algorithm for retrieving soil moisture and surface roughness from polarimetric radar observation," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Pasadena, California, Aug. 1994.

19. Oh, Y., K. Sarabandi, and F.T. Ulaby, "Development of a semi-empirical polarimetric scattering model for microwave radar observations from bare soil surfaces," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Firenze, Italy, July 1995.

20. Oh, Y., K. Sarabandi, and F.T. Ulaby, "An Empirical model for phase difference statistics of rough surfaces," presented at IGARSS'93, Tokyo, 1993.

21. Sarabandi, K., and T.C. Chiu, "A perturbation scattering solution for rough surfaces with nonuniform dielectric profile using volumetric integral equation," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Lincoln, Nebraska, May 1996.

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23. Sabet, K.F., and K. Sarabandi, "Analysis of scattering from curvilinear surfaces using wavelet concepts," *IEEE Antennas Propagat.& URSI Symp.*, Baltimore, Maryland, July 1996.

24. Zahn, D., K.F. Sabet, and K. Sarabandi, "Numerical simulation of scattering from rough surfaces: A wavelet-based approach," *Proc. IEEE Antennas Propagat. Symp.*, Montreal Canada, July 1997.

25. Stiles, J.M., and K. Sarabandi, "A rigorous analysis of the generalized Rayleigh-Gans approximation," *Proc. IEEE Antennas Propagat. Symp.*, Newport Beach CA, June 1995.

26. Stiles, J.M., and K. Sarabandi, "Estimation of soil moisture under short vegetation canopies," *Remote Sensing Science Workshop*, NASA Goddard Space Flight Center, Whashington D.C., Feb. 27- March 1, 1995.

27. Stiles, J.M., K. Sarabandi, and F.T. Ulaby, "Microwave Scattering Model for Grassland and short vegetation canopies," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Pasadena, California, Aug. 1994.

28. Chiu, T.C., K. Sarabandi, and F.T. Ulaby, "Polarimetric Backscattering Measurements of Herbaceous Vegetation : A Sensitivity Study for Soil Moisture Retrieval," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Lincoln, Nebraska, May 1996.

29. arabandi, K., and E.S. Li, "Characterization of soil moisture using a microstrip resonator," *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Pasadena, California, Aug. 1994.

30. Oh, Y., and K. Sarabandi, "An improved numerical simulation of electromagnetic scattering from perfectly conducting random surfaces," *Proc. IEEE Antennas Propagat. Symp.*, Seattle, June 1994.

31. Ulaby, F.T., L. Pierce, M.C. Dobson, S. Chacon, and K. Sarabandi, "Land cover calssification by SAR," Presented at IGARSS'94, Pasadena, California, Aug. 1994.

32. Oh, Y., K. Sarabandi, and F.T. Ulaby, "Scattering from a three-dimensional dielectric hump above an impedance surface," *Proc. IEEE Trans. Antennas Propagat. Symp.*, Ann Arbor, 1993.

33. Oh, Y., K. Sarabandi, F.T. Ulaby, "Re-examination of the Kirchhoff approximation for scattering from a rough surface," *Digest URSI Meeting*, Ann Arbor, 1993.

34. Sarabandi, K., Y. Oh, and F.T. Ulaby, "Scatterometer measurement of differential Mueller matrix of distributed targets," presented at IGARSS'92, Houston, May 1992.

35. Oh, Yisok, K. Sarabandi, and F.T. Ulaby, "Algorithm for measuring moisture and roughness of bare soil surfaces from multi-polarized radar observations," presented at IGARSS'92, Houston, May 1992.

36. Sarabandi, K., "Scattering from dielectric structures above impedance surfaces and resistive sheets," *Proc. of Progress in Electromag. Research Symp.*, Boston, July 1991.

37. Sarabandi, K., Y. Oh, and F.T. Ulaby, "Polarimetric radar measurements of bare soil surfaces at microwave frequencies", *Proc. IEEE Trans. Geosci. Remote Sensing Symp.*, Espoo, Finland, June 1991.

38. De Roo, R. D., F T. Ulaby, Y. Kuga, and M. C. Dobson, "Experimental Studies of the Microwave Backscattering by Well-Characterized Surfaces," *Digest Progress in Electromagnetic Research Symposium (PIERS '89)*, July 1989.

Appendix

Reprints of Journal Papers