IN-43-CR
71427
P_15

Basic Studies in Microwave Remote Sensing

by

Adrian K. Fung and Jonathan Bredow

Final Technical Report

January 23, 1992

Sponsored by NASA grant NAGW-1800

Basic Studies in Microwave Remote Sensing/Field Experiments

ABSTRACT

The purpose of this research is to develop scattering models in support of microwave remote sensing of earth terrains with particular emphasis on model applications to airborne SAR measurements of forest. Practically useful surface scattering models based on a solution of a pair of integral equations including multiple scattering effects have been developed. Comparisons of these models with controlled scattering measurements from statistically known random surfaces indicate that they are valid over a wide range of frequencies. Scattering models treating a forest environment as a two- and a three-layered media have also been developed. Extensive testing and comparisons have been carrried out with the two-layered model. Further studies with the three-layered model are being carried out. A volume scattering model valid for dense media such as a snow layer has also been developed that shows the appropriate trend dependence with the volume fraction of scatterers.

1.0 INTRODUCTION

Following is the report on work accomplished on NASA grant NAGW-1800. Studies have been carried out on the development of theoretical scattering and emission models for earth terrains, laboratory controlled measurements of scattering from irregular statistically known surfaces and ground truth gathering in support of field experiments in the Black Forest in Germany. Following sections summarize the studies completed in these areas.In Section 2 we report on modeling studies; Section 3 describes the controlled experiments performed and Section 4 gives a brief account of our participation in ground truth gathering in support of the field experiment in Freiberg, Germany.

2.0 MODELING STUDIES

Scattering and emission models have been developed over the last thirty years by various investigators for the purpose of assisting data interpretation and the design of experiments. Generally, three types of terrain scattering or emission models have been developed for application to remote sensing of the earth surface: scattering and emission models for (a) randomly rough surfaces, (b) forested areas and (c) snow covered areas. In what follows significant advances in scattering and emission models developed under NASA sponsorship are summarized.

2.1 Surface scattering models

In the past practical surface scattering models have been restricted to the high or low frequency regions or their combinations. More recently, a surface scattering model [Fung and Pan, 1987] based on an integral equation approach has been developed to account for the intermediate frequency region for perfectly conducting surfaces. The verification of such a model has been carried out by computer simulation for a variety of cases in *two* dimensions [Chen et al, 1989] (a sample comparison is given in Fig. 1). In this figure scattering curves according to the Kirchhoff model and the small perturbation model are also shown to provide a basis of reference. It is seen that the new model referred to as the Integral Equation Model (IEM) agrees with the small perturbation model in the low frequency region and approaches the Kirchhoff model in the high frequency region. In the intermediate region it agrees with the moment method simulation where both the Kirchhoff and the small perturbation model lose their validity.

In *three* dimensions verification of IEM has been carried out by comparing the theoretical model with measurements from statistically known perfectly conducting surfaces [Nance et al, 1990] (a sample comparison is given in Fig.2). Here, the illustration shows comparisons of backscattering coefficients at two different incidence angles over a range of frequencies which include the intermediate frequency region. It is seen that good agreements are obtained over the entire frequency range. In terms of the size of the model parameters normalized to the incident wave number this frequency range includes both low and high frequency regions.

The IEM model has also been extended to include scattering from dielectric surfaces [Li and Fung, 1989; Fung et al, 1991] and comparisons were made with field measurements reported by the University of Michigan (a sample comparison is given in Fig. 3). It is important to note that surface parameters have been acquired by the investigators at the University of Michigan and hence the comparisons shown for different polarizations, angles and frequencies *do not involve model parameter selection*! These comparisons that we have done indicate that the IEM is a practically useful surface scattering model (Chen et al, 1991).

An emission model for a randomly rough surface can be developed by integrating the bistatic scattering coefficient used in active scattering. Thus, an emission model depends on the total power content of the bistatic scattering coefficient rather than the power along a specific direction. Theoretically, once a the bistatic scattering coefficent model is developed for the active sensing problem the emission model follows from it. Recognizing this relationship we shall not dwell further on the corresponding emission problem.

Another extension of the surface scattering model is to account for rough surfaces that are skewed along some direction [Fung and Chen, 1991; Fung et al, 1991]. Wind-driven surfaces fall into this type but such surfaces are not commonly seen over land except in the desert region. This extension is achieved by considering rough surfaces with non-Gaussian surface height statistics and carrying the calculation to the third-order in surface statistics. The common practice in the past is to stop at the second-order statistics represented by the surface correlation function. It is well known that this function is centro-symmetric and hence cannot explain the difference between upwind and downwind observations. The third-order statistics are represented by the bispectrum of the surface which is not widely investigated and requires further study.

2.2 Scattering Models for Forested Area

The specific approach taken in forest model development is that we first model the scattering properties of each forest component and verify the component models using laboratory measurements [Karam et al, 1988; Karam and Fung, 1989]. After all of the component models are found satisfactory, we then integrate them to form a complete forest canopy model [Karam and Fung,1990; Karam et al, 1991]. To justify the forest canopy scattering and attenuation models, comparisons have been carried out with some published measurements of marginally well characterized forested areas [Mougin et al, 1990; Lopes et al, 1991]. This forest model is a discrete model based on the radiative transfer approach. In particular, it includes (i) canopy and trunk interactions with a rough ground surface, (ii) second-order calculations in cross polarized scattering, (iii) branches of different sizes, lengths and orientation distributions and (iv) a crown region with two layers: a layer of leaves and small stems and another layer of branches and leaves. When the trunk-layer is included, this model has three layers. Such a model has been shown to be able to generate a scattering coefficient quite different from existing two layer models [Karam et al, 1991] because the amount of attenuations on branches and leaves are different from the two-layer model when the same number of branches and leaves and their orientations distributions are assumed. In effect, it demonstrates that tree structure can be an important factor in forest modeling at some frequencies. Some sample comparisons of this model with measurements are given in Fig. 4 and 5. Agreements are obtained at both L and X bands for like and cross polarizations using the same forest parameters. These data sets have been compared with a two-layer model [McDonald et al, 1990; 1991] where it is shown that at X-band cross polarization cannot be matched. In addition, the forest parameters these investigators used for L band are different from those they used for X-band, although measurements are on the same orchard. The reason for the difference in the models performance is believed to be due to the effect of *forest structure* and the lack of *second-order* terms in MacDonald et al's model. Additional airborne experiments have been conducted over several test sites in Europe the past summer along with information about the forests. More detailed comparisons of models with measurements from better defined forest conditions will be possible in the near future. In conclusion, we believe that practically useful forest model is now available for applications.

2.3 Scattering Models for Snow-covered Areas

Snow is a medium densely populated with ice scatterers. In theoretical studies the word dense is generally used when the volume fraction of the scatterer within a host medium exceeds a few percent. For such media two-types of scattering models both based on the radiative transfer approach have been developed in the literature. Their assumptions, however, are completely different. One approach accounts for the dense nature of the medium by introducing a *correlation* function between the positions of the scatterers [Wen et al, 1990]. In this case the phase function used is formulated in terms of the far field so that scatterers interact in the far field. Another approach does not assume that there is correlation between scatterer positions. Instead, the phase function is calculated based on the complete electromagnetic field i.e. far field approximation is not made [Fung and Eom, 1985; Tjuatja et al, 1990]. Recently, this latter approach has been extended to allow scatterers of arbitrary size [Fung and Tjuatja, 1991]. At this point in time it is not clear whether one or the other or both of these mechanisms are important. The difficulty here is a lack of experimental evidence regarding the behavior of scattering from known dense media. Field experiments from snow indicate that the near field phase function is correct [Fung and Eom, 1985; Ulaby et al, 1986, Appendix E, p.2065] because the loss in snow should increase with the volume fraction. On the other hand, optical extinction experiments on scatterers floating in a fluid medium show that extinction should decrease with the volume fraction as predicted by the correlation model. To resolve this problem well designed experiments are recommended to determine the real mechanism behind the dense media scattering and extinction properties. For the problem of scattering from a snow or sea ice medium the complete-field phase function approach leads to results that are in good agreement with the experimental observations (see Fig. 6 in Fung and Eom, 1985). Hence, we can again state that there is a practically useful scattering model for the snow medium.

3.0 LABORATORY MEASUREMENTS

The purpose of this study is to acquire bistatic and backscattering data from statistically known randomly rough surfaces over a wide range of angles and frequencies. It has been shown in the previous section that such measurements are needed for scattering model verification. In addition, it is anticipated that these data will provide guidance to model development and design of field experiments.

Generation of statistically known surfaces

To physically produce a statistically known surface with a specified surface statistics consists of two major steps: (i) generate a surface with specified surface height statistics and a specified correlation function on a digital computer and (ii) use the bi-cubic spline method [Press et al, 1989] to obtain enough surface points if necessary and then feed the surface profile information to a computer numerically controlled (CNC) mill [Rochier et al, 1989]. While the milling machine can mill on many types of material such as aluminum, wood, rigid foam etc, we used rigid foam in this study. After the surface is milled, it is painted with silver paint to make it into a perfectly conducting surface.

More specifically, let the specified surface height distribution be

$$p(z) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{z^2}{2\sigma^2}\right], \qquad \text{(EQ 1)}$$

where σ is the standard deviation of surface heights and the specified correlation function be $r(j) = \exp[-(j/L)^2]$. First, we use a random number generator to generate a set of Gaussian deviates, x_j. Then, we apply a digital filtering technique [Fung and Chen, 1985] to obtain the discrete surface profile,

$$C_k = \sum_{j=-M}^{M} W_j x_{j+k} \qquad \text{(EQ 2)}$$

where $W_j = \sqrt{\frac{2}{L\sqrt{\pi}}} exp\left[-2\left(\frac{j}{L}\right)^2\right]$.

Usually, the CNC mills require more surface points than we generate. If so, we can apply the bi-cubic spline method to obtain more surface points. This approach is more efficient than a direct generation of the same number of points using digital filtering alone. In the past errors due to the size and shape of the cutter need be considered and taken out [Rochier et al, 1989]. Modern CNC mills have built in software to take care of this problem. Hence, only a set of discrete, sufficiently closely spaced points are needed. In general, the specifications of the CNC mill must be consulted since too close a spacing also causes the machine to stall.

Bistatic and Monostatic Measurements

Both bistatic and monostatic scattering measurements have been taken on statistically known surfaces under laboratory controlled conditions. The frequency range covered is 4 to 12 GHz over an angular range of 30 to 60 degrees from vertical and 30 to 180 degrees in azimuth. An illustration of backscattering measurements versus frequency is given in Figure 2 along with model predictions in the backscattering mode for two incidence angles, 30 and 60 degrees. Additional cases have been reported at the PIERS symposium in 1991[Nance Fung and Bredow, 1990].

4.0 FIELD MEASUREMENTS

In a collaborative effort with the Joint Research Center (JRC) of Italy, extensive ground-truth data was collected over the Black Forest area of Freiburg, Germany in preparation for the first overflight of the NASA/JPL DC-8 AIRSAR system. The campaign is known as the MAC Europe experiment. Two flights took place during the summer of 1991, one on June 15, and the other on July 20. During these two periods, a team of national and international scientists were involved in the collection of the ground truth data. Measurements important to our research were carried out. These include the measurement of the complex dielectric constant of soil, trunks, branches, and leaves and the angular distribution of branches and leaves, and trunk heights. Additional measurements included volumetric water content of soil, leaf area index via fish eye photographs, standard black and white photographs and videotapes of trees from which important statistical parameters can be extracted, and water potential measurements. Corner reflectors measuring 0.9 metres and 1.8 metres were deployed for calibration of the SAR images at P- (0.43 GHz), L-(1.24 GHz), and C-bands (5.28 GHz). In addition to this recent ground truth data, previous data from the same forest area, collected during the MAESTRO 1 experiment in 1989, are currently being used to test and validate a three-layer forest canopy model developed at the University of Texas at Arlington.

The field measurements are needed for the validation of the theoretical models. To do so, the ground truth data are transformed into electromagnetic parameters, which in turn are used as input parameters to the two-layer and three-layer canopy scattering models. The quality of the ground truth is, therefore, of utmost importance. The validation of the models is carried out by comparing the theoretically computed results to the actual polarimetric data collected by the AIRSAR system over the same period of time as when ground truth data were collected. Before this comparison can take place, the reduction and analysis of the AIRSAR data are performed using computer tools such as POLCAL provided by NASA/

JPL and CALTOOL and POLTOOL provided by JRC. POLCAL and POLTOOL synthesize the data to any desired transmit/receive polarization configuration. POLCAL and CALTOOL are then used to perform phase, channel cross-talk, and absolute calibrations on the synthesized image. The resulting image is a representation of the backscattering coefficient of the entire site for the given choice of polarization.

Once the models are thoroughly verified, they can be used to generate data at frequencies and angles in addition to those collected by the AIRSAR system. These expanded data are needed for example to train neural networks for the retrieval of important forest components such as soil moisture content, soil temperature profile, water content in the trunks, branches and leaves, and biomass. The accuracy of these retrieved geophysical parameters will be compared to the ground truth already at hand.

5.0 Bibliography

Chen, M.F. and A.K.Fung, "A numerical study of the regions of validity of the Kirchhoff and small perturbation rough surface models" Radio Science, vol.23, no.2, pp.163-170, March 1988

Chen, K.S. and A.K.Fung, A scattering mode for ocean surface, IGARSS '91, Helsinki University of Technology, Espoo, Finland., June 3 - 6, pp. 1251-1254, 1991

Chen, M.F., Chen, K. S. and A.K. Fung," A study of the validity of the integral equation model by moment method simulation" Remote Sensing of Environment vol.29, pp.217-228, 1989

Chen, K. S., Fung, A.K., Sarabandi, K. and F.T. Ulaby, Backscattering from a randomly rough dielectric surface, Part II Results and Applications, IEEE Geoscience and Remote Sensing, (submitted) 1991

Chen, M. S. and M. Manry, Back-propagation representation theorem using power series, International Joint Conf. on Neural Net, IJCNN'90, Vol.I, pp.643-648, San Diego, California, June 17-21, 1990.

Chen, M.S. and M.T. Manry, Basis vector analyses of back-propagation neural networks, Proceedings of the 34th Midwest Symposium on Circuits and Systems, Monterey, California, May 14-17 1991a.

Chen, M.S. and M.T. Manry, Power series analyses of back-propagation neural networks, Proc. of IJCNN 91, Seattle WA., pp. I-295 to I-300, 1991b.

Forsythe, G.E., Malcolm, M.A., and C.B. Moler, Computer Methods for Mathematical Computations, Prentice-Hall, 1977.

Fung, A.K. Li, Z. and K.S. Chen, Backscattering from a randomly rough dielectric surface, Part I Theory, IEEE Geoscience and Remote Sensing, (submitted) 1991

Fung, A.K. and M.F. Chen, "Numerical simulation of scattering from simple and composite random surfaces", J. Optical Society of America, Vol. 2, No. 12, pp. 2274 - 2284, December 1985

Fung,A.K. and K.S. Chen, "Kirchhoff model for a skewed random surface" JEWA, vol. 5, no. 2, 205-216, 1991

Fung, A.K. and H.J. Eom, "A study of backscattering and emission from closely packed inhomogeneous media" IEEE Trans. GRS, vol. 23, no. 5, pp.761-767, 1985

Fung, A.K. and G.W. Pan, "A scattering model for perfectly conducting random surfaces: part 1. Model development" International J. of Remote Sensing vol.8, no. 11, PP.1579-1593, 1987

Fung, A.K., and S. Tjuatja, Snow parameter effects in scattering and emission, IGARSS '91, Helsinki University of Technology, Espoo, Finland., June 3 - 6, pp. 2319-2322, 1991

Karam, M., A.K. Fung, and M. Antar, "Electromagnetic wave scattering from some vegetation samples", IEEE Trans.Geoscience and Remote Sensing vol.26,no.6, pp.799-808, 1988

Karam,M.A. and A.K. Fung, "Leaf-shape effects in electromagnetic scattering from vegetation" IEEE Trans.Geoscience and Remote Sensing, vol.27, no. 6, pp. 687-697, 1989

Karam, M., and A.K.Fung," A canopy scattering model and its applications to a deciduous forest," Proceedings of the IGARSS '90, vol.1,pp.137-140,Univerisity of Maryland, May, 1990

Karam, M.A. Fung, A.K. Lopes, A. and E. Mougin, A fully polarimetric scattering model for a coniferous forest, IGARSS '91, Helsinki University of Technology, Espoo, Finland., June 3 - 6, pp. 19-22, 1991

Li, Z. and A.K. Fung, Scattering from a randomly rough dielectric surface, PIERS,1989

Lopes,A., Mougin,E., LeToan,T., Karam, M. and A.K.Fung, "A Simulation study on the influence of leaf orientation on elliptically polarized microwave propagation in a coniferous forest", JEWA, vol.5, no.7, pp. 753-776, 1991

McDonald, K.C. Dobson, M.C. and F.T. Ulaby, "Using MIMICS to model L-Band Multiangle and multitemporal backscatter from a walnut orchard." IEEE Trans. GRS, vol. 28, no. 4, pp. 477-491, 1990

McDonald, K.C. Dobson, M.C. and F.T. Ulaby, "Modeling Multifrequency diurnal backscatter from a walnut orchard." Proc.of International IEEE GRSS,(IGARSS'91) pp. 1125-1128, 1991

Mougin,E,Lopes,A,Karam,M.,and A.K. Fung, "Modeling the microwave polarimetric transmission through forest canopies", Proceedings of the IGARSS '90, vol.3,p.2211-2214,University of Maryland, College Park, Md., May 20 - 24, 1990

Nance, E., Fung, A.K. and J. Bredow, "Comparison of integral equation predictions and experimental backscatter measurements from random conducting rough surfaces" IGARSS '90, University of Maryland, College Park, Md., May 20 - 24, pp. 477-480, 1990

Press, W.H., Flannery, B.P., Teukolsky and W.T. Vetterling, Numerical Recipes, Cambridge University Press, p. 100, 1989

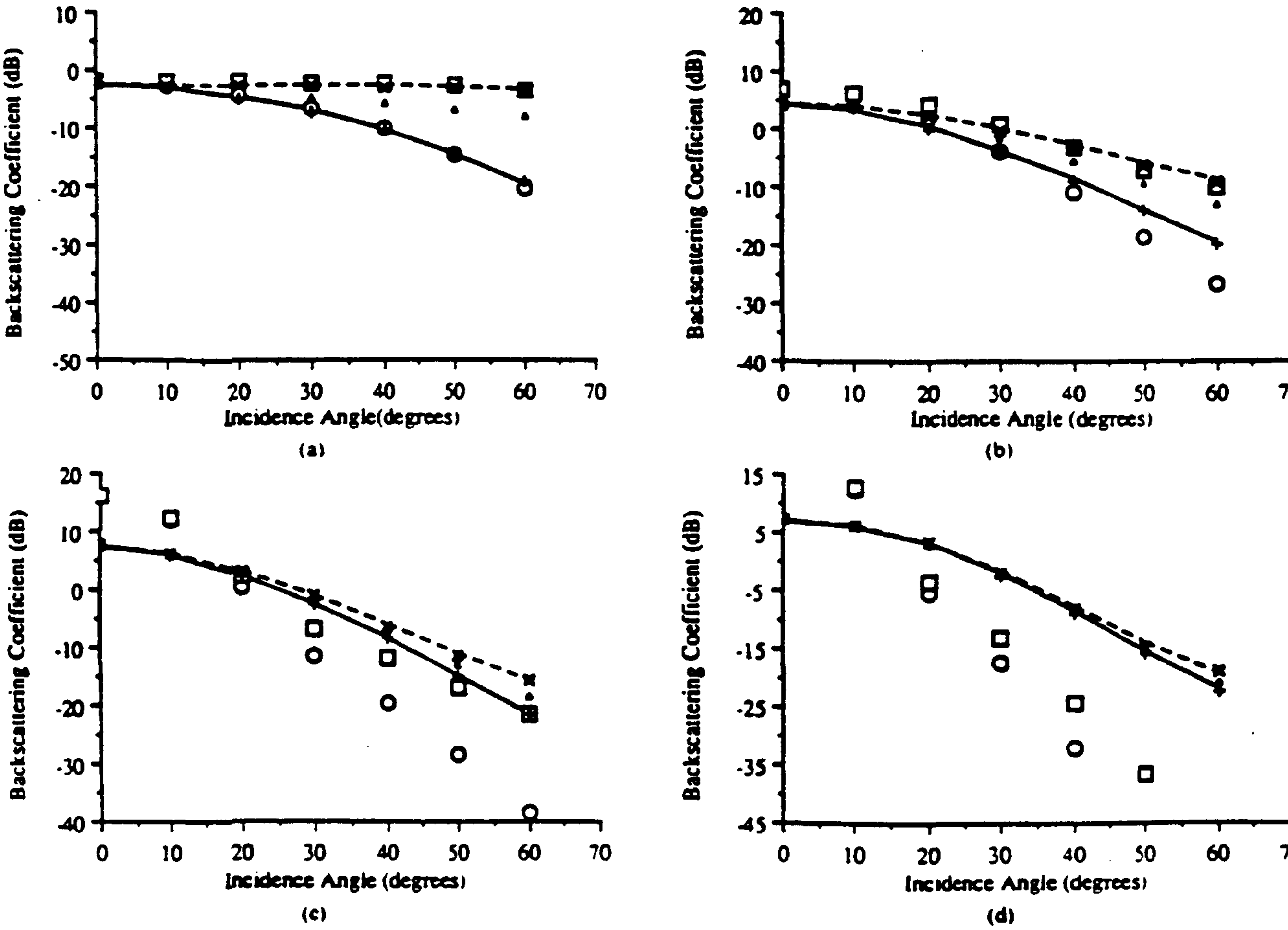
J.D.Rochier, A.J. Blanchard and M.F. Chen, The generation of surface targets with specified surface statistics, Int. J. Remote Sensing, vol. 10, no. 7, pp. 1155-1174, 1989

Tjuatja, S., Fung, A.K., and J.Bredow, "Comparisons between a dense medium scattering model and sea ice measurements", IGARSS '90, University of Maryland, College Park, Md., May 20 - 24, 1990

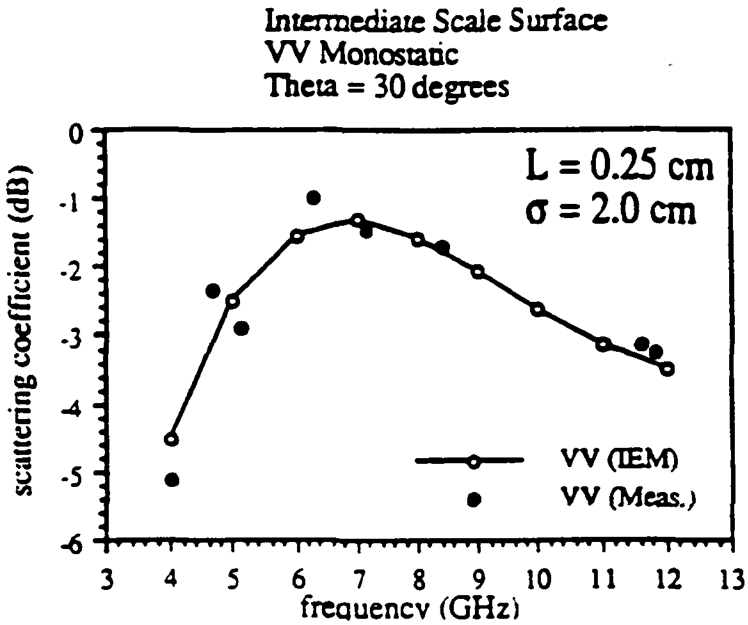
Tsang,L.,Chen,Z.,Oh S., R.J.Marks and A.T.C. Chang, Inversion of snow parameters from passive microwave remote sensing measurements by a neural network trained with a multiple scattering model, IGARSS,91pp. 1965-1967

Ulaby, F.T., Moore, R.K. and A.K. Fung, Microwave Remote Sensing, vol. 3, Artech House, 1986

Wen,B.,Tsang,L.,Winebrenner,D.P. and A. Ishimaru, Dense medium radiative transfer theory: comparison with experiment and application to microwave remote sensing and polarimetry, IEEE Trans. GRS vol. 28, no. 1, pp. 46-59, 1990



Backscattering Coefficient (dB)
Incidence Angle(degrees)
(a)
Backscattering Coefficient (dB)
Incidence Angle (degrees)
(b)
Backscattering Coefficient (dB)
Incidence Angle (degrees)
(c)
Backscattering Coefficient (dB)
Incidence Angle (degrees)
(d)



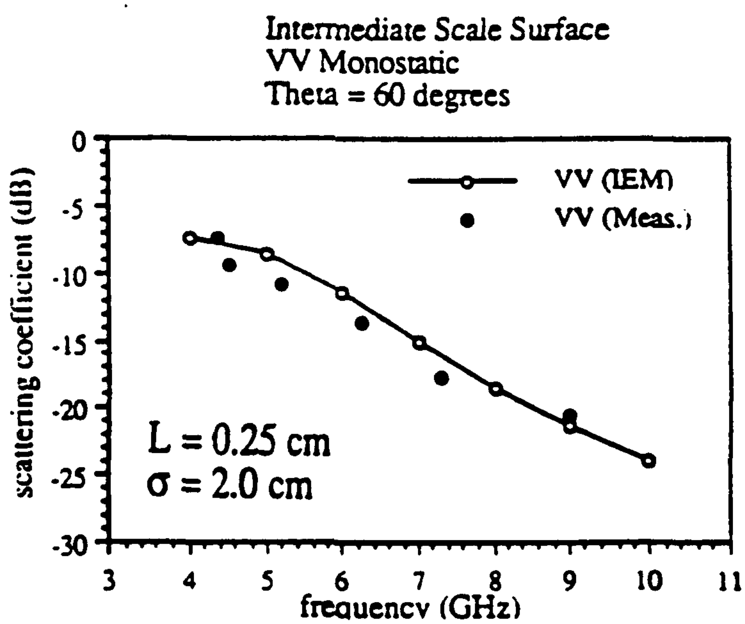


Figure 2. Comparisons of the IEM model with measurements on statistically known surface.

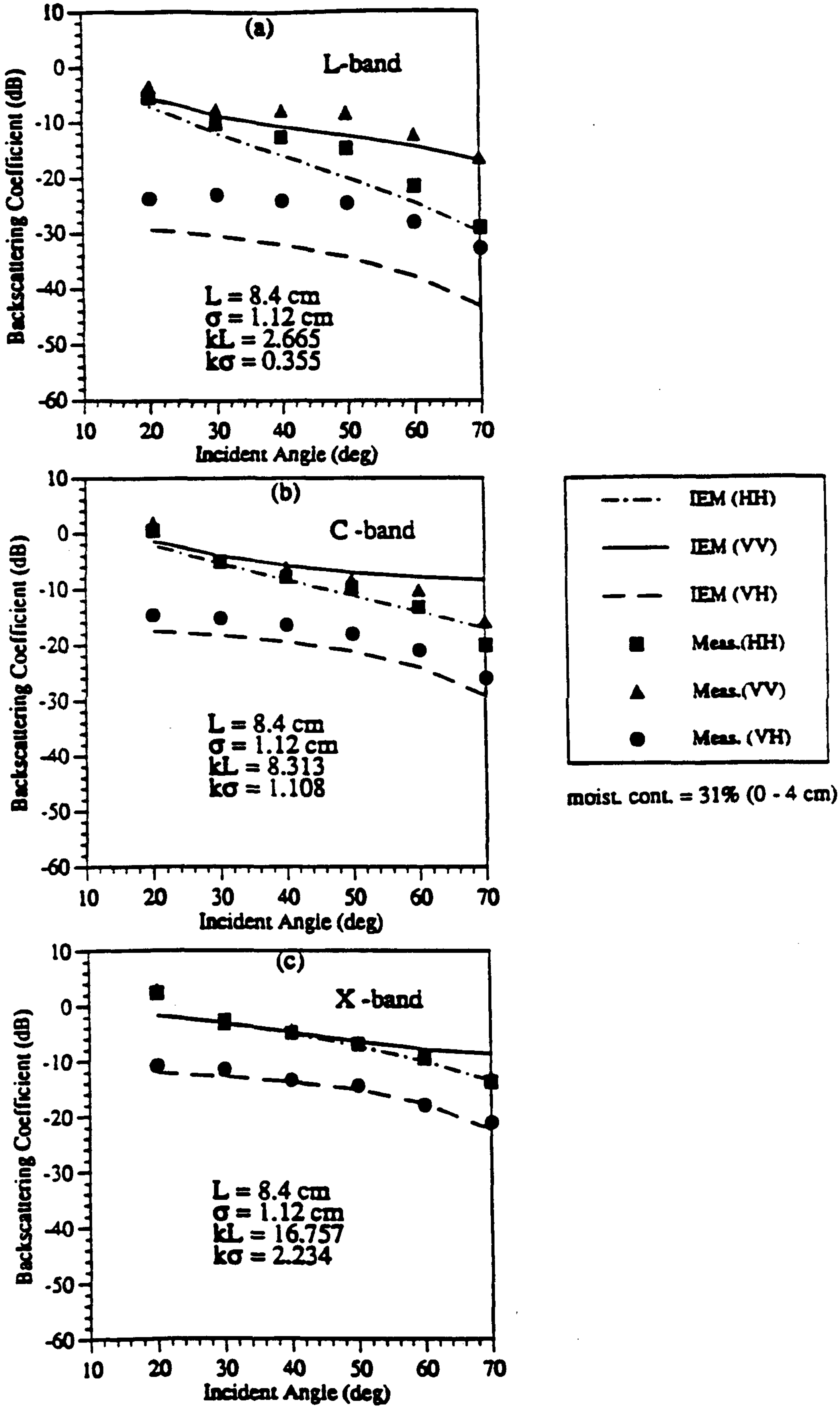
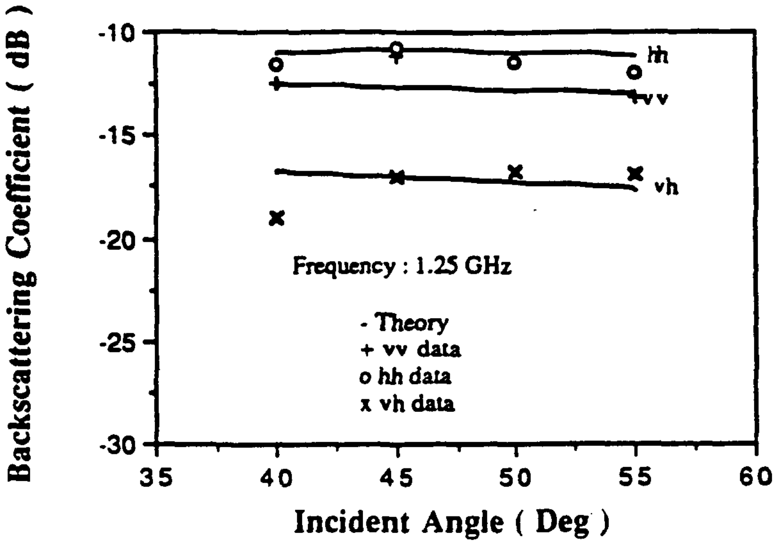


Figure 3. Comparisons of IEM with scattering from a known soil surface.



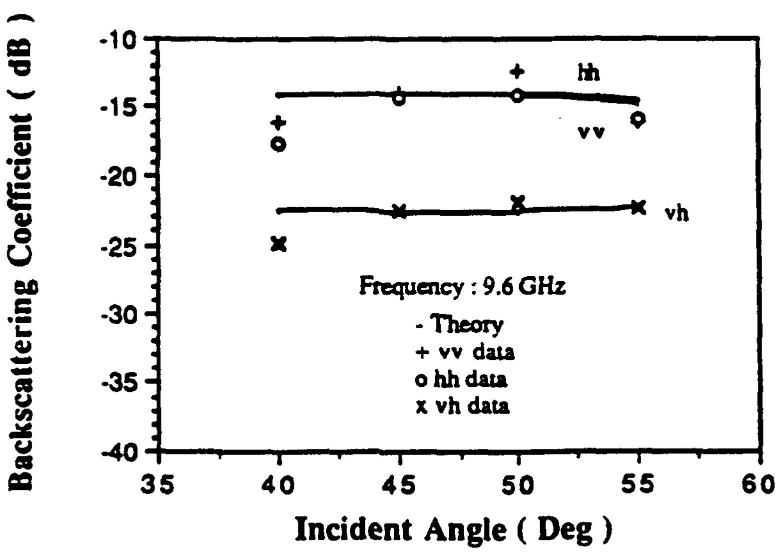
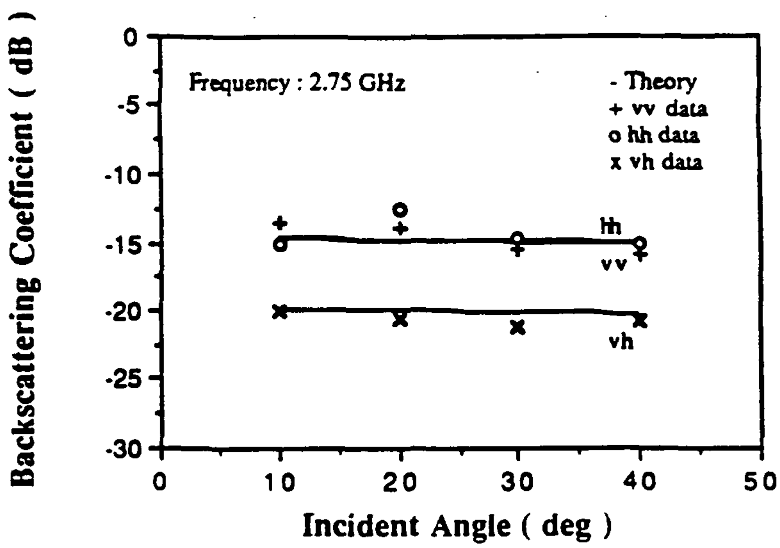


Fig. 4 Comparison between theory and measurements from a walnut canopy at L- and X- bands for like and cross polarizations



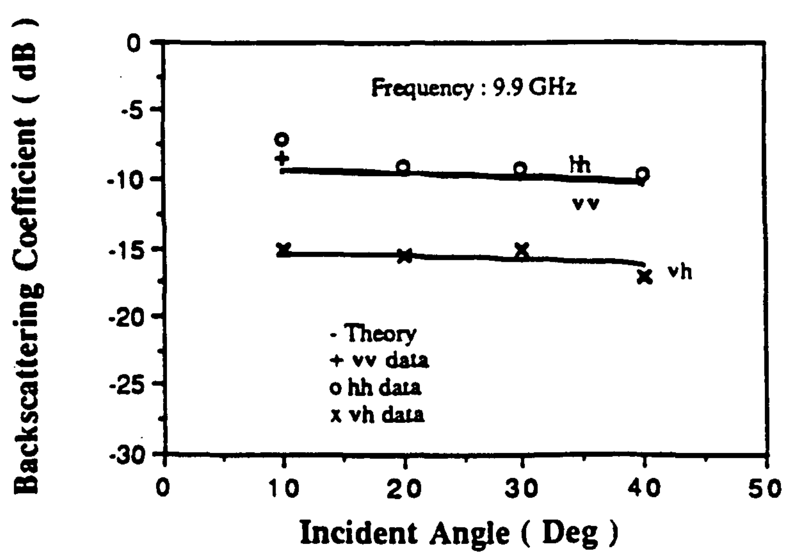


Fig. 5 Comparison between theory and measurements from cypress trees at S- and X- bands for like and cross polarizations.

MATRIX CONVERTERS

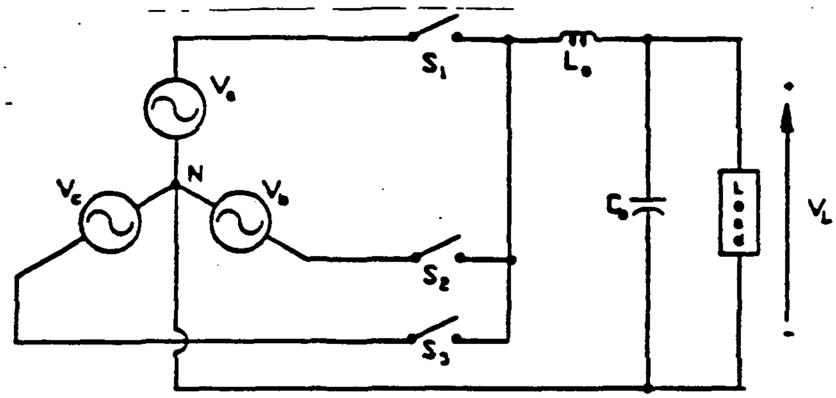


Fig. 1

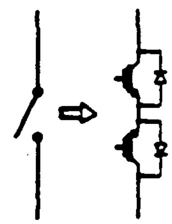
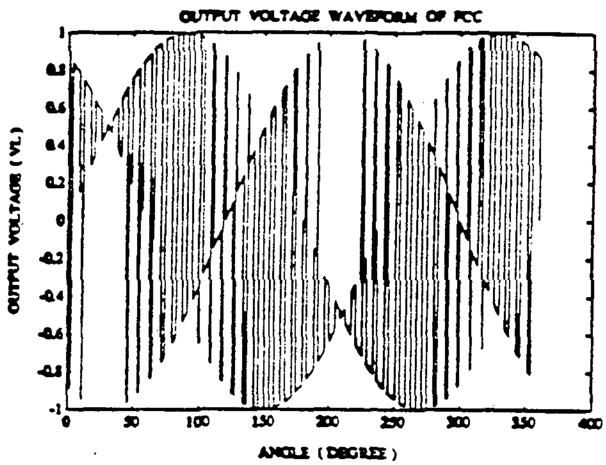
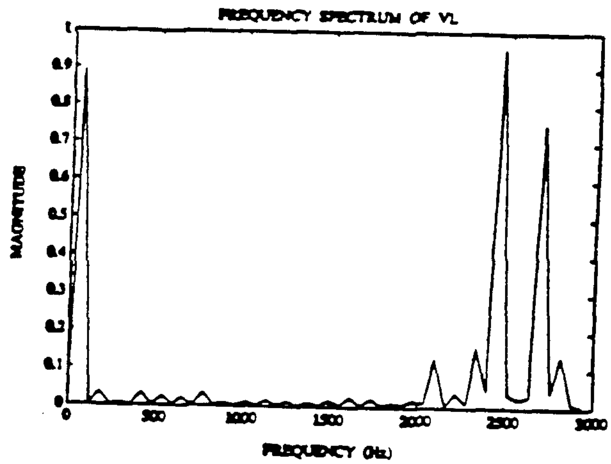


Fig. 1.a





- *High quality output voltage*
- *Output voltage and frequency are continuously adjustable*
- *Zero voltage switching is possible*