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Final Report

DISCRETE RANDOM MEDIA TECHNIQUES FOR MICROWAVE MODELING OF VEGETATED TERRAIN

by

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ABSTRACT

The research work described in the final report has been done for NASA under Grant NAG-5-265 during the period August 1982 to May 1990. The purpose of the grant was to investigate microwave remote sensing models of vegetated terrain. The basic problem is to determine canopy characteristics such as biomass, canopy height and the moisture of the underlying soil. The report describes a discrete scatter model which has been employed to model backscatter in the active (radar) case and to model brightness temperature in the passive (radiometric) case. The acquisition of ground truth data is discussed, as well as the comparison of theory and experiment. The overall conclusion of the work has been that the discrete scatter model in conjunction with efficient scatter algorithms and the distorted Born approximation is a most appropriate methodology to use for modeling purposes in the microwave region.

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I. INTRODUCTION

The observation of the earth's terrain from space can provide valuable information about the terrain's vegetation cover and underlying soil characteristics. Active and passive sensors, such as radars and radiometers, receive radiation from vegetation subelements. These signals can be used to infer properties of the vegetation and the ground lying below it. To utilize this information, the received radiation must be directly related to the vegetation canopy structure. The discrete scatterer methodology provides a modeling technique which supplies the necessary relationship in the microwave frequency regime. When employing this modeling method, vegetation subelements are replaced by discrete lossy dielectric scatterers with prescribed orientation statistics. Analysis of this model yields the desired connection between backscattered signals and the vegetation biophysical parameters.

The goal of the modeling effort is to remotely sense vegetation type, to determine crop growth stage and to find plant and ground moisture levels. This information can then be used as input data for agricultural, forestry and global circulation models. Although optical and infrared measurement methods yield valuable remote sensing information, microwave sensing in the L and C band region of the frequency spectrum is particularly desirable for the determination of canopy architectural characteristics. It is here that the wavelength is comparable to the canopy subelement sizes. The resulting resonant interaction leads to backscattered data which are highly dependent on plant shape and orientation.

The work under this grant is described in the following section, Section II. Section II has five subsections which discuss the individual projects that were performed. In subsection A the discrete modeling of a soybean canopy is described. Leaves and stems are replaced by lossy dielectric discs and rods.The distorted Born approximation is then employed to compute the backscattering coefficients. Finally, the forward model just discussed is used as the basis for an inversion procedure to find the leaf inclination angle distribution from the backscattering coefficient variation as a function of angle. In section B more careful ground truth measurements of soybean plants are considered. As a result of these measurements, the model used in A is generalized to include variations in leaf shape (leaves modeled as elliptical discs) leaf area and non-uniform azimuthal angular leaf distribution.

In the following two subsections the application of the discrete theory the passive problem is discussed. The Peak relationship is used to derive brightness temperature from the knowledge of the bistatic scattering coefficient and the physical temperature of the terrain. Comparison of the theory with experimental results is also considered. In subsection D an efficient method for computing cross sections is presented. This is particularly useful for the passive problem. There average values of cross sections are needed over the complete scattering hemisphere.

A high frequency model for a leaf canopy is described in subsection E. At high frequencies the main difficulty is computing the average cross sections since the scattering patterns vary so rapidly. To avoid this problem the average integral are asymptotically evaluated. Application of these asymptotic cross sections to the distorted Born or transport calculations of backscattering coefficient is made.

Finally, in Section III a list of publications and papers which have been presented at meetings is given.

II. REVIEW OF GRANT PROGRESS

This section represents the main body of the report where progress in active and passive modeling of terrain covered by vegetation is discussed. As described above, the section is subdivided in topic areas A-F.

A. SOYBEAN CANOPY MODELING AND INVERSION

Simple plant canopies such as soybeans can be modeled by replacing the plant's leaves and stems by dielectric disks and rods respectively as is shown in Fig. 1. The relative dielectric constant used for the discs and rods is the equivalent dielectric constant of the plant material. The use of this equivalent dielectric neglects scattering effects caused by internal variations within the plant. This is small however, because of the long wavelength involved.

Scattering amplitudes have been computed for both the disc and stem elements. The resulting formulas for the scattering amplitudes are particularly simple because they take advantage of the small ratio of thickness to radius in the case of the discs and radius to length in the case of the rods. The simple formulation is particularly important since the results must be averaged over both inclination and size distributions.

Backscattering from the modeled plant canopy has been treated by two techniques: the distorted Born approximation and the transport theory. The two methods are equivalent when the albedo of the scatterers is small and no coherent (planar) boundaries are present. It has been shown for the case of a flat ground that the transport theory neglects certain coherent interference terms which are taken into account by the distorted Born approximation. It should be noted that this effect is a low frequency (L-band) phenomenon because at higher frequencies the surface appears rougher, and as a result, coherence effects disappear. Since the distorted Born method is applicable in the L-band frequency regime, since it contains the interference terms and since it is relatively simple in formulation as compared to vector transport theory, it has been used almost exclusively, to calculate the backscattering coefficients.

Application of the distorted Born theory to the modeling of crops such as soybeans has yielded interesting results. Fig. 2 shows some of these results

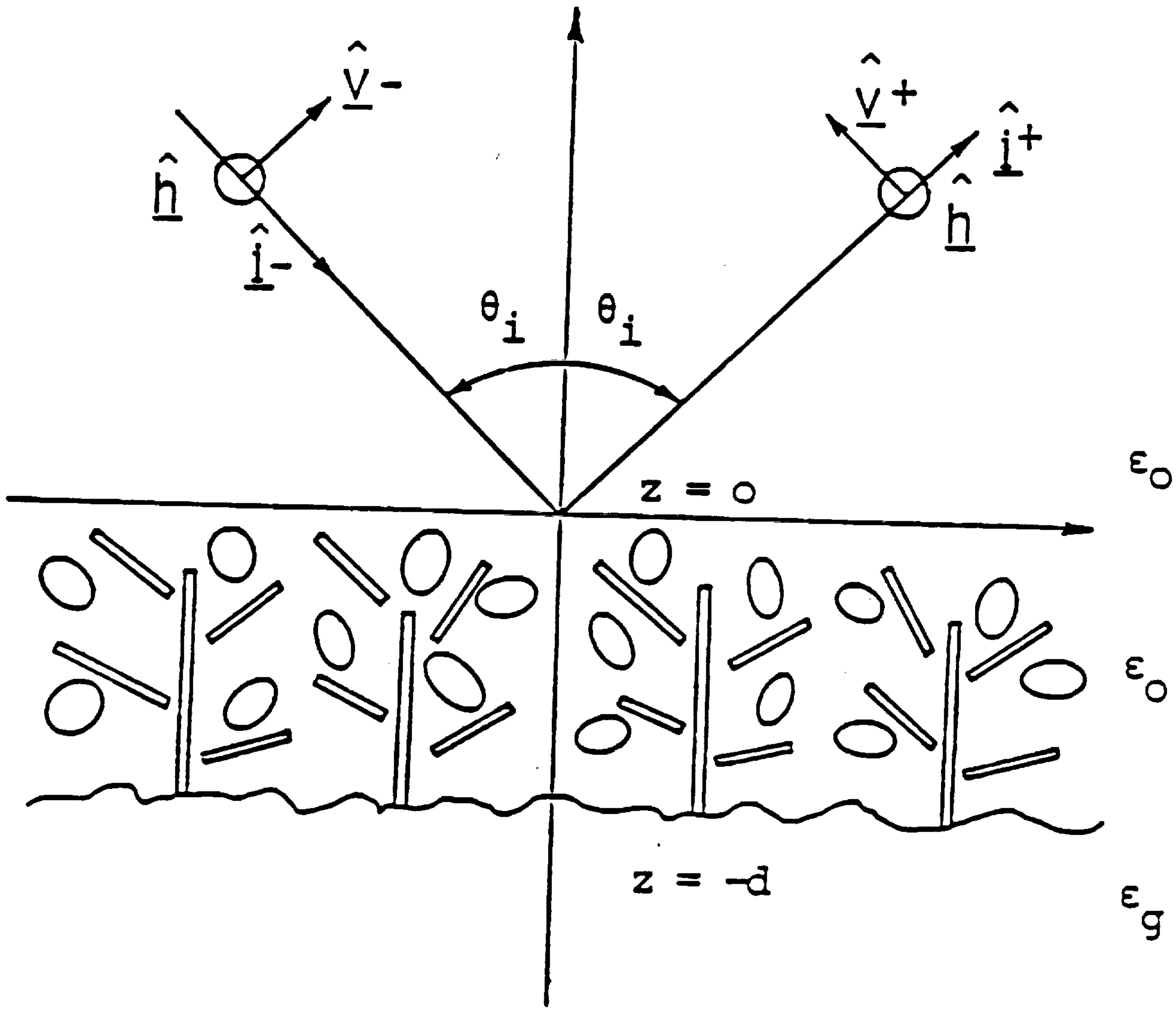

Fig. 1. Vegetation Layer Modeled by Leaves and Stems

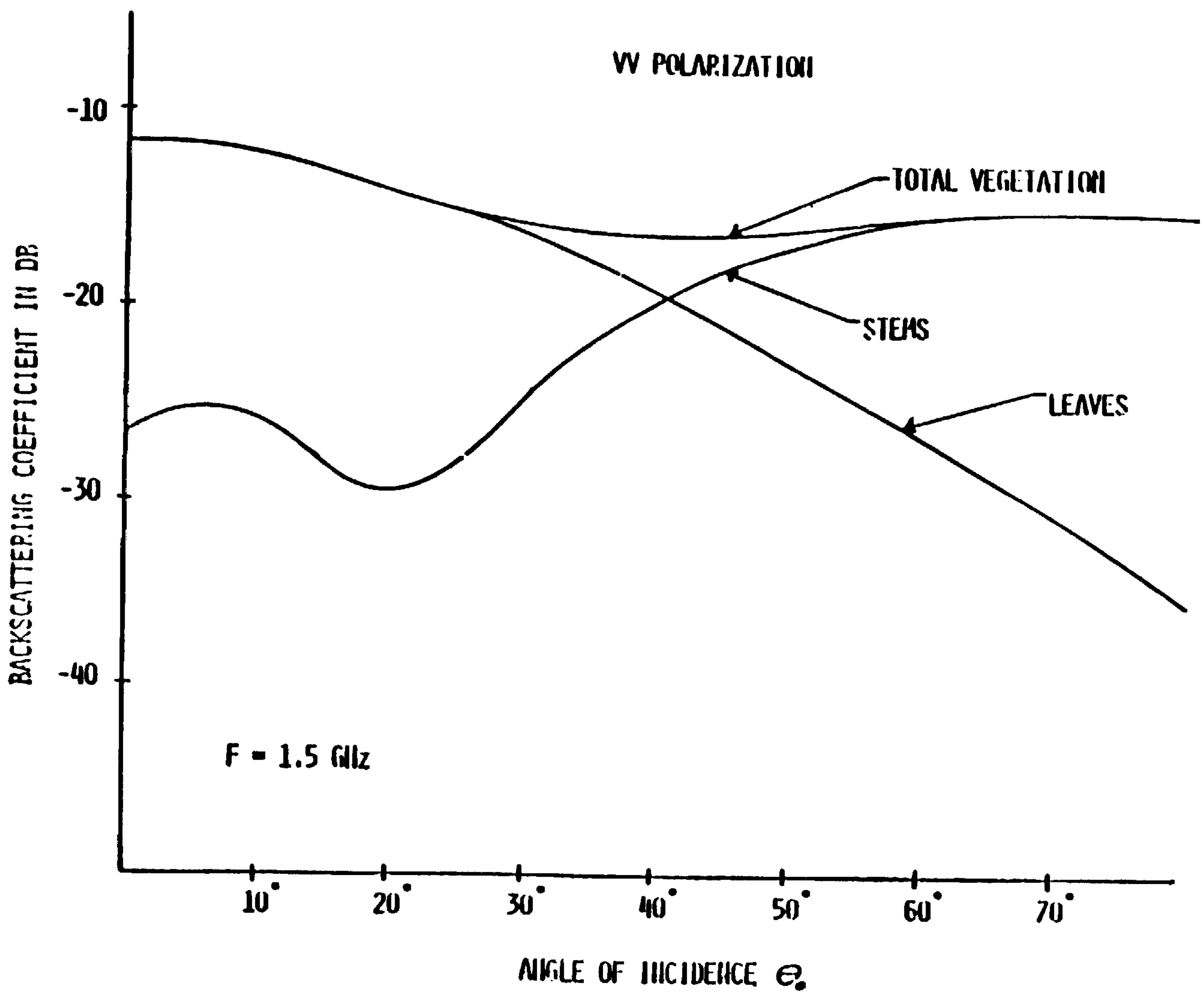

Fig. 2. Backscattering Coefficient versus Angle of Incidence for Mature Soybean Model

for a frequency of 1.5 GHz. The figure is a plot of σ^0_{vv} versus angle of incidence. An examination of the figure shows that for vertical-like polarized returns the leaves are dominant at low angles and the stems are most important at large angles of incidence. This is not surprising since the electric field is aligned with most stems at large angles of incidence.

The model whose results are shown in Fig. 2 consists of leaves having radii of 2.5, 3.5 and 5.0 cm. Each of these leaf types has a density of $333/m^2$. The stems are all taken to be 20 cm long and with a density of $1000/m^3$. The leaf and stem size characteristics were obtained by the principal investigator who made on-site measurements at Beltsville.

Although Fig. 2 just shows the vertical-vertical backscattering coefficient, simple expressions were obtained for the horizontal-horizontal case as well as the cross polarized returns. These appear to be valid for frequencies below 4 GHz as long as the correct dielectric constants for the discs and rods are used. The de-Loor formula has been used for the calculation of disc and stem dielectric constants however, at lower frequency ($\approx$ 1-2 GHz) a conductive contribution should be included.

The final step in any remote sensing problem is the inversion process. Attention has been focused on the relationship between the backscattering coefficient σ^2_{hh} and the joint probability density of disc radii and inclination angles. The expression derived by the distorted Born approximation has been used. An examination shows that it is nonlinear in nature. The relationship has been linearized in the 1-2 GHz region where the skin depth is large. The linearized expression (a Born approximation) is a Fredholm integral equation of the first kind. Inversion problems of this type are usually ill-conditioned and must be regularized.

To simplify the inversion procedure further, it has been assumed that the radii and inclination angle densities are independent. If it is assumed that the density of one variable is known, then the other can be found through the integral equation with the knowledge of the backscattering coefficient for various angles of incidence. Such an inversion is shown in Fig. 3. Here the leaves have fixed radius of 4 cm. The inclination angles density is shown by the solid line in Fig. 3. The combined joint density is then used to generate σ^0_{hh} for various angles of incidence. The calculated values of the backscattering coefficient are corrupted by noise and a Phillips-Twomey inversion algorithm is used to compute the inclination angle density at certain discrete points. The results, which are quite good, are shown by small circles, squares and stars in Fig. 3.

B. SOYBEAN GROUND TRUTH

The work on this portion of the grant has focused on understanding plant architecture and related model development. Ground truth data for a soybean canopy has been obtained. Results of the analysis of this data have been used to test existing modeling methodology to determine if it was adequate. To perform this test, the existing circular disc model has been generalized to account for elliptic discs. In addition, the more general problem of scatterers have a non-uniform azimuth distribution has been completed.

The ground truth data for soybeans was obtained in early August, 1985 at the Agricultural Research Center in Beltsville, Maryland. There soybean leaf and stem parameters were measured at three individual places in the same plot At two locations leaf height, orientation (inclination and azimuth) and thickness were measured. Individual leaf shapes were drawn on graph paper Stem and stalk lengths and thicknesses were recorded.

The soybean ground truth data was subsequently analyzed. Histograms have been computed for leaf height, area, inclination, angle, azimuth angle. In addition, leaf densities for leaf length and width were constructed so that parameters for elliptical leaves could be derived. As a representative example, the soybean leaf area density is shown in Figure 4. The area data

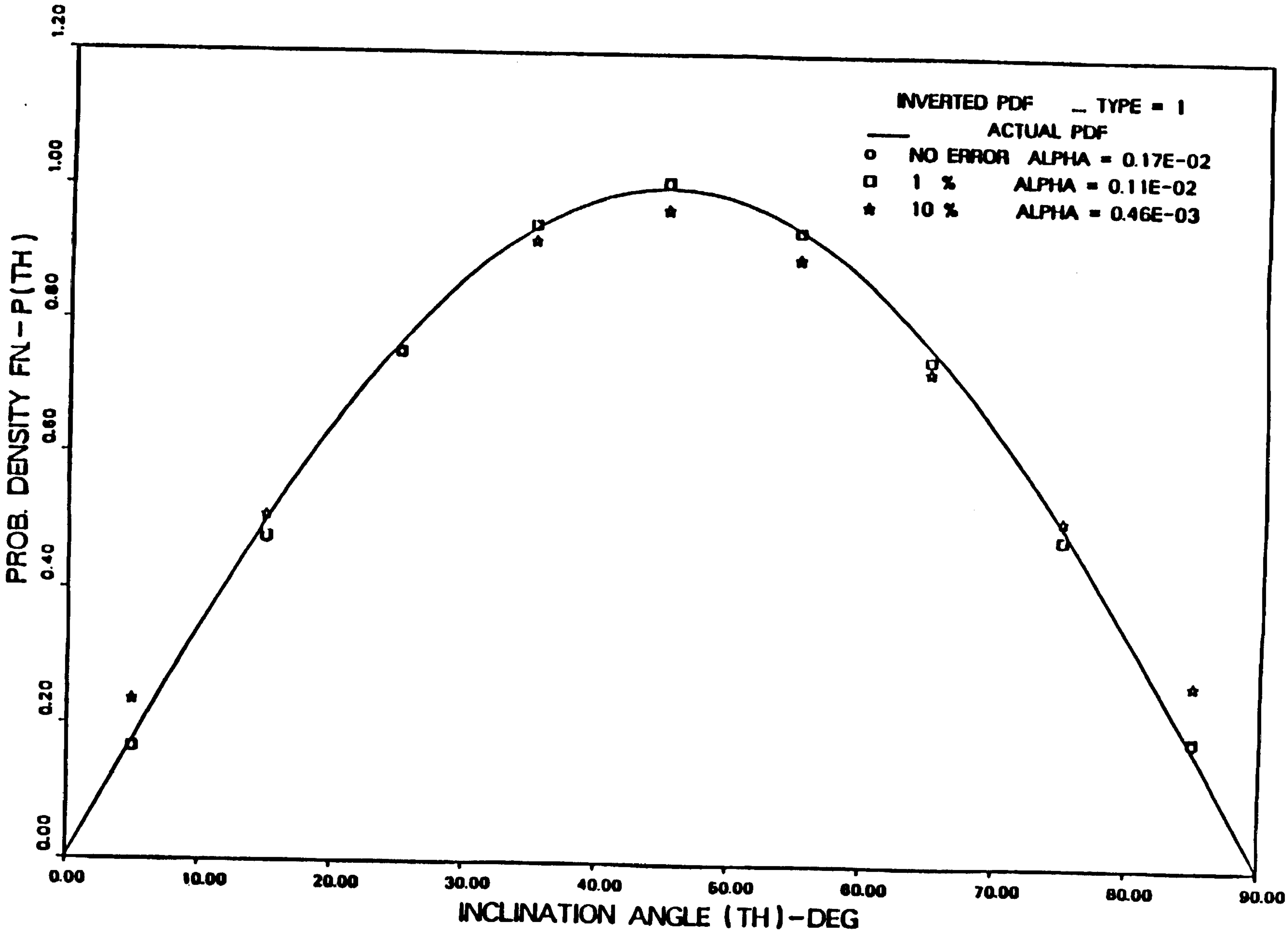

Fig. 3. Probability Density Inversion versus Leaf Inclination Angle.

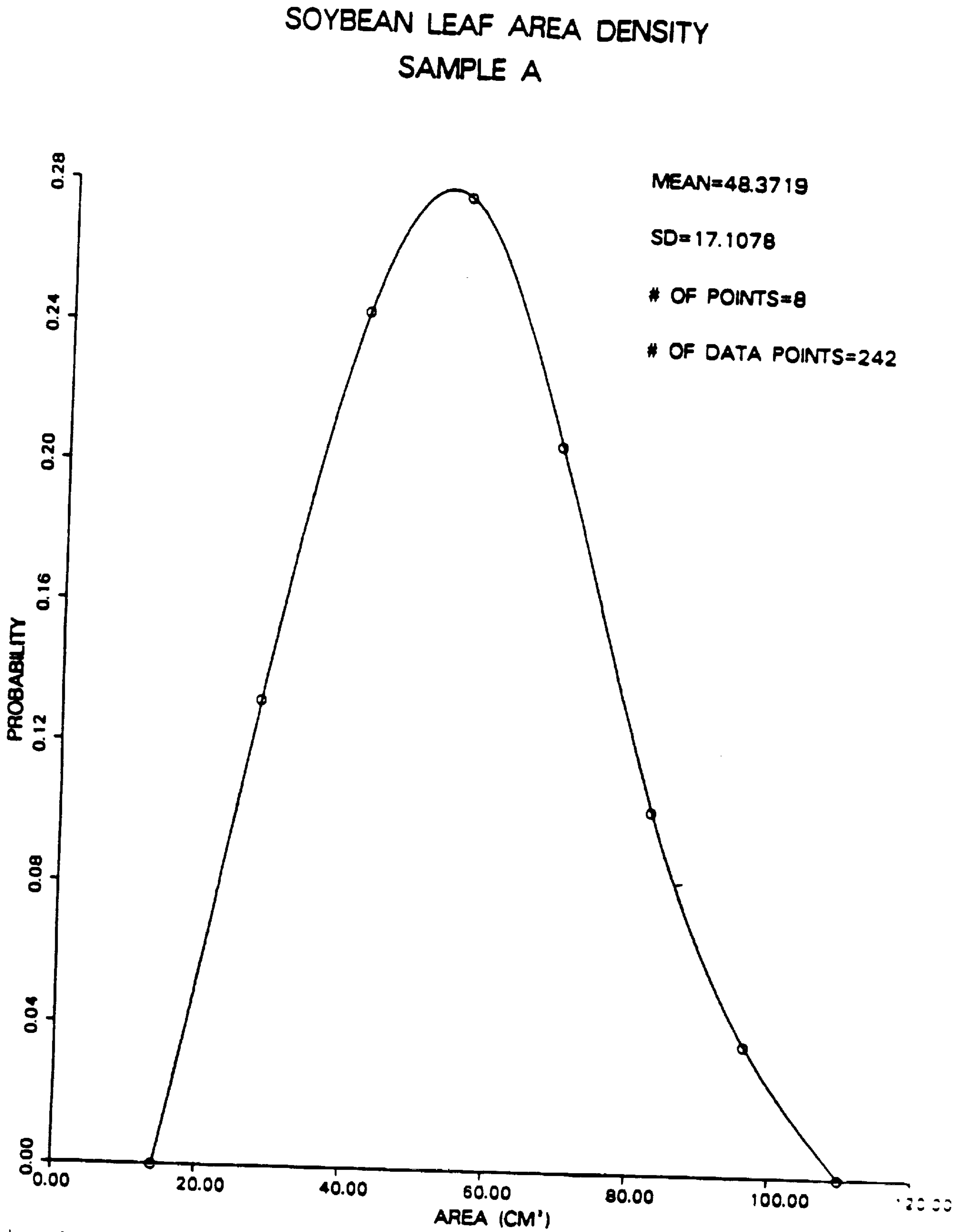

Figure 4. Soybean Leaf Area Density Measured at Beltsville, MD, August, 1985.

was measured from the graph paper tracing of the leaves. A total of 242 leaves were measured and a histogram with 8 equally spaced bins was employed. The results of the histogram were then curve fitted by a cubic spline.

The length and width measurements of the leaves verified the obvious fact that soybeans do not have circular leaves. To test the effect of the non-circularity on the backscattering coefficients, the backscatterer from a layer of elliptical discs was computed. The results show that the non-circular shape of the leaf has little effect at 1 GHz for all polarizations. At 3 GHz the results are different. Although the shape does not affect the like polarized waves, the cross polarized returns are shape dependent as is shown in Figure 5. This is not surprising since it is usually the cross polarized signals that respond to changes in shape.

Preliminary analysis of the data has shown that the soybean leaves are not, in general, uniformly distributed in the azimuthal coordinate. This is because the leaves tend to point out into the space between the rows. To treat this case the discrete scatter model was analyzed for the nonuniform azimuthal case. The analysis is complicated by the coupling of H and V polarizations at the level of the mean. A compact expression for the backscattering coefficients was obtained, however, by employing matrices and Kronecker products.

The results of computation for this generalized model show little effect for like polarized waves but a strong effect on cross polarized returns. In addition to these results, the reflected mean field shows a symmetric distribution is represented by A=0 while the asymmetric case has A=1. The dip in the horizontal reflected field is due to the coupling of horizontal and vertical components in the medium.

C. BRIGHTNESS TEMPERATURE OF CANOPY (BT)

The discrete scattering method has been applied to the calculation of

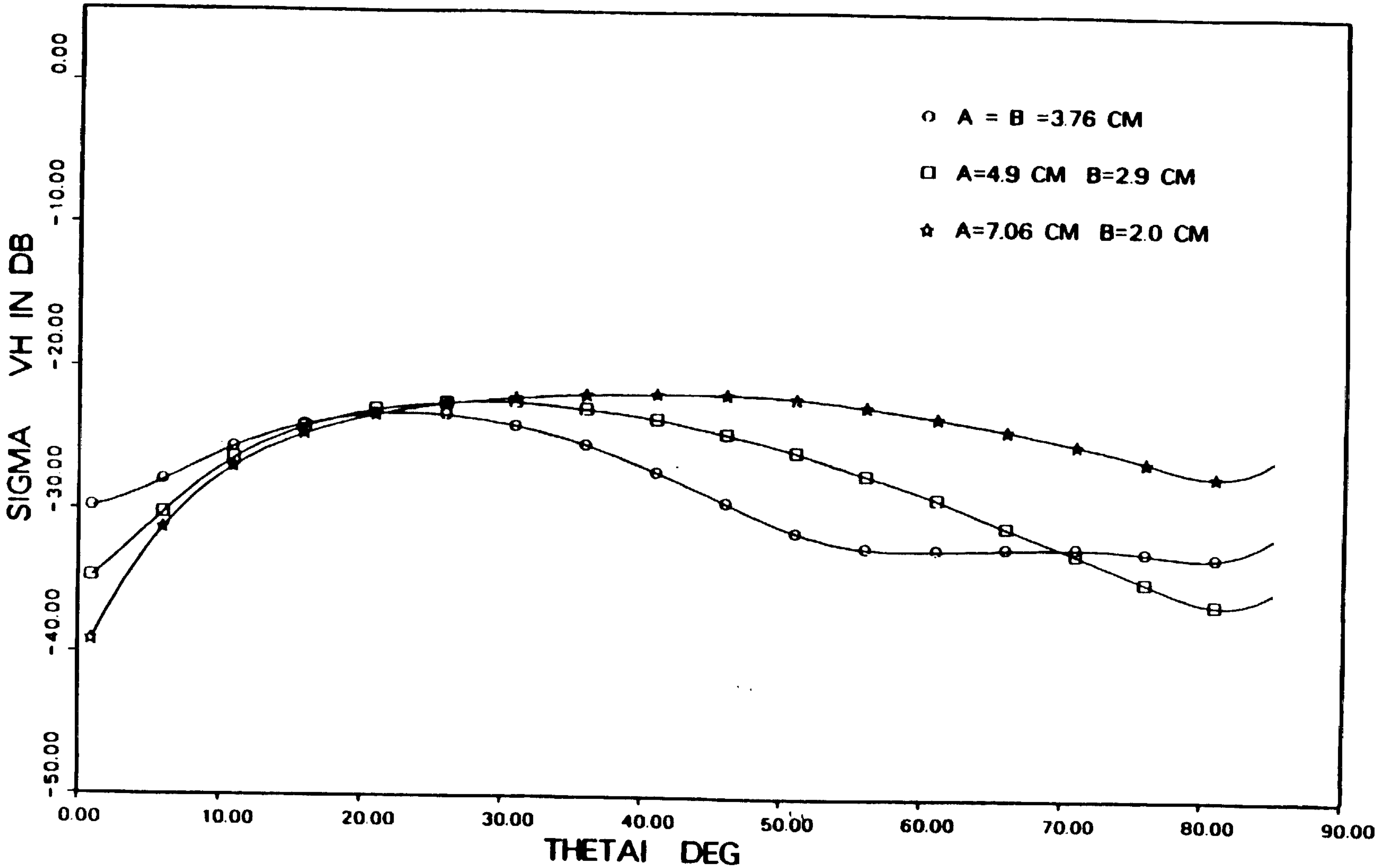

Figure 5. Effect of Leaf Eccenticity on the Cross Polarized Backscattering Coefficient

brightness temperatures from vegetation canopies. The Peak relationship has been employed where by the results for the active problem, that is the bistatic scattering coefficient, can be used directly to obtain both the horizontal and vertical brightness temperatures of the canopy. The passive model developed, which is for leaf canopies only, has a simple structure but contains a four dimensional integral. Presently, methods for efficiently evaluating this integral have been investigated.

As reported previously, a passive model has been developed to compute horizontal and vertical brightness temperatures from a soybean canopy at L band. The soybeans have been replaced by circular discs having a prescribed radii and inclination angle distributions. The leaves are assumed to be uniformly distributed in the azimuthal coordinate. The calculation of the brightness temperatures required computing integrals over the two scattering angles, the two orientation angles and the radius distribution. By use of a low frequency expansion the numerically intensive calculation was speeded up considerably.

To verify the theory, radiometer and ground truth data was taken in the summer of 1987 at Beltsville, Maryland. At the time of the measurements, orientation angles and the areas of a substantial number of soybean leaves were measured. From these measurements inclination angles and radius distributions were developed. Furthermore, the density of leaves were determined, as well as the dielectric constant of the leaves and the underlying soil. Thus all model parameters thought to be of importance were measured. Measurements of brightness temperatures were made for both dry and wet soils.

Comparison of the theory and the experiment are shown in the two accompanying figures (Figs. 6 and 7) for the horizontally polarized case. The curve labeled TB_{exp} is the experimental data. The TB_o is the theoretical bare surface values without vegetation, TB_{sp} is the brightness temperature taking

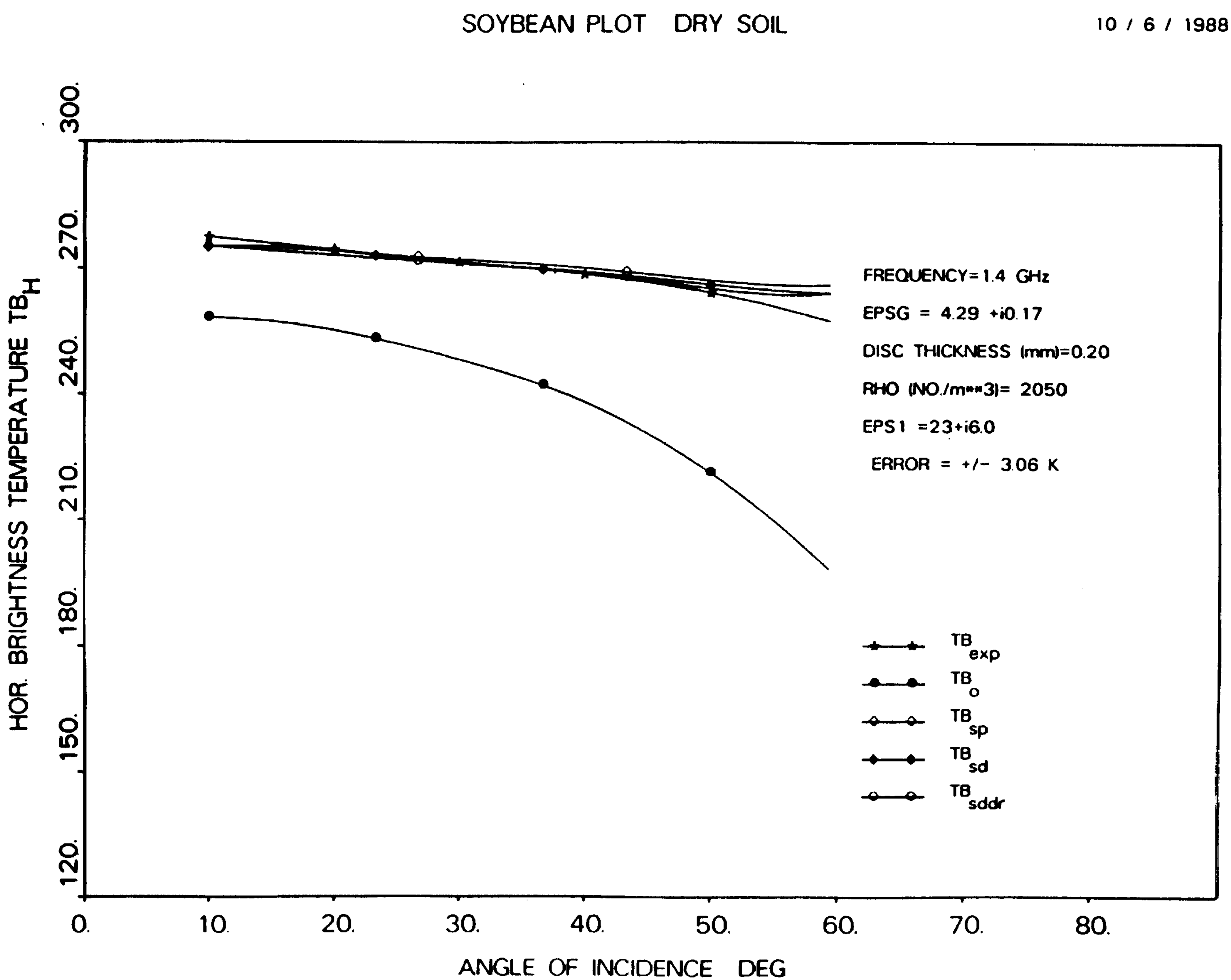

Fig. 6. Brightness Temperature vs Angle of Incidence for Dry Soil

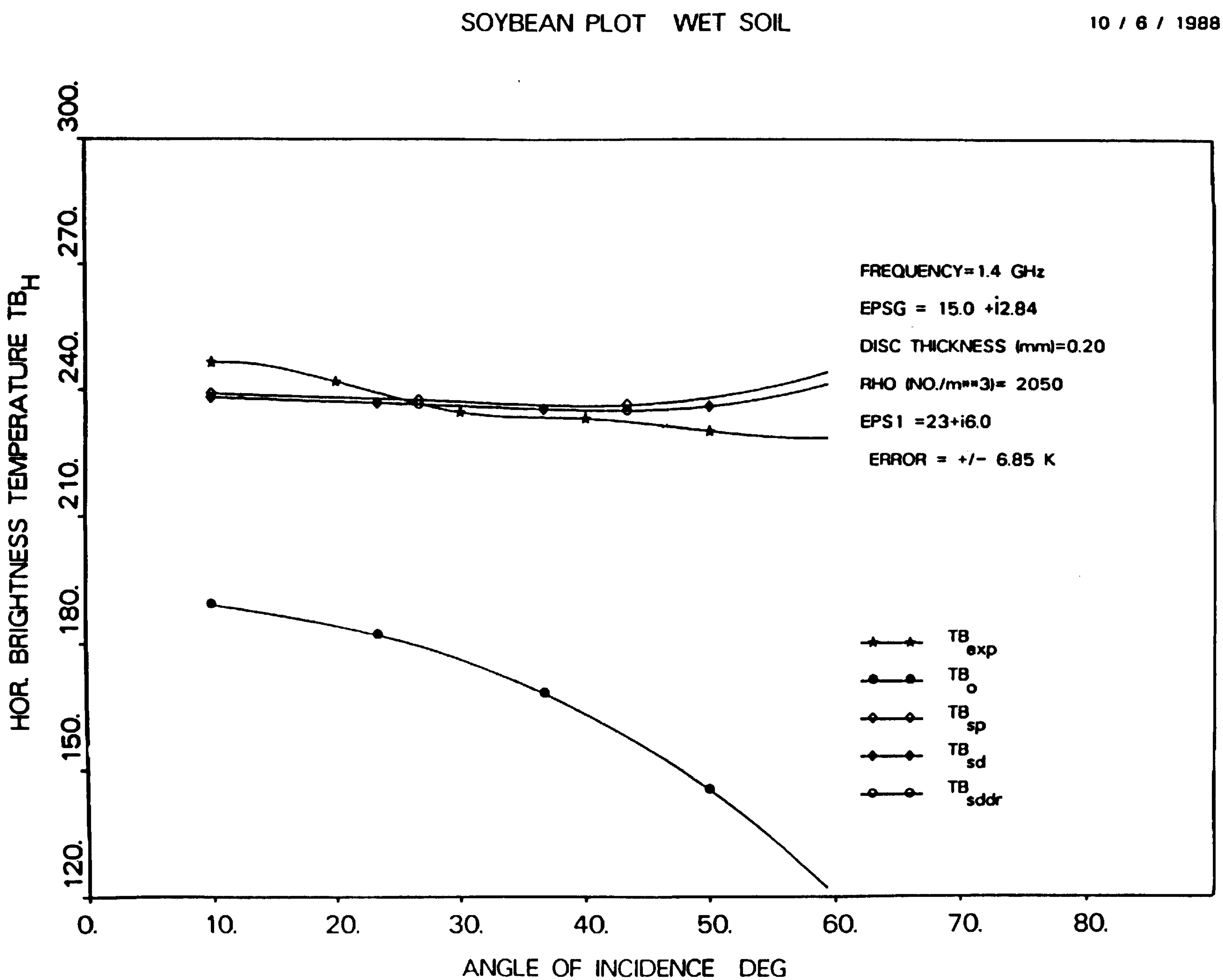

Fig. 7. Brightness Temperature vs Angle of Incidence for Wet Soil

the attenuating effect of the layer into account and TB_{sd} and TB_{sddr} show the effect of adding scattering effects into the calculation. One graph is for dry ground and the other for wet. An examination of the curves, shows that in both cases the match between experiment and theory is quite good, however the dry soil case is better.

For the vertically polarized case subsurface mechanisms are being investigated to try and explain the observed effect. Early in the investigation it was noticed that the main difference between the Fresnel predicted values and the experimental values occurred at the Brewster angle. Since at this angle the wave couples strongly into the ground, it was thought that some inhomogeneity such as a layer was disturbing this coupling mechanism. To test this hypothesis, the problem of a ground with a vertically stratified layer was analyzed. It was found that layer with with as little as 15% change in dielectric could cause substantial changes in the vertical brightness temperature at the Brewster angle without effecting the horizontal brightness temperature markedly. Further studies of this effect are being made.

D. PULSE PROPAGATION

During the past several years, radar ranging techniques have come into increased use. They provide a method for isolating backscatter from individual layers of the canopy. Other investigators have developed algorithms which relate backscatter to attenuation and scattering in the canopy. Their derivation is based on the water cloud mode. We have rederived these results and generalized them by using the distorted Born approximation. The improved algorithms, which have been obtained, relate radar backscatter to the average scatterer characteristics. The formulas incorporate polarization effects as well as the interference effect between the ground and the vegetation. The results are for a finite incident beam with a given polarization. The incident beam has a specified pulse shape. The theoretical results give the backscattered pulse as a function of time. The final algorithm contains explicitly the effects of the direct, direct-reflected and the reflected contributions to the scattering.

E. EFFICIENT COMPUTATION OF CROSS SECTIONS

Discrete microwave modeling of vegetation, via the single or multiple scattering methods, involves the computation of the average phase function for each scattering type used in the model. The calculation, which involves averaging the phase function over all scatterer orientations and sizes, is usually computationally intensive. This calculation has been made more efficient by employing either low frequency or high frequency expansion techniques. The efficient method have been developed for both discs and cylinders. These techniques have been used in a passive model of a soybean canopy and in an orchard. Both models required averaging over many element types (different size leaves and branches) and thus are computational intensive.

As mentioned above the efficient cross section methods were used in a passive L band model of a soybean canopy. The model was based on the Peake formula to relate scattering coefficient of the soybean layer to its brightness temperature. The model results are presently being compared with experimental results obtained at Beltsville, MD in the summer of 1987 using a 1.4 GHz radiometer. To facilitate the comparison of theory and measurement, ground truth data consisting of leaf azimuth and inclination angles, leaf area, leaf thickness and leaf dielectric constant have been measured. The use of this data in the theory resulted in the need to perform a five-dimensional integral over leaf radii, orientation and scattering angles. The efficient calculation of scattering cross sections made such a calculation possible in reasonable CPU times.

F. X-BAND CANOPY MODEL

In the past the GWU radar vegetation model has been applicable for both L and C band frequencies. Over the past year the model has been extended to the X band frequency range. The development of this model has been a two step process. First, the average characteristics of scatterers must be found at X band and then their backscattering characteristic as an ensemble must be computed. Computation of the average bistatic scattering cross section of a leaf, branch or trunk becomes increasingly difficult as the wavelength becomes small compared to the size of the object. Basically, the scattering pattern of an individual scatterer oscillates more and more as the wavelength decreases. Computing the average overall the scatterer orientations takes an increasing amount of computer time. To bypass this difficulty, the average integrals over the scattering cross section have been asymptotically evaluated. This greatly reduced the computation time and, in addition, the resulting average scattering cross section can now be interpreted in terms of geometric-optic constructs.

At L and C bands the distorted Born approximation is used to compute the radar backscattering cross section from the scattering characteristics of individual scatterers. This approximation basically assumes that multiple scattering is not important. At X band frequencies, this approximation is no longer true and a multiple scattering approach must be used. The vector transport approach has been used to compute backscatter from forests at X band frequencies. The transport equations used have been modified to account for individual scatterers. At high frequencies or small wavelengths the average bistatic scattering cross section has a large peak in the forward scattering direction. This is introduced in the vector transport equations as a separate delta function contribution. If the equations are not iterated a new "high frequency" distorted Born approximation is developed which is valid in the X band frequency domain. The method has been applied to leaves and is presently being applied to finite size dielectric cylinders.

III. PUBLICATIONS AND CONFERENCE PAPERS

"Average Reflected Power from a One Dimensional Slab of Discrete Scatterers," with S. Saatchi, Radio Science, 25, pp. 407-417, 1990.

"Average Reflected Power from a One Dimensional Slab of Discrete Scatterers," presented at URSI International Symposium on Electromagnetic Theory, Stockholm, Sweden, August 1989.

"Electromagnetic Backscattering from a Layer of Random Discs in the Small Wavelength Limit," with O. Yazici, presented at Progress in Electromagnetic Research Symposium, Boston MA, July 1989.

"Self Consistent Approach to Average Waves in a One Dimensional Discrete Random Medium," with S. Saatchi, presented at Progress in Electromagnetic Research Symposium, Boston, MA, July 1989.

"Comparison of Theoretical and Measured Brightness Temperature of a soybean Canopy," with D.M. LeVine, P. O'Neill, S.Saatchi, O. Yazici and T. Jackson, presented at IGARSS'89, Vancouver, Canada, July 1989.

"X-Band Backscatter Modeling of Orchard Canopy," with N. S. Chauhan, presented at IGARSS'89 Meeting, Vancouver, Canada, July 1989.

"Radiowave Propagation within Trunk-Dominated Forests: Coherence Bandwidth and Delay Spread," with A. Schneider, presented at IGARSS'89 Meeting in Vancouver, Canada, July 1989.

"Transient Response of a Layer of Discrete Random Media," presented at URSI International Symposium on Electromagnetic Theory, Stockholm, Sweden, July 1989.

"Discrete Microwave Vegetation Models," presented at the Remote Sensing Science Program Annual Workshop, Santa Barbara, CA, January 1989.

"Polarization Utilization in the Microwave Inversion of Leaf Angle Distributions," with N.S. Chauhan, IEEE Trans of GRS, GE-27, pp 395-403, 1989.

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"Microwave Modeling of an Orchard Canopy," with N.S. Chauhan, presented at IGARSS'88 Meeting in Edinburgh, Scotland, September 1988.

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"L-Band Attenuation in a Trunk-Dominated Forest," with A. Schneider and R. Diaz, presented at IGARSS'87 Meeting, Ann Arbor, MI, May 1987.

"Polarization Utilization in the Microwave Inversion of Leaf Angle Distributions," with N. Chauhan, presented at IGARSS'87 Meeting, Ann Arbor, MI, May 1987.

"Two Dimensional Inversion of Leaf Area and Inclination Angle Distributions from Backscattered Data," H.A. Saleh and R.H. Lang, pp. 221-223 in IV.V. Varadan and V.K. Varadan, Editors, Multiple Scattering of Waves in Random Media and Random Rough Surfaces, published by The Pennsylvania State University, University, PA, 1987.

"Vector Solution for the Mean Electromagnetic Fields in a Layer of Random Particles," with S. Seker and D. LeVine, Radio Science, 21, pp. 771-786, September-October, 1986.

"Microwave Backscattering from an Anisotropic Soybean Canopy," with S. Saatchi and D.LeVine, presented at IGARSS'86 Meeting, Zurich, Switzerland, September 1986.

"The Relationship Between the Dyadic Field Correlation Function and Vector Transport Theory," with A. Ghuniem presented at the IEEE-APS/URSI Meeting, Philadelphia, PA, June 1986.

"Microwave Backscattering from Vegetation - A Discrete Scatterer Approach," presented at the Fourth Annual Workshop of the NASA Remote Sensing Science Research Program, La Jolla, CA, February 1986.

"Scattering from Thin Dielectric Disks," with D. LeVine, A. Schneider, H. Carter, IEEE AP-33, pp. 1410-1413, December 1985.

"The Relationship Between the Field Correlation Function and the Specific Intensity," with A. Ghuniem, presented at Conference of Multiple Scattering of Waves in Random Media and Rough Surface, Pennsylvania State University, PA, July, 1985.

"The Relation Between the Correlation Function and the Specific Intensity," with A. Ghuniem, presented at IEEE/APS and URSI Meeting Vancouver, British Columbia, June 1985.

"Inverse Solution for a Slab of Random Dielectric Discs: Orientation and Area Distribution," with H. Saleh, presented at IEEE, APS URSI Meeting Vancouver, British Columbia, June 1985.

"Microwave Inversion of Leaf Area and Inclination Angle Distribution," presented at NASA Fundamental Research Science Radiation and Atmospheric Effects Meeting at MIT, MA, January 1985.

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